MINNESOTA POLLUTION CONTROL AGENCY

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June 22, 2026

VIA EMAIL

To: Interested parties

RE: West River Dairy Expansion

The Minnesota Pollution Control Agency (MPCA) has approved the Findings of Fact, Conclusions of Law, and Order for a Negative Declaration (FOF) on the need for an Environmental Impact Statement (EIS) on the West River Dairy Expansion (Project). The FOF document concludes that this project does not have the potential for significant environmental effects. The decision for a Negative Declaration completes the state environmental review process under Environmental Quality Board (EQB) rules, Minn. R. ch. 4410. Final governmental decisions on permits or approvals for the project may now be made.

The MPCA appreciates comments submitted on the Environmental Assessment Worksheet (EAW). The comments were considered by MPCA staff during the environmental review process and responses to these comments are provided in the FOF.

Interested parties can review the FOF and the EAW documents at the following locations: the MPCA office in Saint Paul; the Hennepin County Library at 300 Nicollet Mall, Minneapolis; and the Marshall-Lyon County Library at 201 C Street, Marshall, Minnesota. Interested parties can also view the documents on MPCA's website at: https://www.pca.state.mn.us/business-with-us/recently-completed-mpca-reviews. Please contract Charles Peterson, charles.peterson@state.mn.us, if you have issues accessing the documents. Please contact the MPCA's Saint Paul office at 651-757-2098 for copies of these documents.

Sincerely,

Katrina Hapka

This document has been electronically signed.

Katrina Hapka
Supervisor
Environmental Review Unit
Resource Management and Assistance Division

Attachments

cc: See next page.

cc: Molly Mehl, NRCS Tribal Liaison (electronic) (w/attachments)
Kelly Kingbird, Tribal Liaison (electronic) (w/attachments)
Scott Doig, Tribal Liaison (electronic) (w/attachments)
Vanessa Alberto, Tribal Liaison (electronic) (w/attachments)
Alan Walts, Tribal Liaison (electronic) (w/attachments)
Allison Smart, Tribal Liaison (electronic) (w/attachments)
Walt Ford, Tribal Liaison (electronic) (w/attachments)
Billie Isham, Tribal Liaison (electronic) (w/attachments)
Jackie Dionne, Tribal Liaison (electronic) (w/attachments)
Ravyn Gibbs, Tribal Liaison (electronic) (w/attachments)
Bradley Harrington, Tribal Liaison (electronic) (w/attachments)
Levi Brown, Tribal Liaison (electronic) (w/attachments)
Shannon Kesner, Tribal Liaison (electronic) (w/attachments)
Melissa King, Tribal Liaison (electronic) (w/attachments)
Wendy Helgamo, Tribal Liaison (electronic) (w/attachments)
Corey Strong, Tribal Liaison (electronic) (w/attachments)
Curt Yoakam, Tribal Liaison (electronic) (w/attachments)
Isaac Weston, Minnesota Indian Affairs Council (electronic) (w/attachments)
Katrina Kessler, MPCA (w/attachments)
Peter Tester, MPCA (w/attachments)
Korey Southerland, MPCA (w/attachments)
Glenn Skuta, MPCA (w/attachments)
Anna Hotz, MPCA (w/attachments)
Lisa Scheirer, MPCA (w/attachments)
Brian Timerson, MPCA (w/attachments)
David Malakowsky, MPCA (w/attachments)
Mark Gernes, MPCA (w/attachments)
Nick Timmerman, MPCA (w/attachments)
Paul Wymar, MPCA (w/attachments)

STATE OF MINNESOTA
MINNESOTA POLLUTION CONTROL AGENCY

In The Matter Of The Decision On The Need For An Environmental Impact Statement For The Proposed West River Dairy Expansion Project Stevens County, Synnes Township, Minnesota

FINDINGS OF FACT CONCLUSIONS OF LAW AND ORDER

INTRODUCTION

As directed by Minn. Stat. 116D.03 and 116D.04 and pursuant to Minn. ch. 4410, the Minnesota Pollution Control Agency (MPCA) staff prepared and distributed an Environmental Assessment Worksheet (EAW) for the proposed West River Dairy Expansion (Project) in Section 1, Synnes Township, Stevens County. Based on the MPCA staff environmental review, the EAW, comments, and information received during the comment period, and other information in the record of the MPCA, the MPCA hereby makes the following Findings of Fact, Conclusions of Law, and Order.

FINDINGS OF FACT

Project Description

1. Riverview LLP (Proposer) proposes expanding the existing West River Dairy 7,855-cow (10,997 AU) facility (Facility) by adding 11,000 dairy cows (15,400 AU) to the facility in Section 1 of Synnes Township, Stevens County. Cows will be housed in a cross-ventilated, total-confinement, free-stall barn and will use clay-lined basins with impermeable covers to collect and store manure and wastewater. Liquid manure will be land applied as fertilizer on cropland. The Project is in the Pomme de Terre Watershed (HUC 07020002) within the Minnesota River Basin at 52755 280th St, Morris, MN 56267.
2. The application for an MPCA individual National Pollutant Discharge Elimination System (NPDES) permit (Feedlot Permit) was submitted on December 12, 2025.

Procedural History

3. An EAW is a brief document designed to provide the basic facts necessary for the Responsible Governmental Unit (RGU) to determine whether an Environmental Impact Statement (EIS) is required for a proposed project or to initiate the scoping process for an EIS (Minn. R. 4410.0200, subp. 24). The MPCA is the RGU for this Project.
4. Pursuant to Minn. R. 4410.4300, subp. 1, the Project requires the preparation of an EAW because the Minn. R. 4410.4300, subp. 29.A. 1,000 AU animal feedlot threshold is exceeded.
5. The MPCA provided public notice of the Project as follows:
6. The MPCA notified local governmental units and Tribal Nations in counties of interest of receipt of the EAW on March 12, 2024, May 9, 2025, and November 4, 2025.

7. The Environmental Quality Board (EQB) published the Notice of Availability of the EAW for public comment in the EQB Monitor from February 10, 2026, to May 7, 2026.
    - The EAW was available for review on the MPCA website at: https://mpca.commentinput.com/comment/search.
    - The MPCA provided a news release to media in Stevens County, Minnesota on March 10, 2026.
8. The Proposer's coverage under a feedlot permit was open for public comment from February 10, 2026, to May 7, 2026.
    - The MPCA conducted a public meeting on April 28, 2026.
9. Comments from Tribal Nations were sought early and throughout the environmental review process, as follows: early coordination notification were emailed to tribal contacts in counties of interest on March 12, 2024, May 9, 2025, and November 4, 2025. MPCA asked Proposer to contact the State Historic Preservation Office (SHPO), Minnesota Indian Affairs Council (MIAC), and Office of the State Archaeologist (OSA) regarding the project proposal. MPCA emailed the complete EAW packet for public comment period to tribal contacts in counties of interest. MPCA will email the final findings of fact package (FOF package) to tribal contacts in counties of interest.
10. During the comment period on the EAW ending on May 7, 2026, the MPCA received two comments from the Minnesota Department of Natural Resources, and 1,314 community members and 60 comments on the Feedlot Permit during the joint comment period. Only one of the 60 comments on the Feedlot Permit was related to the Feedlot Permit; the remaining 59 were for the EAW. Well after the comment period closed, the MPCA received two additional comments submitted by the Minnesota Center for Environmental Advocacy (MCEA) and the Land Stewardship Program (LSP). Although not a part of the record or MPCA's decision, the MPCA did review the two comments which were similar to other comments made during the comment period, and they do not alter the MPCA's decision to issue a negative declaration.
11. On May 11, 2026, the MPCA requested and received approval from the EQB for a 15-day extension of the decision-making process on the need for an EIS for the Project in accordance with Minn. R. 4400.1700, subp. 2(B).
12. The list of comments received during the public comment period is Appendix A to these Findings. The MPCA prepared written responses to the comments received on the EAW and Feedlot Permit during the public comment period in Appendix B.
13. An Errata Sheet is in Appendix C to these Findings.

The four criteria for determining the potential for significant environmental effects

14. The MPCA shall base its decision on the need for an EIS on the information gathered during the EAW process and the comments received during the comment period. (Minn. Stat. 116D.04, Subd. 2a(d); Minn. R. 4410.1700, subp. 3). The MPCA must order an EIS for projects that have the potential for significant environmental effects (Minn. R. 4410.1700, subp. 1). In deciding whether a Project has the potential for significant environmental effects, the MPCA must compare the impacts that may be reasonably expected to occur from the Project with the criteria set forth in Minn. R. 4410.1700, subp. 7. The four criteria are:
    A. Type, extent, and reversibility of environmental effects;

B. Cumulative potential effects. The RGU shall consider the following factors:

- whether the cumulative potential effect is significant;
- whether the contribution from the Project is significant when viewed in connection with other contributions to the cumulative potential effect;
- the degree to which the Project complies with approved mitigation measures specifically designed to address the cumulative potential effect; and
- the efforts of the Proposer to minimize the contributions from the Project.

A. The extent to which the environmental effects are subject to mitigation by the ongoing public regulatory authority. The RGU may rely only on mitigation measures that are specific and that can be reasonably expected to effectively mitigate the identified environmental impacts of the Project.

B. The extent to which the environmental effects can be anticipated and controlled as a result of other available environmental studies undertaken by public agencies or the Project Proposer, including other EISs.

The MPCA Findings with respect to each of these Criteria

A. Type, extent, and reversibility of environmental effects

15. The first criterion that the MPCA must consider when determining if a project has the potential for significant environmental effects is the "type, extent, and reversibility of environmental effects" (Minn. R. 4410.1700, subp. 7(A)). The MPCA Findings with respect to these criteria are set forth below.

16. A summary of the types of Project impacts the MPCA finds may be reasonably expected to occur from the Project include:

    a. Surface water quality
    b. Groundwater quality
    c. Air quality (hydrogen sulfide, ammonia, odor)
    d. Greenhouse gas emissions

17. Public comments received during the comment period that raised additional issues include:

    e. Groundwater appropriations
    f. Traffic

18. With respect to the extent and reversibility of impacts that are reasonably expected to occur from the Project, the MPCA makes the following Findings:

19. Description of the types of Project impacts the MPCA finds may be reasonably expected to occur:

19.1.1 Surface Water Quality

19.1.2 The EAW outlines construction and operational requirements used to comply with the water quality discharge standards of Minn. R. pt. 7020.2003 and the Feedlot Permit. This includes the requirement to design, construct, operate and maintain the Facility to contain all contaminated runoff and the direct precipitation up to the volume from a 25-year 24-hour storm event. The Project provides 14 months of manure and process wastewater storage (versus nine months required by Minn. R. 7020.2100.)

19.1.3 Minn. R. 7020.2015 and the Feedlot Permit prohibits all animals at an animal feedlot facility from entering waters of the state.

19.1.4 The Project's Nutrient Management Plan (NMP), and the Feedlot Permit include measures and requirements to prevent impacts to surface water and groundwater from land application of manure that are applicable to all manure generated by the Facility. All other manure land applied within the same watershed is subject to similar measures and requirements found in Minn. R. 7020.2225, to prevent impacts from to surface water and groundwater.

19.1.5 Storage structures for liquid manure will meet the design criteria of Minn. R. 7020.2100. Additionally, a professional engineer licensed in Minnesota is required to design and oversee the construction of liquid manure storage structures. The Proposer is required to examine any Liquid Manure Storage Area (LMSA) drain tile outlet monthly for water flow and signs of discoloration or odor in any water in the drain tile, and maintain and monitor a minimum of three feet of freeboard for the Project's LMSAs.

19.1.6 Minn. R. 7020.2225 and the Feedlot Permit require the Proposer to manage all manure following an NMP approved by the MPCA.

19.1.7 The Project's NMP, incorporated by reference into the Feedlot Permit, meets all rule and permit requirements and thus ensures the Proposer (and recipients of manure) will utilize the nutrients properly to protect water quality. The NMP is a planning tool that is used to ensure nutrients are properly utilized and land application of manure methods and practices prevent impacts to waters on a field-by-field basis.

19.1.8 The NMP describes how manure generated by the Project will be applied to meet all rules and regulations and protect surface water and groundwater quality.

19.1.9 The NMP for the Project requires total nutrients (manure and other sources) be applied following the Feedlot Permit and Minn. R. 7020.2225 requirements.

19.1.10 Manure application rates may also be limited when soil phosphorus test results exceed levels listed in Minn. R. 7020.2225 and the Feedlot Permit. Phosphorus management is required in special protection areas when soil phosphorus test results exceed 21 parts per million (ppm) Bray P1 or 16 ppm Olsen. Additional Feedlot Permit restrictions apply to fields testing exceedingly high for soil phosphorus.

19.1.11 Based on typical crop rotations for planned application acres, the number of acres available for the Project are adequate to ensure that the estimated plant-available nitrogen (N) from the manure and process wastewater generated by the Facility does not exceed the expected crop N needs for non-legume crops or the expected N removal for legume crops.

19.1.12 To minimize impacts from surface runoff at the manure application sites, the Proposer must observe setbacks to waters, open tile intakes, sinkholes, mines, quarries, and wells as specified in Minn. R. 7020.2225 and the Feedlot Permit. Where a county also has setback requirements for land application of manure, the Proposer must follow the most restrictive of the state or county setback requirements. Additionally, application of liquid manure is prohibited during the months of December, January, February, and March if winter conditions exist.

19.1.13 The Feedlot Permit requires the transport of manure in a manner to prevent it from leaking or spilling onto public roadways. If manure leakage or spillage occurs, it must be cleaned up and land applied following Minn. R. 7020.2010 and the Feedlot Permit.

19.1.14 The Proposer has identified 16,669 acres of cropland available for manure application. Based upon the approved NMP, this is adequate for land application of the manure at agronomic rates.

19.1.15 The NMP for the Project indicates all manure applications to fields will be injected or incorporated within 24 hours, which further limits potential impacts due to runoff from the land application sites. This also limits the potential for bacterial transport from the manure application sites to waters.

19.1.16 When ownership of manure generated by the Project is transferred to a third-party recipient, the Feedlot Permit requires the Proposer, before or at the time of manure land application, to provide the manure recipient with the most current manure nutrient analysis, a sensitive features map for each field where the transferred manure will be applied, for and a summary of requirements that manure recipients must follow, including protective measures identified in the Permittee's approved nutrient management plan to minimize risk of surface and groundwater contamination from manure applications. The recipient of the manure must ensure the agronomic rates of the crop are not exceeded by the application of nutrients from manure, including contributions from any other source. Manure recipients must follow the NMP of the Proposer, including location and timing restrictions, record keeping, and nitrogen best management practices (BMPs). The manure recipient must also apply manure following required setbacks and other requirements of Minn. R. 7020.2225 and the Feedlot Permit.

19.1.17 All manure recipients must keep records of the quantity and nutrient content of the manure applied as well as the location and rate of application. These records must be provided back to the Proposer within 60-days of application. The Proposer must submit all records annually to the MPCA.

19.1.18 The Proposer must keep records of manure application activities for the six most recent years. The records must include the amount and nutrient content of manure, location where the manure is applied, the rate, timing, and method of application, and nitrogen application best practices.

19.1.19 If a manure spill occurs, the Proposer must comply with the Emergency Response Plan developed as part of the permit application process and incorporated into the Feedlot Permit. Minn. Statute 115.061. The Feedlot Permit requires the Proposer to report manure spills to the MN Duty Officer and requires all responsible parties to take immediate action to stop the discharge and recover the material.

19.1.20 The MPCA does not reasonably expect significant adverse impacts to water quality, however, if they were to occur the Proposer must modify the operation and management of the Project. The MPCA requires modification of the Feedlot Permit coverage for those items found to cause pollution of waters, including modification of the NMP, for impacts from land application, and the impacts to waters would be reversed.

19.1.21 All manure application areas are within the Pomme de Terre River Watershed, and several are adjacent to impaired waters including: Lake Hattie (WID: 75-0200-00), Unnamed Basin (WID: 75-0375-00), Pomme de Terre River (WID: 07020002-501), Muddy Creek (WID:

07020002-511), Dry Wood Creek (WID: 07020002-556), Unnamed Stream (WID: 07020002-551), and Unnamed Stream (WID: 07020002-576).

19.1.22 County Tile 30 outlets into two unnamed creeks (WID 070200002-551 and 07020002-552), which then flows to the Pomme de Terre River (WID 07020002-501), and then eventually to the Minnesota River (WID 070200001-552).

19.1.23 The Federal Clean Water Act (CWA) (33 U.S.C. and 303 (d)) (1972) requires that each state develop a plan to identify and restore a waterbody that is deemed impaired by state regulations. The Environmental Protection Agency (EPA) requires a Total Maximum Daily Load (TMDL) in accordance with the Clean Water Act. A TMDL identifies pollutants causing impairment and how many of those pollutants can enter the waterbody while still meeting water quality standards.

19.1.24 Minnesota's "Final Animal Agriculture Generic Environmental Impact Statement" (2002) and the University of Minnesota Agriculture Extension Program state that manure not only supplies nutrients but can also improve the biological and physical properties of soil, making it more productive and less erosive. Manure provides valuable organic matter to soil that improves soil tilth, aids in the retention of water and nutrients, and promotes growth of beneficial microorganisms. Manure, when properly used as part of a soil management program, improves soil quality, builds soil structure, and increases the level of soil organic matter.

19.1.25 There are no aquatic invasive species or impaired waters within one mile of the Project site.

19.1.26 The Project site is designed to capture and reuse most or all of stormwater runoff, reducing the untreated runoff that currently leaves the property.

19.1.27 The Feedlot Permit incorporates by reference the MPCA Construction Stormwater (CSW) permit and requires a Stormwater Pollution Prevention Plan. Both regulate the collection and management of stormwater.

19.1.28 The Feedlot Permit requires the management, collection, and storage of process wastewater, including stormwater that comes in contact with pollutant sources defined in the permit.

19.1.29 Minn. R. 7020.2225 and the feedlot permit include measures and requirements to prevent impacts to surface waters and "not cause or contribute to non-attainment of applicable state water quality standards"

19.1.30 The MPCA finds that information presented in the EAW and other information in the environmental review record are adequate to assess potential impacts to surface water quality that are reasonably expected to occur from the Project.

19.1.31 The MPCA finds the Project, as proposed, does not have the potential for significant environmental effects based on the type, extent and reversibility of impacts related to surface water quality, which are reasonably expected to occur.

19.2 Groundwater Quality

19.2.1 The Proposer will install an inspection port near the LMSAs to enable monthly visual inspections. After construction, the Proposer will ensure the drain-tile system is functioning correctly for each LMSA and look for signs of discoloration or odor that may indicate an issue with the liner.

19.2.2 The risk of contamination of groundwater quality due to the LMSAs is low due to the engineered concrete structures and clay-lined design for the Project.

19.2.3 LMSAs at the Project site will exceed the required soil seepage standard, and LMSA clay-liner thickness will be increased from two feet to five feet.

19.2.4 The Proposer may encounter shallow groundwater during construction of the LMSAs, so they will install a perimeter drain-tile system at an elevation that is lower than the liner within the LMSA to reduce external groundwater pressure on the walls and to control seasonal subsurface saturation near the LMSAs.

19.2.5 To minimize the potential for nitrate leaching into the groundwater at the manure application sites, the Project is required to follow Minn. R. Ch. 7020 and Feedlot Permit requirements relating to application of nutrients (manure) generated from the Project in combination with other nutrient sources.

19.2.6 Potential sources of N include commercial fertilizer, manure applied during the current crop year, manure applied during the previous crop year, irrigation water, and legumes grown during previous years.

19.2.7 The Project's nutrient management plan describes how manure in combination with other nutrient sources will be applied at agronomic rates. N rates must be limited so that the estimated plant-available nitrogen (N) from all N sources does not exceed the expected crop N needs for non-legume crops or the expected N removal for legume crops.

19.2.8 To further minimize the potential for nitrate leaching into the groundwater, the Feedlot Permit requires the Project implement BMPs. One of the listed BMPs must be followed for land application during warm soil moths of June, July, August, September. Potential BMPs requirements include: application to actively growing crops, planting cover crops, use of a nitrapyrin-based nitrogen stabilizing product, delaying application until soil temperature has reached 50 degrees or less for two consecutive days, crop rotations that include growing perennial crops two years during any five-year period and reduced rate split N applications.

19.2.9 The Proposer will follow the state or county setbacks from ditches, lakes, tile intakes, and wells, whichever is more protective/restrictive, to prevent nutrient runoff into those features.

19.2.10 The MPCA finds that information presented in the EAW and other information in the environmental review record are adequate to assess potential impacts to the groundwater quality that are reasonably expected to occur from the Project.

19.2.11 The MPCA finds the Project, as proposed, does not have the potential for significant environmental effects based on the type, extent and reversibility of impacts related to groundwater quality, which are reasonably expected to occur.

19.3 Air Quality Related to Hydrogen Sulfide Emissions

19.3.1 The Proposer conducted air dispersion modeling to estimate the atmospheric concentrations of hydrogen sulfide. The Proposer's modeling used the American Meteorological Society Regulatory Model (AERMOD) developed by the American Meteorological Society and the U.S. Environmental Protection Agency. The model evaluated the air quality impacts of the Project. AERMOD is a widely accepted air dispersion model, which uses conservative assumptions to predict air quality.

19.3.2 The air modeling predicts the Project will comply with the 30 parts per billion (ppb) hydrogen sulfide Minnesota Ambient Air Quality Standards (MAAQS). Under the hydrogen sulfide MAAQS, the third exceedance of the MAAQS within any 5-day period is a violation. The air modeling demonstrates compliance when the high-third-high hydrogen sulfide concentration (added to background concentration) for any 5-day period at each property-line receptor is below the ambient standard of 30 ppb.

19.3.3 The air modeling predicts the Project emissions alone will result in a maximum property-line hydrogen sulfide concentration of 12.44 ppb. The estimated ambient air concentration for hydrogen sulfide in the Project area is 17 ppb. The total (Project emissions plus existing background) hydrogen sulfide concentration is predicted to be 29.44 ppb at the Project's property lines.

19.3.4 When analyzing Sub-Chronic Inhalation Health Risk Value (iHRV), air modeling predicts the Project will not exceed the 10 micrograms per cubic meter ($\mu g/m^3$) subchronic (13-week) hydrogen sulfide iHRV at neighboring residences. iHRVs are concentrations of chemicals emitted to air that are unlikely to pose a significant risk of harmful effects when humans are exposed to those concentrations over a specified period.

19.3.5 The air modeling predicts the Project emissions alone will result in a maximum monthly hydrogen sulfide concentration of 0.21 $\mu g/m^3$ at the nearest residence. The estimated hydrogen sulfide background concentration in the Project area is 1.0 $\mu g/m^3$. The total Project emissions plus existing background H_2S concentration in the air is predicted to be 1.21 $\mu g/m^3$. Note, while the iHRV is for a 13-week period, AERMOD is not capable of averaging concentrations for that time- period, so a monthly averaging period was used instead. The monthly averaging period is acceptable because it produces a more conservative or protective prediction than the 13-week period.

19.3.6 Odor mitigation measures include: synthetic covers for all but one open air manure storage basins (one basin will be covered with straw – special O&M requirements included in permit), solids separated from the liquid portion of manure eliminating the need to agitate liquid manure storage areas - agitation creates odor and releases emissions, and all liquid manure is pumped through hoses to cropland, injected during application. These measures are included in the Feedlot Permit as either explicit requirements or incorporated by reference from the permit application materials including manure storage area design plans and specifications and the nutrient management plan.

19.3.7 The MPCA finds that information presented in the EAW and other information in the environmental review record are adequate to assess potential impacts to air quality related to hydrogen sulfide emissions that are reasonably expected to occur from the Project.

19.3.8 Based on the air modeling results discussed above, the MPCA finds that potential impacts to air quality related to hydrogen sulfide emissions expected from the Project do not present the potential for significant environmental effects.

19.4 Air Quality Related to Ammonia Emissions

19.4.1 The air modeling predicts the Project will not exceed the 3,200 $\mu g/m^3$ (1-hour) acute ammonia iHRV at the Project's property-line.

19.4.2 The air modeling predicts the Project emissions alone will result in a maximum hourly property-line ammonia concentration of 1861 $\mu g/m^3$. The estimated ammonia background concentration in the Project area is 148 $\mu g/m^3$. The maximum total (Project emissions plus existing background) property-line ammonia concentration is predicted to be 2009 $\mu g/m^3$.

19.4.3 The air modeling predicts the Project will not exceed the 80 $\mu g/m^3$ (1-year) chronic ammonia iHRV at neighboring residences to the Project site.

19.4.4 The air modeling predicts the Project emissions alone will result in a maximum 1-year time averaged ammonia concentration of 9.39 $\mu g/m^3$ at neighboring residences. Air modeling results indicate the Project, and the 15 neighboring feedlots will not create exceedances of the chronic ammonia iHRV at the neighboring residences. When a background ammonia concentration of 5.72 $\mu g/m^3$ is added to the AERMOD concentration, the maximum annual ammonia concentration for a neighboring residence is 15.11 $\mu g/m^3$, which is below the chronic ammonia iHRV of 80 $\mu g/m^3$.

19.4.5 The MPCA finds that information presented in the EAW and other information in the environmental review record are adequate to assess potential impacts to air quality related to ammonia emissions that are reasonably expected to occur from the Project.

19.4.6 Based on the air modeling results discussed above, the MPCA finds that potential impacts to air quality related to ammonia emissions expected from the Project do not present the potential for significant environmental effects.

19.5 Air Quality Related to Odor Emissions

19.5.1 Although Minnesota has not established ambient air quality standards to regulate odor, the Proposer completed air dispersion modeling for odor. Based on the air dispersion modeling analysis, AERMOD modeling results indicate that after construction, the Project will not exceed the odor strength described as "Moderate" at the south property line.

19.5.2 AERMOD calculated the ground-level odor concentrations at the property lines for the Project and at 11 of the Facility's neighboring residences. The maximum hourly odor concentrations along the Facility's property lines were below the "moderate" odor threshold of 244 OU, except for one hourly exceedance along the near-south property line. The maximum odor concentration for the near south property line was 260 OU. The calculated hourly odor concentration at any property-line receptor was less than or equal to the "faint" odor threshold of 83 OU at least 99.67 percent of the time.

19.5.3 The Proposer submitted an air emissions and odor management plan to the MPCA with its Feedlot Permit application. The plan includes measures the Proposer will take to minimize the generation of odors from the Project and associated manure application activities, including synthetic covers over basins in Facilities 101, 102, and 106 to reduce the release of gases and odors from stored manure. The Proposer will use below ground manure storage pits and immediately inject manure into the soil as its manure application method to minimize odors. The Proposer has also taken other measures as listed in EAW item 6.B. to further reduce odors. Per the Feedlot Permit's air emissions plan, if odor complaints are received and validated by the MPCA, the Proposer must implement methods to mitigate odors, and if monitoring indicates exceedances of State H_2S Standard, the Proposer must

plan and implement measures to control emissions. The MPCA finds that information presented in the EAW and other information in the environmental review record are adequate to assess potential impacts to air quality related to odor that are reasonably expected to occur from the Project.

19.5.4 Based on the modeling results discussed above, the MPCA finds that potential impacts to air quality related to odor at the property lines and nearby residences does not present the potential for significant environmental effects.

19.5.5 Summary of Air Quality Impacts

19.5.6 The Proposer conducted air dispersion modeling to estimate the atmospheric concentrations of hydrogen sulfide, ammonia, and the intensity of odorous gases at the Project property lines and nearest neighbors.

19.5.7 The MPCA expects the Project to meet applicable air quality standards and criteria.

19.5.8 With respect to the reversibility of air quality impacts expected to occur from the Project, air emissions from the Project will continue while it remains in operation and would cease only if the Project were temporarily or permanently closed.

19.5.9 If excessive air emissions or violations of the hydrogen sulfide MAAQS were to occur, or if the Project exceeded iHRVs for hydrogen sulfide or ammonia, air quality impacts are likely to be correctable. The MPCA could initiate an investigation and require the Proposer to make operation and maintenance changes. Therefore, the MPCA finds that any impacts on air quality that may occur from the Project are reversible.

19.5.10 The MPCA finds that information presented in the EAW and other information in the environmental review record are adequate to assess the potential impacts on air quality that are reasonably expected to occur because of the Project.

19.5.11 The MPCA finds the Project, as proposed, does not have the potential for significant environmental effects based on the type, extent, and reversibility of impacts on air quality that are reasonably expected to occur from the Project.

19.6 Greenhouse Gas Emissions

19.6.1 The MPCA considered greenhouse gas (GHG) emission sources that are within the scope of the Project.

19.6.2 The Project will directly release GHG emissions, which can widely disperse within the atmosphere, and which vary both in terms of their global warming potential and their persistence in the atmosphere.

19.6.3 To provide a common unit of measure, the MPCA uses the individual global warming potential (GWP 100) of methane and nitrous oxide to convert to carbon dioxide equivalency (CO_2e). GWP 100 is the standard value used in nearly every regulatory and reporting framework, including EPA's GHG inventories. MPCA accepts the use of GWP 100 values.

19.6.4 Using U.S. Environmental Protection Agency (EPA) emission factors found in Table 8A of the EAW, Scope 1 Construction Sources are 1,915 CO_2e tons per year for one year. After construction and during operation of the Project, Source 1 Mobile Equipment Combustion, Scope 1 Stationary Equipment Combustion, Scope 2 Fugitive Emissions, and Scope 2 Off-site Electricity will be approximately 72,210 CO_2e tons per year. CO_2 emitted to the atmosphere

from combustion of biomass, is considered biogenic CO_2 as defined in Table 4 of the Environmental Quality Board's EAW climate guidance and is considered carbon neutral.

Scope	Type of emission	Emission sub-type	Project-related CO_2e emissions (tons/year)	Calculation method(s)
Scope 1	Construction Land use and combustion	Construction Area; stationary; mobile	1,915 Construction One year only	MPCA Guidance
Scope 1	Land use	Conversion	97	MPCA Calculator[1]
Scope 1	Land use	Area enteric fermentation CH_4	47,531	MPCA Calculator
Scope 1	Land use	Area-barn/manure storage CH_4	19,603	MPCA Calculator
Scope 1	Land use	Area-barn/manure storage N_2O	3,988	MPCA Calculator
Scope 1	Land use	Are-barn/manure land application N_2O	5,841	MPCA Calculator
Scope 1	Land use	Carbon sink-alfalfa conversion	-2,662	MPCA Calculator
Scope 1	Combustion	Stationary heaters	126	MPCA Guidance
Scope 1	Combustion	Mobile equipment	1,626	MPCA Guidance
Scope 1	Land use	Area-ammonia replacement	-9,038	Barr Engineering
Scope 2	Electricity	Grid-based	5,098	MPCA Guidance
Total			72,210	

19.6.5 The Project has a net increase of 72,210 CO_2e per year in GHG emissions, primarily from livestock digestion (enteric fermentation), and manure storage. The total net GHG emissions during the life of the Project (approx. 30 years), including the construction and operation phases, is estimated to be 2.17 million tons CO_2e.

19.6.6 There are no MAAQS or National Ambient Air Quality Standards (NAAQS) for GHG emissions.

19.6.7 Currently, there are no federal or Minnesota thresholds of GHG significance for determining the impacts of GHG emissions from an individual project on global climate change.

19.6.8 In the absence of a threshold of GHG significance, the MPCA looks to existing regulation. Minn. R. 4410.4300, subp. 15(B), establishes a mandatory category requiring preparation of an EAW for stationary source facilities generating a combined 100,000 tons per year of GHG emissions after installation of air pollution control equipment. GHGs include carbon

[1] Based on assumptions using the standard weight of a dairy cow in this region.

dioxide, methane, nitrous oxide, hydrofluorocarbons, perfluorocarbons, and sulfur hexafluoride. The purpose of an EAW is to assess environmental effects associated with a proposed project to aid in the determination of whether an EIS is needed. On the premise of greenhouse gas emissions, environmental regulations establish 100,000 tons per year as a trigger to prepare an EAW to aid in determining potential significant environmental effects. A reasonable conclusion is that the Project's GHG emissions below 100,000 tons per year after installation of control equipment are not considered significant.

19.6.9 The MPCA finds that information presented in the EAW and other information in the environmental review record is adequate to assess potential impacts related to GHG emissions that are reasonably expected to from the Project.

19.6.10 The MPCA finds the Project, as proposed, does not have the potential for significant environmental effects based on the type, extent, and reversibility of impacts related to GHG emissions, which are reasonably expected to occur.

20. Categories of written public comment received during the comment period raised additional issues:

20.1 Groundwater appropriations

20.1.1 Commenters expressed concerns about the volume of groundwater the Project will use.

20.1.2 The Project will use an off-site well (UN# 740629, APEC/Off-Site Well), approximately three miles southeast of the Project.

20.1.3 The APEC/Off-Site Well is an existing well originally constructed for an ethanol plant (APEC) (not constructed) under MN DNR Permit #2008-0230 with an original allocation of 452 million gallons per year (MGY)

20.1.4 The APEC/Off-Site Well is near the Pomme de Terre River valley and is screened in a Quaternary Water Table Aquifer (QWTA), while the wells for the existing facility are screened in the Quaternary Buried Artesian Aquifer (QBAA) beneath the Project site.

20.1.5 The appropriation was established based on the results of a seven-day aquifer pump test that identified sufficient water in the water-table aquifer and confirmed that the aquifer is hydraulically connected to the Pomme De Terre River. As recommended in the Aquifer Test Report, pumping conditions were imposed by the DNR to protect the river in the event of drought or low surface-water flows.

20.1.6 The Proposer has applied for a new water appropriation from the APEC/Off-Site Well for 226 MGY at a proposed maximum pumping rate of 1,000 gallons per minute (gpm) for livestock watering. This original allocation (452 MGY) will be terminated during the permitting process with DNR.

20.1.7 The Proposer consulted with DNR on the use of the APEC/Off-Site Well and confirmed that an additional aquifer test would not be needed from the well provided the new application proposed equal or lesser annual quantities and instantaneous pump rates to what was authorized in permit 2008-0230.

20.1.8 DNR is evaluating the proposed use of that well against statutory and rule requirements. MN DNR is completing a re-evaluation of stream flow in the Pomme de Terre River, and if a permit is authorized, it would be expected to include permit conditions based on stream flow. Conditions would be modified from those currently included with 2008-0230, including restrictions on the ability to appropriate water during summer months.

Additionally, DNR will evaluate the impacts of water appropriation on rare features in the Pomme de Terre River downstream of the appropriation site.

20.1.9 Although the on-site wells and the off-site well are screened in different aquifers, DNR's analysis shows that the shallow and deep aquifers in this area are hydraulically connected and function as a single groundwater system with limited water availability. Because of these hydraulic connections, cumulative existing and proposed water appropriations will be evaluated during the DNR's water appropriation permitting process.

20.1.10 The Proposer will develop an alternative contingency plan that differs from the original appropriation.

20.1.11 As a contingency measure for seasonal fluctuations and/or potential pumping restrictions, two water storage basins (Facilities 501 and 502), will be constructed as part of the Project. The basins will be filled with well water outside restricted periods. The water storage basins will also store an average of 90 MGY of collected stormwater per year, reducing reliance on a single water source.

20.1.12 Stormwater will be collected using existing infrastructure, such as stormwater basins, to direct runoff into the water storage basins. Stormwater does not encounter manure or feed storage areas. The process is similar to the required capture of precipitation in stormwater basins; however, instead of releasing the captured water, clean stormwater is used to offset the water pumped for cow consumption.

20.1.13 The Proposer will comply with all DNR pumping restrictions for the APEC/Off-Site Well.

20.1.14 The MPCA finds that information presented in the EAW and other information in the environmental review record is adequate to address the concerns related to groundwater appropriation. The impacts on groundwater that are reasonably expected to occur from the Project have been considered during the review process and methods to prevent significant adverse impacts have been developed.

20.1.15 The MPCA finds that the Project, as it is proposed, does not have the potential for significant environmental effects based on the type, extent, and reversibility of impacts related to groundwater appropriation that are reasonably expected to occur from the Project.

20.2 Traffic

20.2.1 Commenters expressed concern about damage to roadways from construction and operation of the Project.

20.2.2 The Proposer will complete road improvements on 520th Avenue between County Road 8 and the Project site to accommodate increased heavy-traffic use.

20.2.3 The Proposer will develop and utilize an underground manure transfer line. The underground line system transports manure from the Facility to a field, typically in the middle of the field. This is an efficient way to transport manure while reducing the need for heavy equipment. This results in less impact on local infrastructure and a minimized risk of manure spills from overland transport.

20.2.4 The underground manure line connects to a drag hose system via an aboveground valve system. The drag hose system is then utilized to apply manure throughout a field.

20.2.5 Minnesota Department of Transportation data indicates Annual Average Daily Traffic (AADT) near the Project on Stevens County Road 8 is 520 vehicles.

20.2.6 The Proposer estimates the Project would increase current traffic counts by approximately 45 vehicles per day.

20.2.7 Therefore, the traffic on Stevens County Road 8 would increase by up to 8.7%, and the potential for traffic congestion is considered low. No improvements to County Road 8 are considered necessary to accommodate this increase in traffic.

20.2.8 The MPCA finds that information presented in the EAW and other information in the environmental review record is adequate to address the concerns related to traffic. The impacts on roads from traffic that are reasonably expected to occur from the Project have been considered during the review process and methods to prevent significant adverse impacts have been developed.

20.2.9 The MPCA finds that the Project, as it is proposed, does not have the potential for significant environmental effects based on the type, extent, and reversibility of impacts related to traffic that are reasonably expected to occur from the Project.

B. Cumulative potential effects

21. The second criterion that the MPCA must consider when determining if a project has the potential for significant environmental effects is the "cumulative potential effects." In making this determination, the MPCA must consider whether the cumulative potential effect is significant; whether the contribution from the project is significant when viewed in connection with other contributions to the cumulative potential effect; the degree to which the project complies with approved mitigation measures specifically designed to address the cumulative potential effects; and the efforts of the proposer to minimize the contributions from the project. Minn. R. 4410.1700 subp.7(B). The MPCA findings with respect to this criterion are set forth below.

22. The EAW, public comments, and the MPCA follow-up evaluation did not disclose related or anticipated future projects that may interact with this Project in such a way as to result in significant cumulative potential environmental effects.

23. The EAW addressed the following areas for cumulative potential effects for the Project:

- Manure Application
- Groundwater Extraction

23.1 Manure Application

23.1.1 Cumulative potential effects related to manure application were discussed in EAW Item 12.B.5 and 21.c. Findings 19.1 and 19.2 is incorporated herein as part of the MPCA's cumulative potential effects evaluation for water quality impacts from manure application, in that the Nutrient Management Plan through the Feedlot Permit addresses state-regulated allowances for nutrient application customized for each manure application site.

23.1.2 The land use in the region, including the Project site and manure application sites, are primarily row-crop agriculture, which can contribute to non-point source pollution of surface waters.

23.1.3 There are 10 active NPDES permitted Concentrated Animal Feeding Operations (CAFOs) within an impaired water body's sub watershed in the Pomme de Terre River Watershed (2024 MPCA TMDL Report). This includes facilities with over 1,000 Animal Units with nine swine and one dairy operation. Most of these facilities are in the lower Pomme de Terre

River Watershed adjacent to the available manure acres listed in the Project. Impairments within the entire Pomme de Terre River watershed cumulatively affect this lower watershed unit since it receives the effects of all the upstream water.

23.1.4 Proper operation and management of the Project and adherence to appropriate manure land application practices in the MPCA-approved NMPs will prevent the potential of manure and/or manure-contaminated runoff from impacting waters of the state.

23.1.5 The Feedlot Permit includes an Operations and Maintenance (O&M) plan for manure pumping/transfer of manure to application fields, to maintain and monitor pumping/transfer equipment and take action should equipment fail.

23.1.6 Since the Feedlot Permit and NMPs require preventative measures to protect surface water and groundwater quality, the MPCA does not anticipate the Project will contribute to any potential adverse effect on water quality from manure applications. Therefore, the MPCA finds that the Project is not expected to contribute significantly to adverse cumulative potential effects on water quality from manure applications.

23.2 Groundwater Extraction

23.2.1 The Aquifer Test Report (April 2007) includes an assessment of potential impacts to surface-water features, including the historical examination of the Pomme de Terre River flows.

23.2.2 The Aquifer Test Report (April 2007) found the well-water levels measured during the pumping test and the predicted drawdown provide strong evidence that pumping at the proposed appropriation rate would not result in lost wetland acres, functions, or values.

23.2.3 Based on the results of the Aquifer Test Report (April 2007), engineers found the water-table aquifer used by the APEC/Off-Site Well provides ample water and is hydraulically connected to the Pomme de Terre River. River flows need to be considered, therefore, the DNR will evaluate cumulative existing and proposed water appropriations during the DNR's water appropriation process.

23.2.4 As a contingency measure for seasonal fluctuations and/or potential pumping restrictions, two water storage basins (Facilities 501 and 502), will be constructed as part of the Project. The basins will be filled with well water outside restricted periods. The water storage basins will also store an average of 90 MGY of collected stormwater per year, reducing reliance on a single water source.

23.2.5 The MPCA finds the information presented in the EAW and other information in the environmental review record does not demonstrate the Project has the potential for significant environmental effects to groundwater based on significant cumulative potential effects because the Project will comply with a DNR water appropriation permit.

24. Cumulative effects summary

24.1 Based on information on the Project obtained from the Feedlot Permit application processes, information on water quality, information on manure application and groundwater appropriation presented in the EAW, and consideration of potential effects due to related or anticipated future projects, the MPCA does not expect significant cumulative effects from the Project.

24.2 The MPCA finds the Project, as proposed, does not have the potential for significant environmental effects related to cumulative potential effects that are reasonably expected to occur.

C. The extent to which the environmental effects are subject to mitigation by ongoing public regulatory authority

25. The third criterion that the MPCA must consider when determining if a project has the potential for significant environmental effects is "the extent to which the environmental effects are subject to mitigation by ongoing public regulatory authority. The RGU may rely only on mitigation measures that are specific and that can be reasonably expected to effectively mitigate the identified environmental impacts of the project." Minn. R. 4410.1700, subp. 7(C). The MPCA Findings with respect to this criterion are set forth below.

26. The following permits or approvals will be required for the Project.

Permits and approvals

Unit of Government	Permit or approval required
MPCA	Individual NPDES Feedlot Permit
MPCA	Construction Stormwater Permit
Stevens County	Conditional Use Permit
DNR	Groundwater appropriations permit

27. Individual NPDES Feedlot Permit: The MPCA requires the Proposer to obtain a Feedlot Permit for the Project. The Feedlot Permit incorporates construction and operation requirements and includes operating plans that address manure management, emergency response protocols, and odor/air quality management. The attachments will be an enforceable condition of the Feedlot Permit.

28. Construction Stormwater: Construction stormwater requirements are incorporated by reference into the Feedlot Permit. Owners of feedlots not seeking Feedlot Permit coverage are still required to comply with all requirements of the current MPCA construction stormwater general permit but are not required to obtain construction stormwater permit coverage unless the construction will disturb five or more acres.

29. The DNR Water Appropriation Permit: The groundwater source is an off-site well (UN# 740629, APEC/Off-Site Well), approximately three miles southeast of the Project. The APEC/Off-Site Well is appropriated for the withdrawal of 226 million gallons per year (MGY) for livestock watering as outlined in existing MN DNR Permit #2008-0230. Stormwater collection will account for 90 MGY and site basin storage will account for 157 MGY. The total water available for the Project of 316 MGY. When separated for groundwater only, the Proposer expects to use approximately 226 MGY of groundwater, for a total consumption of approximately 4.52 billion gallons over 20 years.

Water Sources

Source	Well number	Permit #	Amount	Use
APEC/Off-site well	UN # 740629	DNR permit #2008-0230	226 MGY*	Livestock watering

Source	Well number	Permit #	Amount	Use
Stormwater collection/reuse			90 MGY**	Project runoff directed to Water Storage Basins to be used for livestock watering.
Water storage basins (Facilities 501 and 502)		DNR permit #2008-0230	157 MGY^	Contingency water storage if pumping restrictions on APEC/Off-Site Well are required.
Total water available for the Project			316 MGY (226 + 90)	

*Pumping restrictions possible based on river flow (see groundwater items below).
**Average annual estimated Project runoff water available for livestock watering.
^Water storage basins will hold water from both the APEC/Off-Site Well and stormwater runoff for Project livestock watering.

30. Stevens County Conditional Use Permit: The Proposer is required to obtain all required building and conditional use permits required by local units of government to ensure compliance with local ordinances. The conditional use permit will address local zoning, environmental, regulatory, and other requirements that are needed to avoid adverse effects on adjacent land uses.

31. The above-listed permits include general and specific requirements for the mitigation of the environmental effects of the Project. The MPCA finds that the environmental effects of the Project are subject to mitigation, as explained in these Findings and the EAW, by ongoing public regulatory authority.

C. The extent to which environmental effects can be anticipated and controlled as a result of other available environmental studies undertaken by public agencies or the Project Proposer, including other EISs.

32. The fourth criterion that the MPCA must consider is "the extent to which environmental effects can be anticipated and controlled as a result of other available environmental studies undertaken by public agencies or the project proposer, including other EISs," Minn. R. 4410.1700, subp. 7(D). The MPCA Findings with respect to this criterion are set forth below.

33. The MPCA reviewed the following documents as part of the environmental impact analysis for the Project:

- Data presented in the EAW.
- Feedlot permit application, with construction specifications, MMP, and attachments.
- U.S. Government's U.S. Greenhouse Gas Emissions and Sinks: 1990-2022 (2024).
- MPCA's legislative report Greenhouse Gas Emissions in Minnesota: 2005-2022 (2025).
- MPCA's report Greenhouse gas reduction potential of agricultural best management practices (2022).
- The Center for Climate Strategies in Collaboration with Minnesota State Agencies' report.

- Minnesota Climate Strategies and Economic Opportunities (2016).
- Minnesota's "Final Animal Agriculture Generic Environmental Impact Statement" (2002).
- Permits and environmental review of similar projects.
- TMDL recommended Best Management Practices.
- Other documents not listed here.

34. The MPCA also relies on information provided by the Proposer, people commenting on the EAW, staff experience, and other available information obtained by staff.
35. The environmental effects of the Project have been addressed by the design and permit development processes, and by ensuring conformance with regional and local plans. No elements of the Project pose the potential for significant environmental effects that are not addressed or mitigated by the requirements of the permits listed above or in the EAW.
36. Based on this environmental review, previous environmental studies by public agencies or the Proposer, and staff expertise and experience on similar projects, the MPCA finds that the environmental effects of the Project that are reasonably expected to occur can be anticipated and controlled.
37. The MPCA adopts the rationale stated in the attached Response to Comments (Appendix B) as the basis for response to any issues not specifically addressed in these Findings.

CONCLUSIONS OF LAW

38. The MPCA has jurisdiction in determining the need for an EIS for this Project. The EAW, the Feedlot Permit development process, and the evidence in the record are adequate to support a reasoned decision regarding the potential significant environmental effects that are reasonably expected to occur from this Project.

39. The MPCA identified areas for potential significant environmental effects. The Project design and permits ensure the Proposer will take appropriate mitigation measures to address significant effects. The MPCA expects the Project to comply with all environmental rules, regulations, and standards.

40. Based on a comparison of the impacts that are reasonably expected to occur from the Project with the criteria established in Minn. R. 4410.1700, subp. 7, the Project does not have the potential for significant environmental effects.

41. An EIS is not required for the proposed West River Dairy Expansion Project.

Any Findings that might properly be termed conclusions and any conclusions that might properly be termed Findings are hereby adopted as such.

ORDER

The Minnesota Pollution Control Agency determines that there are no potential significant environmental effects reasonably expected to occur from the proposed West River Dairy Feedlot Expansion Project and that there is no need for an Environmental Impact Statement.

IT IS SO ORDERED

June 22, 2026

Date signed

Peter Tester

This document has been electronically signed.

Peter Tester
Deputy Commissioner
Minnesota Pollution Control Agency

Appendix A

Minnesota Pollution Control Agency

West River Dairy Expansion

Environmental Assessment Worksheet (EAW)

List of comment letters received

1. Greg Reuter. Letter received February 25, 2026.
2. Paul Wulf. Letter received February 26, 2026.
3. Travis Moser. Letter received February 26, 2026.
4. Marc Stevens. Letter received March 02, 2026.
5. Mitch Koehl. Letter received March 02, 2026.
6. Daniel Zimmerli. Letter received March 02, 2026.
7. Robert Schultz. Letter received March 02, 2026.
8. Pete McDonnell. Letter received March 02, 2026.
9. Melissa Driscoll. Letter received March 02, 2026.
10. Aaron Christopher. Letter received March 02, 2026.
11. Diane Wood. Letter received March 02, 2026.
12. Robert Christie. Letter received March 02, 2026.
13. Katie Subra. Letter received March 02, 2026.
14. Anna Loney. Letter received March 02, 2026.
15. Nancy Ellison. Letter received March 02, 2026.
16. Alison Leathers. Letter received March 02, 2026.
17. Diane Johnson. Letter received March 02, 2026.
18. Joshua Howe. Letter received March 02, 2026.
19. Janet Lenius. Letter received March 03, 2026.
20. Paul Moss. Letter received March 03, 2026.
21. Jack Judkins. Letter received March 03, 2026.
22. Mark Klinski. Letter received March 03, 2026.
23. Kathleen Wold. Letter received March 03, 2026.
24. Elizabeth Brandt. Letter received March 03, 2026.
25. Nancy Zaworski. Letter received March 03, 2026.
26. Robert Walser. Letter received March 03, 2026.
27. Nick Olson. Letter received March 03, 2026.
28. Audrey Arner. Letter received March 03, 2026.
29. Faye Duvall. Letter received March 03, 2026.
30. Evan Skaurud. Letter received March 03, 2026.

31. James Tjepkma. Letter received March 03, 2026.
32. Michael Kennedy. Letter received March 03, 2026.
33. David Anderson. Letter received March 03, 2026.
34. Pam Hartwell. Letter received March 03, 2026.
35. Myron Sylling. Letter received March 03, 2026.
36. Mike Menzel. Letter received March 03, 2026.
37. Daniel Belgum. Letter received March 03, 2026.
38. Mary Polta. Letter received March 03, 2026.
39. Robin Moore. Letter received March 03, 2026.
40. John Gabbert. Letter received March 03, 2026.
41. Mike Yost. Letter received March 03, 2026.
42. Laura Matanah, Compassionate Action for Animals. Letter received March 03, 2026.
43. Kay Drache. Letter received March 03, 2026.
44. Amy Grace. Letter received March 03, 2026.
45. Rob Super. Letter received March 03, 2026.
46. Benedict Wagner. Letter received March 03, 2026.
47. Mary Zink. Letter received March 03, 2026.
48. Mary Zink. Letter received March 03, 2026.
49. John LaFave. Letter received March 04, 2026.
50. Rebekah Schulz. Letter received March 04, 2026.
51. Kim Hiltner. Letter received March 04, 2026.
52. Cinnie Schad. Letter received March 04, 2026.
53. Dayna Burtness. Letter received March 04, 2026.
54. Taylor Gramm. Letter received March 04, 2026.
55. Laura Inman. Letter received March 04, 2026.
56. Mason Koehl. Letter received March 04, 2026.
57. Ellen Rozek. Letter received March 04, 2026.
58. Clark Koehl. Letter received March 04, 2026.
59. Sadie Pendaz Foster. Letter received March 04, 2026.
60. Evelyn Benson. Letter received March 05, 2026.
61. Heather Benson. Letter received March 05, 2026.
62. Marissa Munsterman. Letter received March 05, 2026.
63. Adam Koehl. Letter received March 05, 2026.
64. Megan Horsager. Letter received March 05, 2026.
65. Lucas Koehl. Letter received March 05, 2026.
66. John Peck. Letter received March 05, 2026.
67. Mark Gutierrez. Letter received March 06, 2026.
68. Emily Kelly. Letter received March 06, 2026.
69. Uli Koester. Letter received March 06, 2026.

70. Grant Visser. Letter received March 06, 2026.
71. Kaleb Koehl. Letter received March 06, 2026.
72. Byron Wulf. Letter received March 06, 2026.
73. Thomas Borgen. Letter received March 07, 2026.
74. Perry Skaurud. Letter received March 07, 2026.
75. Angela Anderson. Letter received March 07, 2026.
76. Kimberly Bemis. Letter received March 07, 2026.
77. Jim Murn. Letter received March 07, 2026.
78. Sydney Bauer. Letter received March 07, 2026.
79. Miriam Gieske. Letter received March 07, 2026.
80. Nate Hultgren. Letter received March 07, 2026.
81. Cameron Berthiaume. Letter received March 08, 2026.
82. Lizzy Haywood. Letter received March 08, 2026.
83. Mary Ellen Frame. Letter received March 08, 2026.
84. Gabriela Santiago. Letter received March 08, 2026.
85. Naomi Skulan. Letter received March 09, 2026.
86. Danielle Green. Letter received March 09, 2026.
87. Gwendolyn Fassett. Letter received March 09, 2026.
88. Bonnie Haugen. Letter received March 09, 2026.
89. Maddie Brown. Letter received March 09, 2026.
90. Diane Michelfelder. Letter received March 09, 2026.
91. Yeshwant Kethineni. Letter received March 09, 2026.
92. Emily West. Letter received March 09, 2026.
93. Nathan Koehl. Letter received March 09, 2026.
94. Melissa Swenson. Letter received March 09, 2026.
95. Rebecca Tryon. Letter received March 09, 2026.
96. David Smith. Letter received March 09, 2026.
97. AnnaKilian. Letter received March 09, 2026.
98. Ian Hoxworth. Letter received March 09, 2026.
99. Sarah Hollinger. Letter received March 09, 2026.
100. Eric Zeltwanger. Letter received March 09, 2026.
101. Andrew Falk. Letter received March 09, 2026.
102. Benjamin Koehl. Letter received March 09, 2026.
103. Beth Kieffer. Letter received March 09, 2026.
104. Cathy Solvie. Letter received March 09, 2026.
105. Brandon Semel. Letter received March 09, 2026.
106. Terry Maloney. Letter received March 09, 2026.
107. Sylke Boyd. Letter received March 09, 2026.
108. Agnes Dieter. Letter received March 09, 2026.

109. Alia McIntosh. Letter received March 10, 2026.
110. Kathy Dunn. Letter received March 10, 2026.
111. Grant Ascheman. Letter received March 10, 2026.
112. Jennifer Keller. Letter received March 10, 2026.
113. Wesley Sisson. Letter received March 10, 2026.
114. Edwin Garcia. Letter received March 10, 2026.
115. Douglas Hauge. Letter received March 10, 2026.
116. Catherine Day. Letter received March 10, 2026.
117. Kristi Trout. Letter received March 10, 2026.
118. Laura S. Letter received March 10, 2026.
119. Cecily Melde Erickson. Letter received March 10, 2026.
120. Gail Johnson. Letter received March 10, 2026.
121. Sammy Johnson. Letter received March 10, 2026.
122. Kristen McNeill. Letter received March 10, 2026.
123. Casandra Carskadon. Letter received March 10, 2026.
124. Jeremy Katopol. Letter received March 10, 2026.
125. Jaqueline Hadrath. Letter received March 10, 2026.
126. Fred Tio. Letter received March 10, 2026.
127. Kay Slama. Letter received March 10, 2026.
128. Charlie Rea. Letter received March 10, 2026.
129. Kathryn Droske. Letter received March 10, 2026.
130. Kelli Olson. Letter received March 10, 2026.
131. Joel Hoffmann. Letter received March 10, 2026.
132. Eric Koehl. Letter received March 10, 2026.
133. Brenna Rollie. Letter received March 10, 2026.
134. Robert Filipczak. Letter received March 10, 2026.
135. Jeff Engebretson. Letter received March 10, 2026.
136. Julie Lloyd. Letter received March 10, 2026.
137. Sue Bruer. Letter received March 10, 2026.
138. Tracy Zickur. Letter received March 10, 2026.
139. Christine Newcomer. Letter received March 10, 2026.
140. Diane Baum. Letter received March 10, 2026.
141. Sheryl Lyke. Letter received March 10, 2026.
142. Edith Thiel. Letter received March 10, 2026.
143. Greg Anderson. Letter received March 10, 2026.
144. Tyler Solvie. Letter received March 10, 2026.
145. Megan Helling. Letter received March 10, 2026.
146. Steve Deslauriers. Letter received March 10, 2026.
147. Micah Norman-Pace. Letter received March 10, 2026.

148. Kersti Malmberg. Letter received March 10, 2026.
149. Kimberly Milligan. Letter received March 10, 2026.
150. Kimberly Milligan. Letter received March 10, 2026.
151. Deanna Arce. Letter received March 10, 2026.
152. Rachel Johnson. Letter received March 10, 2026.
153. Rachael Rich. Letter received March 10, 2026.
154. Tracey Anderson. Letter received March 10, 2026.
155. Andrea Swenson. Letter received March 10, 2026.
156. Jennifer Winn. Letter received March 10, 2026.
157. Cory Ahrens. Letter received March 10, 2026.
158. David Jungst. Letter received March 10, 2026.
159. Alex Marie. Letter received March 10, 2026.
160. Darin Broton, Minnesota AgriGrowth. Letter received March 10, 2026.
161. Amy Storbakken. Letter received March 10, 2026.
162. Kaye Marohl. Letter received March 10, 2026.
163. Lucas Olson. Letter received March 10, 2026.
164. Autumn Johnson. Letter received March 10, 2026.
165. Levi Koehl. Letter received March 10, 2026.
166. Scott Heinrich. Letter received March 10, 2026.
167. Martha Wheeler. Letter received March 10, 2026.
168. Devin Nohl. Letter received March 10, 2026.
169. Angela Lund. Letter received March 10, 2026.
170. Vern Simula. Letter received March 10, 2026.
171. Emily Johnson. Letter received March 10, 2026.
172. Tracy Otten. Letter received March 10, 2026.
173. Kristen Ringham. Letter received March 10, 2026.
174. Caroline Collet. Letter received March 10, 2026.
175. Justin McGuire. Letter received March 10, 2026.
176. Julie Kill. Letter received March 10, 2026.
177. Jenniger Mashuga. Letter received March 10, 2026.
178. Dori Coler. Letter received March 10, 2026.
179. Alan LaValier. Letter received March 10, 2026.
180. Mckayla Kaardal. Letter received March 10, 2026.
181. Mike Odell. Letter received March 10, 2026.
182. Tracy Schad. Letter received March 10, 2026.
183. Anthony Anker. Letter received March 10, 2026.
184. Audrey Gunn. Letter received March 10, 2026.
185. Leslie MacKichan. Letter received March 10, 2026.
186. Seraphina Ridgeway. Letter received March 10, 2026.

187. Jerry Loxtercamp. Letter received March 10, 2026.
188. Alexander Grabowska. Letter received March 10, 2026.
189. Mike Bieniek. Letter received March 10, 2026.
190. Judith Flicker. Letter received March 10, 2026.
191. Brent Koehl. Letter received March 10, 2026.
192. Billy Schwartz. Letter received March 10, 2026.
193. Diane Anspach. Letter received March 10, 2026.
194. Katherine Johnson. Letter received March 10, 2026.
195. Joshua Truong. Letter received March 10, 2026.
196. Max Guo. Letter received March 10, 2026.
197. Sally Fernholz. Letter received March 10, 2026.
198. Carmen Fernholz. Letter received March 10, 2026.
199. Mary Beam. Letter received March 10, 2026.
200. Sadie Schrader. Letter received March 10, 2026.
201. Lexi Fischer. Letter received March 11, 2026.
202. Julie Knopp. Letter received March 11, 2026.
203. Angelica Agents. Letter received March 11, 2026.
204. Anna Overby. Letter received March 11, 2026.
205. Brinna Langford. Letter received March 11, 2026.
206. Lisa Koehler. Letter received March 11, 2026.
207. Brenna Munoz. Letter received March 11, 2026.
208. Victoria Piotter. Letter received March 11, 2026.
209. Alexandria Muff. Letter received March 11, 2026.
210. Julia Cedergren. Letter received March 11, 2026.
211. Mitch Trumble. Letter received March 11, 2026.
212. Crystal Poppe. Letter received March 11, 2026.
213. Patti Vega. Letter received March 11, 2026.
214. Marjie Carr-Oxley. Letter received March 11, 2026.
215. Lynne Riley. Letter received March 11, 2026.
216. Jaimee Frank. Letter received March 11, 2026.
217. Marjie Carr-Oxley. Letter received March 11, 2026.
218. Sawyer Buhman. Letter received March 11, 2026.
219. Lynne Riley. Letter received March 11, 2026.
220. Lynne Riley. Letter received March 11, 2026.
221. Marjie Carr-Oxley. Letter received March 11, 2026.
222. Marjie Carr-Oxley. Letter received March 11, 2026.
223. Erin Jimcosky. Letter received March 11, 2026.
224. Marjie Carr-Oxley. Letter received March 11, 2026.
225. Paul Carlson. Letter received March 11, 2026.

226. Marjie Carr-Oxley. Letter received March 11, 2026.
227. Sloan Parker. Letter received March 11, 2026.
228. Reid Gosmire. Letter received March 11, 2026.
229. Kaitlyn OConnor. Letter received March 11, 2026.
230. Nicola Philpott. Letter received March 11, 2026.
231. Marjie Carr-Oxley. Letter received March 11, 2026.
232. John Schreier. Letter received March 11, 2026.
233. Xander Godfrey-Singh. Letter received March 11, 2026.
234. Ryan Meehan. Letter received March 11, 2026.
235. Ed Brands. Letter received March 11, 2026.
236. Karen Arnold. Letter received March 11, 2026.
237. Kevin Koehl. Letter received March 11, 2026.
238. Melissa Harper-France. Letter received March 11, 2026.
239. Sarah Hernandez. Letter received March 11, 2026.
240. Jolene Turner. Letter received March 11, 2026.
241. Randi Jorgensen. Letter received March 11, 2026.
242. Jennifer Nowatzki. Letter received March 11, 2026.
243. Dionne Porter. Letter received March 11, 2026.
244. Ren Ze. Letter received March 11, 2026.
245. Will Carlen. Letter received March 11, 2026.
246. Kristin Bertram. Letter received March 11, 2026.
247. Alicia Sandor. Letter received March 11, 2026.
248. Pixie Green. Letter received March 11, 2026.
249. Grace Davies. Letter received March 11, 2026.
250. Carter Voorde. Letter received March 11, 2026.
251. Hayley Saccoman. Letter received March 11, 2026.
252. Shanta Mayweather. Letter received March 11, 2026.
253. Kathy Burt. Letter received March 11, 2026.
254. Bonnie Morgan Norgren. Letter received March 11, 2026.
255. Pamela Gades. Letter received March 11, 2026.
256. Shanta Mayweather. Letter received March 11, 2026.
257. Anne Morena. Letter received March 11, 2026.
258. Debra Luetmer. Letter received March 11, 2026.
259. Tawnya Gelle. Letter received March 11, 2026.
260. Tierney Graf. Letter received March 11, 2026.
261. Ann Williams. Letter received March 11, 2026.
262. Jenifer Culbertson. Letter received March 11, 2026.
263. Tanna Rens. Letter received March 11, 2026.
264. Wendy Pilot. Letter received March 11, 2026.

265. Michael Finn. Letter received March 11, 2026.
266. Claire Kaisermann. Letter received March 11, 2026.
267. Dominic Decker. Letter received March 11, 2026.
268. Rachel Coler Mulholland. Letter received March 11, 2026.
269. Alexandra Beane. Letter received March 11, 2026.
270. Kelsey Hambor. Letter received March 11, 2026.
271. Meghan Manahan. Letter received March 11, 2026.
272. Melody Kitchen. Letter received March 11, 2026.
273. Janice Kostad. Letter received March 11, 2026.
274. Karrie Vrabel. Letter received March 11, 2026.
275. Winnie Cheung. Letter received March 11, 2026.
276. Kayla Jacobson. Letter received March 11, 2026.
277. Lia Saaskilahti. Letter received March 11, 2026.
278. Roden Turner. Letter received March 11, 2026.
279. Sheila Nelson. Letter received March 11, 2026.
280. Emily Rosenmeier. Letter received March 11, 2026.
281. Jodi Gruhn. Letter received March 11, 2026.
282. John Sheehan. Letter received March 11, 2026.
283. Heather Waye. Letter received March 11, 2026.
284. Anna Borell. Letter received March 11, 2026.
285. Kurtis Koehl. Letter received March 11, 2026.
286. Steph Kuehn . Letter received March 11, 2026.
287. Cari Lombardi. Letter received March 11, 2026.
288. Mark Berkson. Letter received March 11, 2026.
289. Amy Kinneman. Letter received March 11, 2026.
290. Linda Hanke. Letter received March 11, 2026.
291. Mark Kaelke. Letter received March 11, 2026.
292. Lisa A. Letter received March 11, 2026.
293. Amanda Huggett. Letter received March 11, 2026.
294. Roxanne Friedenfels. Letter received March 11, 2026.
295. Lori Clark. Letter received March 11, 2026.
296. Thomas Hoch. Letter received March 11, 2026.
297. Candace Marx. Letter received March 11, 2026.
298. Loren Stoner. Letter received March 11, 2026.
299. Elizabeth Brandt. Letter received March 11, 2026.
300. Shelly Bell. Letter received March 11, 2026.
301. Leland Stoe. Letter received March 11, 2026.
302. Douglas Nopar. Letter received March 11, 2026.
303. Birgitta Anderson. Letter received March 11, 2026.

304. Em Perttu. Letter received March 11, 2026.
305. Abby A. Letter received March 11, 2026.
306. Steve Thompson. Letter received March 11, 2026.
307. Dean Peterson. Letter received March 11, 2026.
308. Janet Thompson. Letter received March 11, 2026.
309. Celeste Knoff. Letter received March 11, 2026.
310. Jeffrey Borchert. Letter received March 11, 2026.
311. Austin Voltin. Letter received March 11, 2026.
312. Faye Duvall. Letter received March 11, 2026.
313. Marz Beckman. Letter received March 11, 2026.
314. Kim Fortin. Letter received March 11, 2026.
315. Todd @ Cheryl Jackson. Letter received March 11, 2026.
316. Audrey Kingstrom. Letter received March 11, 2026.
317. Karen Ahrens. Letter received March 11, 2026.
318. Kim Hiltner. Letter received March 11, 2026.
319. Emily Marsolek. Letter received March 11, 2026.
320. Allie Arthur. Letter received March 11, 2026.
321. Mary Vlazny. Letter received March 11, 2026.
322. Robert Rinkenberger. Letter received March 11, 2026.
323. Thomas Sybrant. Letter received March 11, 2026.
324. Malee Johnson. Letter received March 11, 2026.
325. Gretchen Goodman. Letter received March 11, 2026.
326. Danielle White. Letter received March 11, 2026.
327. Sumi Srinivasan. Letter received March 11, 2026.
328. Holly Swiglo. Letter received March 11, 2026.
329. Ann Peckskamp. Letter received March 11, 2026.
330. Maurice Spangler. Letter received March 11, 2026.
331. Taylor Borgman. Letter received March 11, 2026.
332. Jazmin Goire. Letter received March 11, 2026.
333. Deborah Liang. Letter received March 11, 2026.
334. Ana Shickich. Letter received March 11, 2026.
335. Michael Kennedy. Letter received March 12, 2026.
336. Jennifer Love. Letter received March 12, 2026.
337. Cassie Dudley. Letter received March 12, 2026.
338. Brook Pederson. Letter received March 12, 2026.
339. Kirstan Ketter. Letter received March 12, 2026.
340. Emily B. Letter received March 12, 2026.
341. Jeremy Culver. Letter received March 12, 2026.
342. Laura Aldrich-Wolfe. Letter received March 12, 2026.

343. Faustine Micheyl Moran. Letter received March 12, 2026.
344. Kelly Parker. Letter received March 12, 2026.
345. Kaitlin Kramer. Letter received March 12, 2026.
346. Bonita Underbakke. Letter received March 12, 2026.
347. Laura Haule. Letter received March 12, 2026.
348. Dylan Summerville. Letter received March 12, 2026.
349. Paige Van Pelt. Letter received March 12, 2026.
350. Jack Judkins, Grandpa Roy's Pickles. Letter received March 12, 2026.
351. Katie Hauge. Letter received March 12, 2026.
352. Peg Furshong. Letter received March 12, 2026.
353. Lauren Robinson. Letter received March 12, 2026.
354. Lisa Cain. Letter received March 12, 2026.
355. Gage Norton. Letter received March 12, 2026.
356. Patrick Brueske. Letter received March 12, 2026.
357. Becca Golden. Letter received March 12, 2026.
358. Stuart Knappmiller. Letter received March 12, 2026.
359. Carlos Gutierrez. Letter received March 12, 2026.
360. Dawn Cook Ronningen. Letter received March 12, 2026.
361. Itzel Herrera. Letter received March 12, 2026.
362. Sarah Winikoff. Letter received March 12, 2026.
363. Barbra Burke . Letter received March 12, 2026.
364. Darlene Eckert. Letter received March 12, 2026.
365. Helene Murray. Letter received March 12, 2026.
366. Jody Snow. Letter received March 12, 2026.
367. Jan Kaeter. Letter received March 12, 2026.
368. Ann DuHamel. Letter received March 12, 2026.
369. Elena Machkasova. Letter received March 12, 2026.
370. Heather Stefanek-Peters. Letter received March 12, 2026.
371. Jim Bambenek. Letter received March 12, 2026.
372. Anna Larsson. Letter received March 12, 2026.
373. Rhyan Schicker. Letter received March 12, 2026.
374. Carole Fernholz. Letter received March 12, 2026.
375. Mariah McMahon. Letter received March 12, 2026.
376. James Harkness. Letter received March 12, 2026.
377. Cary Anderson. Letter received March 12, 2026.
378. Tyler Scott. Letter received March 12, 2026.
379. Cora Gertjejanssen. Letter received March 12, 2026.
380. Ramona Heitmann. Letter received March 12, 2026.
381. Anna Mehlhoff. Letter received March 12, 2026.

382. Mary Longfellow. Letter received March 12, 2026.
383. Gayl Gustafson. Letter received March 12, 2026.
384. Brooke Reynolds. Letter received March 12, 2026.
385. Michelle Gobly. Letter received March 12, 2026.
386. Andrew Steiner. Letter received March 12, 2026.
387. Tanner Davison. Letter received March 12, 2026.
388. Francisco Guadarrama Capitaine. Letter received March 12, 2026.
389. Jodi Williams. Letter received March 12, 2026.
390. Joyce Borgerding. Letter received March 12, 2026.
391. Tayler Williamson. Letter received March 12, 2026.
392. Paul Golden. Letter received March 12, 2026.
393. Kelle Green. Letter received March 12, 2026.
394. Jenell Holden. Letter received March 12, 2026.
395. Edi Thorstensson. Letter received March 12, 2026.
396. Jenell Holden. Letter received March 12, 2026.
397. Ben Knelman. Letter received March 12, 2026.
398. K Shomion. Letter received March 12, 2026.
399. Caitlin Rathbone. Letter received March 12, 2026.
400. Amy LeBeau. Letter received March 12, 2026.
401. Tim Ahrens. Letter received March 12, 2026.
402. Jon Moser. Letter received March 12, 2026.
403. Jane Dow. Letter received March 12, 2026.
404. Hannah Bernhardt. Letter received March 12, 2026.
405. Holly Grise. Letter received March 12, 2026.
406. Kevin Hohn. Letter received March 13, 2026.
407. Marshall Hoffman. Letter received March 13, 2026.
408. Sharon Fortunak. Letter received March 13, 2026.
409. Julia Hoffman. Letter received March 13, 2026.
410. Winston Kaehler. Letter received March 13, 2026.
411. Renee Obrecht-Como. Letter received March 13, 2026.
412. Dean Vital. Letter received March 13, 2026.
413. Jonathan P. Letter received March 13, 2026.
414. Francy Jenko. Letter received March 13, 2026.
415. Sara Bosley. Letter received March 13, 2026.
416. Theresa Salchert-Keller. Letter received March 13, 2026.
417. Rachel Day. Letter received March 13, 2026.
418. Mark Paquette. Letter received March 13, 2026.
419. Mary Abel. Letter received March 13, 2026.
420. Karen Nelson. Letter received March 13, 2026.

421. Amy Leinen. Letter received March 13, 2026.
422. Leslie Kaup. Letter received March 13, 2026.
423. Ian Radtke-Rosen. Letter received March 13, 2026.
424. Cristina Ortiz. Letter received March 13, 2026.
425. Sherri Thissen. Letter received March 13, 2026.
426. Ashley Kittelson. Letter received March 13, 2026.
427. Margi Preus. Letter received March 13, 2026.
428. Nicole Frank. Letter received March 13, 2026.
429. Stephen Leinen. Letter received March 13, 2026.
430. Suzanne Lommen. Letter received March 13, 2026.
431. Karen Watson. Letter received March 13, 2026.
432. Tim Phillips. Letter received March 13, 2026.
433. Ray Canapini. Letter received March 13, 2026.
434. John Clifton. Letter received March 13, 2026.
435. Mark Robinson. Letter received March 13, 2026.
436. Caitlin Clemens. Letter received March 13, 2026.
437. Sara Clifton. Letter received March 13, 2026.
438. Jennifer Fox. Letter received March 13, 2026.
439. Erika Nelson. Letter received March 13, 2026.
440. Theresa Zingery. Letter received March 13, 2026.
441. Jennifer Hill. Letter received March 13, 2026.
442. Norm Gross. Letter received March 13, 2026.
443. Paul Adams. Letter received March 13, 2026.
444. Owen Tesson. Letter received March 13, 2026.
445. Cathy Dolan. Letter received March 13, 2026.
446. Lindsay Henkemeyer. Letter received March 13, 2026.
447. John Marks. Letter received March 14, 2026.
448. Maria Weir. Letter received March 14, 2026.
449. Ilga Polleitis. Letter received March 14, 2026.
450. Barbara Haag. Letter received March 14, 2026.
451. Kendra Nielsen. Letter received March 14, 2026.
452. Rhona Wilson. Letter received March 14, 2026.
453. Bridget Shankey. Letter received March 14, 2026.
454. Mary C. Voight. Letter received March 14, 2026.
455. Rachel Nielsen. Letter received March 15, 2026.
456. John Pierce. Letter received March 15, 2026.
457. Deborah Camasta. Letter received March 15, 2026.
458. Lisa Goddard. Letter received March 15, 2026.
459. Nathan Huerkamp. Letter received March 15, 2026.

460. Christopher Loetscher. Letter received March 15, 2026.
461. George John Dubie. Letter received March 16, 2026.
462. John Velie. Letter received March 16, 2026.
463. Leslie McInenly. Letter received March 16, 2026.
464. Greta Conroy. Letter received March 16, 2026.
465. John Doe. Letter received March 16, 2026.
466. Sophie Hannig. Letter received March 16, 2026.
467. Joe Storlien. Letter received March 16, 2026.
468. Jennifer Voght-Erickson. Letter received March 16, 2026.
469. Sarah Backman. Letter received March 16, 2026.
470. Kurtis Wulf. Letter received March 16, 2026.
471. Cory Skaurud. Letter received March 16, 2026.
472. Brian Lacey. Letter received March 16, 2026.
473. Coby Backman. Letter received March 16, 2026.
474. Angela Lofquist. Letter received March 16, 2026.
475. Patricia Burns. Letter received March 16, 2026.
476. Ann Johnson. Letter received March 16, 2026.
477. Lisa Moldan. Letter received March 17, 2026.
478. Kim Carswell. Letter received March 17, 2026.
479. Vanessa Sandoval. Letter received March 17, 2026.
480. Ruth Lindh. Letter received March 17, 2026.
481. Shari Prigge. Letter received March 17, 2026.
482. Nathan Kestner, Minnesota Department of Natural Resources. Letter received March 17, 2026.
483. Madeline Neenan. Letter received March 17, 2026.
484. Matthew Green. Letter received March 18, 2026.
485. Lisa Rogers. Letter received March 18, 2026.
486. Marcella Bode. Letter received March 18, 2026.
487. Courtney Swenson. Letter received March 18, 2026.
488. Nancy Carpenter. Letter received March 18, 2026.
489. Edie Thiel. Letter received March 18, 2026.
490. Susan Frenzel. Letter received March 18, 2026.
491. Susan Frenzel. Letter received March 18, 2026.
492. Tom Mahoney. Letter received March 18, 2026.
493. Mary Nesgoda. Letter received March 18, 2026.
494. Susan Frenzel. Letter received March 19, 2026.
495. Michelle Burns. Letter received March 19, 2026.
496. Hein Enslin. Letter received March 19, 2026.
497. Lisa Notsch. Letter received March 19, 2026.
498. Alan Nikolai. Letter received March 19, 2026.

499. Dustin Walsh. Letter received March 19, 2026.
500. Marcia Schroeder. Letter received March 20, 2026.
501. Carol Dines. Letter received March 20, 2026.
502. Heidi Peters. Letter received March 21, 2026.
503. Charles Martelle. Letter received March 21, 2026.
504. Susan Frenzel. Letter received March 21, 2026.
505. Jacobe Strege. Letter received March 22, 2026.
506. Sharon Kutter. Letter received March 22, 2026.
507. Karen Renaud. Letter received March 22, 2026.
508. Boone Carlson. Letter received March 23, 2026.
509. Tanner Zych. Letter received March 23, 2026.
510. Dixie Houser. Letter received March 23, 2026.
511. Heather Prunty. Letter received March 23, 2026.
512. Monica Ledesma. Letter received March 23, 2026.
513. Charles Koehl. Letter received March 23, 2026.
514. Connie Maier. Letter received March 23, 2026.
515. Rachel McGill. Letter received March 23, 2026.
516. Evangeline Moen. Letter received March 23, 2026.
517. Theresa Harsma. Letter received March 24, 2026.
518. Merrilee Stahler. Letter received March 24, 2026.
519. Heather Nord. Letter received March 24, 2026.
520. Roger Hippe. Letter received March 24, 2026.
521. Stef Kirschbaum. Letter received March 25, 2026.
522. Mechelle Sazama. Letter received March 25, 2026.
523. Rebecca Heinz. Letter received March 25, 2026.
524. Zachariah Grein. Letter received March 25, 2026.
525. Mark Brakke. Letter received March 25, 2026.
526. Ben Lilliston, Institute for Agriculture and Trade Policy. Letter received March 25, 2026.
527. Baldomero Penaloza. Letter received March 25, 2026.
528. Josh Betcher. Letter received March 26, 2026.
529. Juan Mendoza. Letter received March 26, 2026.
530. Greg Shirley. Letter received March 26, 2026.
531. Kurt Schulz. Letter received March 26, 2026.
532. Sally Summer. Letter received March 27, 2026.
533. Adam Zeltwanger. Letter received March 27, 2026.
534. Scott Ruiter. Letter received March 27, 2026.
535. Mason Metzger. Letter received March 27, 2026.
536. Lyle Grimm. Letter received March 27, 2026.
537. Raymond Walters. Letter received March 27, 2026.

538. Rhonda Wellnitz. Letter received March 27, 2026.
539. Kaleb Pugsley. Letter received March 27, 2026.
540. Javier Torillo. Letter received March 27, 2026.
541. Sergio Vazquez. Letter received March 27, 2026.
542. Sandra Simonson. Letter received March 27, 2026.
543. Matt Wellnitz. Letter received March 27, 2026.
544. Esteban Marino Hernandez Lopez. Letter received March 27, 2026.
545. Justin Steiner. Letter received March 27, 2026.
546. Perry Aasness, Midwest Council on Agriculture. Letter received March 27, 2026.
547. Mark Tuls. Letter received March 27, 2026.
548. Rachel Zeltwanger. Letter received March 27, 2026.
549. Lafe Grimm. Letter received March 27, 2026.
550. Juan Manuel Palomo Posada. Letter received March 27, 2026.
551. Michael Steffl, Steffl Drilling & Pump Inc. Letter received March 27, 2026.
552. Ty Feuchtenberger. Letter received March 27, 2026.
553. Christie Singleton. Letter received March 27, 2026.
554. Guillermo Cruz Arroyo. Letter received March 27, 2026.
555. Mary Arroyo. Letter received March 27, 2026.
556. Megan Wulf. Letter received March 27, 2026.
557. Scott Hennen. Letter received March 27, 2026.
558. Rigoberto Cruz. Letter received March 27, 2026.
559. Max Feuchtenberger. Letter received March 27, 2026.
560. Fredy Flores Avila. Letter received March 27, 2026.
561. Craigan Wulf. Letter received March 27, 2026.
562. Gail Hockert. Letter received March 28, 2026.
563. Scott Wulf. Letter received March 28, 2026.
564. Conrad Spangler. Letter received March 28, 2026.
565. Matt Komro, Komro Sales & Service Inc. Letter received March 28, 2026.
566. Lucas Koehl. Letter received March 28, 2026.
567. Felix Camacho. Letter received March 28, 2026.
568. Carlos Portillo. Letter received March 28, 2026.
569. Maggie Knobloch. Letter received March 28, 2026.
570. Ashdon Hacker. Letter received March 28, 2026.
571. Halle Grimm. Letter received March 28, 2026.
572. Jonathan Tomic. Letter received March 28, 2026.
573. Alejandro Diaz Flores. Letter received March 28, 2026.
574. Hunter Massner. Letter received March 28, 2026.
575. Mary Margaret Lawler. Letter received March 29, 2026.
576. Janice Nelson. Letter received March 29, 2026.

577. Brandon Thesing. Letter received March 30, 2026.
578. Brett Petersen. Letter received March 30, 2026.
579. Dustin Hollermann. Letter received March 30, 2026.
580. Dawn Kisgen. Letter received March 30, 2026.
581. Catherine Anderson. Letter received March 30, 2026.
582. Ali Bouta. Letter received March 30, 2026.
583. Kyle Clark. Letter received March 30, 2026.
584. Justin Cronen. Letter received March 30, 2026.
585. Emily Ann Raeker. Letter received March 30, 2026.
586. Jeff Kisgen. Letter received March 30, 2026.
587. Charles Steffl, Step Saver Inc. Letter received March 30, 2026.
588. Debra Hacker. Letter received March 30, 2026.
589. Dave Lemke. Letter received March 30, 2026.
590. Karie Kirschbaum. Letter received March 30, 2026.
591. Brooke Gordon. Letter received March 30, 2026.
592. Michael Yost. Letter received March 30, 2026.
593. Chris Dauer. Letter received March 30, 2026.
594. Sharon Vipond. Letter received March 30, 2026.
595. Bo Massner, McGinnis Appliance Heating & Cooling. Letter received March 30, 2026.
596. Bryce Gibbs, Pinion. Letter received March 30, 2026.
597. Joe Koehl. Letter received March 30, 2026.
598. Lowell Nelson. Letter received March 30, 2026.
599. Tracee Skaurud. Letter received March 30, 2026.
600. Mark Stromswold. Letter received March 31, 2026.
601. Justin Gaukler. Letter received March 31, 2026.
602. Travor Timm. Letter received March 31, 2026.
603. Mike Staples. Letter received March 31, 2026.
604. John Sertich, Nuss Truck & Equipment. Letter received March 31, 2026.
605. Rita Bolluyt. Letter received March 31, 2026.
606. Adam Lichtsinn. Letter received March 31, 2026.
607. Paul Tackes. Letter received March 31, 2026.
608. Steve Molenaar. Letter received March 31, 2026.
609. James Radermacher. Letter received March 31, 2026.
610. Gates Blodgett. Letter received March 31, 2026.
611. Darlene Donahue. Letter received March 31, 2026.
612. Randy Pothen. Letter received March 31, 2026.
613. Chrostopher Spangler, Perspective 180 LLC. Letter received March 31, 2026.
614. Steven Wendling. Letter received March 31, 2026.
615. Kevin Lundberg. Letter received March 31, 2026.

616. Former Neighbor. Letter received March 31, 2026.
617. Karen Hettver. Letter received March 31, 2026.
618. Richard and Catherine Tate. Letter received March 31, 2026.
619. Pat Ascheman. Letter received March 31, 2026.
620. Donita Ascheman. Letter received March 31, 2026.
621. Mario Alvarez. Letter received March 31, 2026.
622. Shurkey Swanke. Letter received March 31, 2026.
623. John Franey. Letter received March 31, 2026.
624. Mike Koehl. Letter received March 31, 2026.
625. David Kruize. Letter received March 31, 2026.
626. Trent Timm. Letter received April 01, 2026.
627. Mark Billstrom. Letter received April 01, 2026.
628. Phillip Horsager. Letter received April 01, 2026.
629. Jeremy Bottelberghe, Redfield LLC. Letter received April 01, 2026.
630. Jeff Karschnik. Letter received April 01, 2026.
631. Kurt Staples. Letter received April 01, 2026.
632. Dave Baker, Representative. Letter received April 01, 2026.
633. Kathryn Buendgen. Letter received April 01, 2026.
634. Lucio Minces. Letter received April 01, 2026.
635. Renee Konz. Letter received April 01, 2026.
636. Judith Derauf. Letter received April 01, 2026.
637. Keith Doane. Letter received April 01, 2026.
638. Jesper Rosendahl. Letter received April 01, 2026.
639. Adam Johnson. Letter received April 01, 2026.
640. Thiago Carvalho. Letter received April 01, 2026.
641. Nedd Knobloch. Letter received April 01, 2026.
642. Seth Berg, Sentry. Letter received April 01, 2026.
643. Taya Hemphill. Letter received April 01, 2026.
644. Brooke Reynolds. Letter received April 01, 2026.
645. Marlowe Engler. Letter received April 01, 2026.
646. Nicole Wallace. Letter received April 01, 2026.
647. Travis Miller. Letter received April 01, 2026.
648. Erin Larson. Letter received April 01, 2026.
649. Emily Johnson. Letter received April 01, 2026.
650. Sarah Super. Letter received April 01, 2026.
651. Amanda Churchill. Letter received April 01, 2026.
652. Claire Lienesch. Letter received April 01, 2026.
653. Wendy Pilot. Letter received April 01, 2026.
654. Ken Koehl. Letter received April 01, 2026.

655. Jocelyn Bullock. Letter received April 02, 2026.
656. Kimberly Ped. Letter received April 02, 2026.
657. Briana Isiminger. Letter received April 02, 2026.
658. Rylee Erickson. Letter received April 02, 2026.
659. John Klein. Letter received April 02, 2026.
660. Eric Smith, Flatland Custom Forage LLC. Letter received April 02, 2026.
661. Deborah Jindra. Letter received April 02, 2026.
662. Julie Greenwood. Letter received April 02, 2026.
663. Laura Haule. Letter received April 02, 2026.
664. Jerry Nelson. Letter received April 02, 2026.
665. Connie Roche. Letter received April 02, 2026.
666. Linda Vest Klein. Letter received April 02, 2026.
667. Brian & Betty Rinke. Letter received April 02, 2026.
668. Nick Hendrickson. Letter received April 02, 2026.
669. Micah Norman-Pace. Letter received April 02, 2026.
670. Peg Honkomp. Letter received April 02, 2026.
671. Dale Kennen. Letter received April 02, 2026.
672. Rachel Scherf, Davis Immigration Lawyers. Letter received April 02, 2026.
673. Michael Davis, Davis Immigration Lawyers. Letter received April 02, 2026.
674. Sandra Sween. Letter received April 02, 2026.
675. John Riley, John Riley Construction. Letter received April 02, 2026.
676. Lenny Stahl. Letter received April 02, 2026.
677. Mark Martins, Agri Placements International Inc. Letter received April 02, 2026.
678. Brian Gjerde, I&S Group, Inc. Letter received April 02, 2026.
679. Mother Nature. Letter received April 02, 2026.
680. Ann Hostler. Letter received April 02, 2026.
681. Randy Dooley, Dooley's Petroleum Inc. Letter received April 02, 2026.
682. Brandon Efraimson, Efraimson Electric Inc. Letter received April 02, 2026.
683. Jerry Lindor. Letter received April 02, 2026.
684. Tom Walsh. Letter received April 02, 2026.
685. Judith Riley. Letter received April 02, 2026.
686. Jackson Walsh. Letter received April 02, 2026.
687. Kay Erickson. Letter received April 02, 2026.
688. Nora Hultgren. Letter received April 02, 2026.
689. Noah Hultgren, Fieldstock Realty LLC. Letter received April 02, 2026.
690. Blake Klaphake. Letter received April 02, 2026.
691. Emily Boecker. Letter received April 03, 2026.
692. Kennedy Stegner. Letter received April 03, 2026.
693. Sandra Yost. Letter received April 03, 2026.

694. Jeffrey Davis, Bryant State Bank. Letter received April 03, 2026.
695. Nate Skindelien, Duinick Concrete. Letter received April 03, 2026.
696. Gail Morris. Letter received April 03, 2026.
697. William Bosch. Letter received April 03, 2026.
698. Lucas Sjostrom, Minnesota Milk Producers Association. Letter received April 03, 2026.
699. Travis Holmgren. Letter received April 03, 2026.
700. Fabian Hernandez. Letter received April 03, 2026.
701. Gene Ward, Webtomix LLC. Letter received April 03, 2026.
702. Karen Stettner. Letter received April 03, 2026.
703. Carol Wenner. Letter received April 03, 2026.
704. David Huang, SeaTac Packaging. Letter received April 03, 2026.
705. Ruth Lovander Foley. Letter received April 03, 2026.
706. Amy Ekren. Letter received April 03, 2026.
707. Anthony Ekren. Letter received April 03, 2026.
708. Talia Koehl. Letter received April 03, 2026.
709. Trenton Nelson. Letter received April 04, 2026.
710. Kendall Waldbeser. Letter received April 04, 2026.
711. Michael Green. Letter received April 04, 2026.
712. Wendy Evink. Letter received April 04, 2026.
713. Chad Seizert. Letter received April 04, 2026.
714. Ron Schlueter. Letter received April 04, 2026.
715. Robert Valnes. Letter received April 04, 2026.
716. Shane Seeger. Letter received April 04, 2026.
717. Sammy Glanzer. Letter received April 04, 2026.
718. Steven Glanzer. Letter received April 04, 2026.
719. Holly Grap. Letter received April 05, 2026.
720. Adam Redlinger Redlinger Bros Plumbing & Heating. Letter received April 05, 2026.
721. David Munn. Letter received April 05, 2026.
722. Jackie Junker. Letter received April 05, 2026.
723. Todd Malecha. Letter received April 05, 2026.
724. Jane Amberg. Letter received April 05, 2026.
725. Gabi Joos. Letter received April 05, 2026.
726. Mike Deseth. Letter received April 05, 2026.
727. Kevin Mills. Letter received April 05, 2026.
728. Samantha Deseth. Letter received April 05, 2026.
729. Ashley Nietfeld. Letter received April 05, 2026.
730. Cheryl Rempel. Letter received April 05, 2026.
731. Nick Elms. Letter received April 05, 2026.
732. Sue Kulberg. Letter received April 06, 2026.

733. Louise Malecha. Letter received April 06, 2026.
734. C Ewalt. Letter received April 06, 2026.
735. Adam Yucuis. Letter received April 06, 2026.
736. Robert Lee. Letter received April 06, 2026.
737. Shane Frahm, AgCountry Farm Credit Services. Letter received April 06, 2026.
738. Corey Poepping, Tri County Insulation, Concrete Lifting & Painting. Letter received April 06, 2026.
739. Patricia Rhoades. Letter received April 06, 2026.
740. Dick Metzger. Letter received April 06, 2026.
741. Lonnie Fosso. Letter received April 06, 2026.
742. Judy Lubenow. Letter received April 06, 2026.
743. Joe Neaton, MN National Farmers Board. Letter received April 06, 2026.
744. Dave Rozenboom, First Premier Bank. Letter received April 06, 2026.
745. Laurie Golden. Letter received April 06, 2026.
746. Sean Indrelie. Letter received April 06, 2026.
747. Sally Carlson-Bancroft. Letter received April 06, 2026.
748. Troy Metzger. Letter received April 06, 2026.
749. Kris Mielnik, Sterling Water Inc. Letter received April 06, 2026.
750. Andrew Morley, Minnesota Chamber of Commerce. Letter received April 06, 2026.
751. James Murphy. Letter received April 06, 2026.
752. Amanda Mayer. Letter received April 06, 2026.
753. Robert Padula. Letter received April 06, 2026.
754. Steven Landwehr. Letter received April 06, 2026.
755. Maureen Mullen. Letter received April 06, 2026.
756. Kara Lundin. Letter received April 06, 2026.
757. Debra Ost. Letter received April 06, 2026.
758. Carrie Redden. Letter received April 06, 2026.
759. Lyn Kerschen. Letter received April 06, 2026.
760. Jane Bartlett. Letter received April 06, 2026.
761. Karen Rom. Letter received April 06, 2026.
762. Becca R. Letter received April 06, 2026.
763. Elias Hultgren. Letter received April 06, 2026.
764. Paula Boogaard. Letter received April 06, 2026.
765. Katherine Myers. Letter received April 06, 2026.
766. Sharon Mansur. Letter received April 06, 2026.
767. Aubree Derksen. Letter received April 06, 2026.
768. David Hauge. Letter received April 07, 2026.
769. Faith Rudnitski. Letter received April 07, 2026.
770. Tara Nelson. Letter received April 07, 2026.
771. Abby Konz. Letter received April 07, 2026.

772. Garrett Luthens. Letter received April 07, 2026.
773. Tony Domnick. Letter received April 07, 2026.
774. Kent Bosch. Letter received April 07, 2026.
775. Evan Grong, Valley Queen Cheese Factory Inc. Letter received April 07, 2026.
776. Nathan DeLeeuw, Dooley's Natural Gas. Letter received April 07, 2026.
777. Kathy Arthun. Letter received April 07, 2026.
778. Steve Veverka. Letter received April 07, 2026.
779. Margie Diggins. Letter received April 07, 2026.
780. William Henke. Letter received April 07, 2026.
781. Cody Harford. Letter received April 07, 2026.
782. Kathleen Von Rueden. Letter received April 07, 2026.
783. Scott Savage, E.A. Bonelli + Associates, Inc. Letter received April 07, 2026.
784. Cody Suter. Letter received April 07, 2026.
785. Michelle Peterson. Letter received April 07, 2026.
786. Audrey Kruger. Letter received April 07, 2026.
787. Amie Tatosian. Letter received April 07, 2026.
788. Sean Gallant, Industrial Environmental Concepts Inc. Letter received April 07, 2026.
789. Lori Peterson. Letter received April 07, 2026.
790. Cassie Dudley. Letter received April 07, 2026.
791. Shane Wiercinski, Filtration Resources Inc. Letter received April 07, 2026.
792. Paul Burck. Letter received April 07, 2026.
793. Jeff Steiner. Letter received April 07, 2026.
794. Patricia Cole. Letter received April 07, 2026.
795. Kay Fuller. Letter received April 07, 2026.
796. Jackie Colesworthy. Letter received April 07, 2026.
797. Jennifer Zeltwanger. Letter received April 07, 2026.
798. Crystal Prom. Letter received April 07, 2026.
799. Thomas Obar. Letter received April 07, 2026.
800. Ethan Hoffman. Letter received April 07, 2026.
801. Nick Meierhofer. Letter received April 07, 2026.
802. Corey Roberts. Letter received April 07, 2026.
803. Sandra O'Brien. Letter received April 07, 2026.
804. Kyle Staebler. Letter received April 07, 2026.
805. Kelsey VanOverbeke. Letter received April 07, 2026.
806. Tyler Young. Letter received April 08, 2026.
807. Sheyla Ramirez. Letter received April 08, 2026.
808. Brian Eisenschenk. Letter received April 08, 2026.
809. Carolyn Anderson. Letter received April 08, 2026.
810. Mary Jo Forbord. Letter received April 08, 2026.

811. John Kopp. Letter received April 08, 2026.
812. Judy Gregg. Letter received April 08, 2026.
813. Isidro Granados. Letter received April 08, 2026.
814. Erika Gilsdorf. Letter received April 08, 2026.
815. Yaasika Quist. Letter received April 08, 2026.
816. Carla Anderson. Letter received April 08, 2026.
817. Randi Wingert. Letter received April 08, 2026.
818. Patricia Bouta. Letter received April 08, 2026.
819. Guido Niederoest. Letter received April 08, 2026.
820. Rodrigo Machemehl. Letter received April 08, 2026.
821. Sonja Trom Eayrs. Letter received April 08, 2026.
822. Laura Thielke. Letter received April 08, 2026.
823. Kim Larson. Letter received April 08, 2026.
824. Paul Kostboth, A1 Development Solutions. Letter received April 08, 2026.
825. Terry VanDerPol. Letter received April 08, 2026.
826. Sam Cnossen. Letter received April 08, 2026.
827. Laura Blauch. Letter received April 08, 2026.
828. Rinse Elsinga, Numidia Inc. Letter received April 08, 2026.
829. Melanie Steele. Letter received April 08, 2026.
830. Corey Rost. Letter received April 08, 2026.
831. Mitchell Coulter. Letter received April 08, 2026.
832. Annicka Westrich. Letter received April 08, 2026.
833. Ginny Halloran. Letter received April 08, 2026.
834. Todd Novy. Letter received April 08, 2026.
835. Scott Herrly. Letter received April 08, 2026.
836. Dylan Reese. Letter received April 08, 2026.
837. Earth day Earth day. Letter received April 08, 2026.
838. Shelly Kremer. Letter received April 08, 2026.
839. Diane Baum. Letter received April 08, 2026.
840. Owen Anderson. Letter received April 09, 2026.
841. Tim Trotter, Edge Dairy Farmer Cooperative. Letter received April 09, 2026.
842. Tim Baumgartner, Edge Dairy Farmer Cooperative. Letter received April 09, 2026.
843. Karalyn Indrelie. Letter received April 09, 2026.
844. Javier Garcia. Letter received April 09, 2026.
845. Mike DeRosier, Interstates Brainerd. Letter received April 09, 2026.
846. Levi Strahm. Letter received April 09, 2026.
847. Kevin Meixel. Letter received April 09, 2026.
848. Ivan Regalado. Letter received April 09, 2026.
849. Joni Heins. Letter received April 09, 2026.

850. Nic McPhee. Letter received April 09, 2026.
851. Kaleb Heins. Letter received April 09, 2026.
852. Vick Konkin. Letter received April 09, 2026.
853. Todd Klein. Letter received April 09, 2026.
854. Christopher Westerman. Letter received April 09, 2026.
855. Chenoa Marks. Letter received April 09, 2026.
856. Anthony Vannelli. Letter received April 09, 2026.
857. Gretchen Tuck. Letter received April 09, 2026.
858. Liza Eng. Letter received April 09, 2026.
859. Carol Pietrick. Letter received April 09, 2026.
860. Matt Sattler. Letter received April 10, 2026.
861. Kurt Grimm, Nutra Drip. Letter received April 10, 2026.
862. Dennis Cuchna. Letter received April 10, 2026.
863. Emily Bruce. Letter received April 10, 2026.
864. Bonnie Nelson. Letter received April 10, 2026.
865. Sonja Trom Eayrs. Letter received April 10, 2026.
866. Holly Windle. Letter received April 10, 2026.
867. Dana Jackson. Letter received April 10, 2026.
868. Barbra Hyk-Zimmer. Letter received April 10, 2026.
869. Mary Polta. Letter received April 10, 2026.
870. Roslyn Hjermstad. Letter received April 10, 2026.
871. Leona Hanson. Letter received April 10, 2026.
872. Kay Drache. Letter received April 10, 2026.
873. Pat Peschman. Letter received April 11, 2026.
874. George Pliml. Letter received April 11, 2026.
875. Sandra Sheets. Letter received April 11, 2026.
876. Kathy Herron. Letter received April 11, 2026.
877. Susan Scherer. Letter received April 11, 2026.
878. Elizabeth Reach. Letter received April 12, 2026.
879. Devin Hammer. Letter received April 12, 2026.
880. Shane Reynolds. Letter received April 12, 2026.
881. Kelly Fredrickson. Letter received April 13, 2026.
882. Jim VanderGissen, PRO Refrigeration Inc. Letter received April 13, 2026.
883. Kim & Deborah K. Larson. Letter received April 13, 2026.
884. Beth Stanford. Letter received April 13, 2026.
885. Mike Quale. Letter received April 14, 2026.
886. Brady Koehl. Letter received April 14, 2026.
887. Anonymous. Letter received April 14, 2026.
888. Michael Crinion, Edge Dairy Farmer Cooperative. Letter received April 14, 2026.

889. Mary Steinbicker. Letter received April 14, 2026.
890. Micky McGilligan. Letter received April 14, 2026.
891. Tom Beer. Letter received April 14, 2026.
892. Donna Wermus. Letter received April 14, 2026.
893. Amy Nankivil. Letter received April 14, 2026.
894. Martha Kirkava. Letter received April 14, 2026.
895. Susan Darley-Hill. Letter received April 14, 2026.
896. Martha Archer. Letter received April 14, 2026.
897. Katherine Winston. Letter received April 14, 2026.
898. Amy Cordry. Letter received April 14, 2026.
899. Mark Muller. Letter received April 14, 2026.
900. Chloe Stotler. Letter received April 14, 2026.
901. Dorothy Dolezal. Letter received April 14, 2026.
902. William Scott Gorman, Pro Refirgeration. Letter received April 14, 2026.
903. Sarah Johnson. Letter received April 14, 2026.
904. Jason Henrich, Flat Rate Inc. Letter received April 14, 2026.
905. Jeanne Landkamer. Letter received April 14, 2026.
906. Allison Greenwald. Letter received April 14, 2026.
907. Jessica Renner. Letter received April 14, 2026.
908. Gwendolyn Fassett. Letter received April 14, 2026.
909. Tiffany Nesbit. Letter received April 15, 2026.
910. Ah-li Monahan. Letter received April 15, 2026.
911. Laura Cullip. Letter received April 15, 2026.
912. Darlys Vogt. Letter received April 15, 2026.
913. Nicole Wenzel. Letter received April 15, 2026.
914. Scott Wirtzfeld. Letter received April 15, 2026.
915. Jessie Pinney. Letter received April 16, 2026.
916. Michelle Carroll. Letter received April 17, 2026.
917. Chris Sonnek. Letter received April 17, 2026.
918. Samantha Meurett. Letter received April 19, 2026.
919. Karen Locke. Letter received April 20, 2026.
920. Dave Vipond. Letter received April 20, 2026.
921. Jacob Sklar. Letter received April 20, 2026.
922. James Lubenow. Letter received April 20, 2026.
923. Monte Strelow, Strelow Ranch Trucking. Letter received April 21, 2026.
924. Linda Olson. Letter received April 22, 2026.
925. Leah Rogne. Letter received April 22, 2026.
926. Robert Rutkowski. Letter received April 22, 2026.
927. Ian Vogel. Letter received April 22, 1939.

928. Christopher Carlson. Letter received April 22, 2026.
929. Steven Vogel. Letter received April 22, 2026.
930. Kally Goschke. Letter received April 23, 2026.
931. Cynthia Huse. Letter received April 23, 2026.
932. Megan O'Hara. Letter received April 23, 2026.
933. Yvonne Weber. Letter received April 23, 2026.
934. Mark Roalson. Letter received April 23, 2026.
935. Melissa Heinen. Letter received April 23, 2026.
936. Roger Wacek. Letter received September 24, 2026.
937. Jan Joannides. Letter received April 24, 2026.
938. Nathan Collins. Letter received April 24, 2026.
939. Linda Herron. Letter received April 25, 2026.
940. Amy Flatten. Letter received April 26, 2026.
941. Phillip Lermon. Letter received April 26, 2026.
942. Brian Miller. Letter received April 27, 2026.
943. Sharon Fortunak. Letter received April 27, 2026.
944. Laurence Margolis. Letter received April 27, 2026.
945. Mark Hockel. Letter received April 27, 2026.
946. Steve Albrecht. Letter received April 27, 2026.
947. Karen Neenan. Letter received April 27, 2026.
948. Kedron Nohl. Letter received April 27, 2026.
949. Daniel Belgum. Letter received April 27, 2026.
950. John Pierce. Letter received April 27, 2026.
951. Joan Meierotto. Letter received April 27, 2026.
952. Daryl Maulfair. Letter received April 28, 2026.
953. Jon Nohl. Letter received April 28, 2026.
954. Kendall Wendling. Letter received April 28, 2026.
955. Lance Lindeman. Letter received April 28, 2026.
956. Emilie Evink. Letter received April 28, 2026.
957. Christian Cabrera. Letter received April 28, 2026.
958. Luis Lopez. Letter received April 28, 2026.
959. Jose Castro. Letter received April 28, 2026.
960. Sergio Vazquez. Letter received April 28, 2026.
961. Alejandra Vazquez. Letter received April 28, 2026.
962. Mario Cervantes. Letter received April 28, 2026.
963. Ernesto Hernandez Montellano. Letter received April 28, 2026.
964. Juan Pablo Brom. Letter received April 28, 2026.
965. Lizeth Carmona. Letter received April 28, 2026.
966. Diego Gutierrez. Letter received April 28, 2026.

967. Julio Villagomez. Letter received April 28, 2026.
968. Pedro Garcia. Letter received April 28, 2026.
969. Carlos Daniel Rosiles Gallegos. Letter received April 28, 2026.
970. Jenessa Solvie. Letter received April 28, 2026.
971. Jose Gutierrez. Letter received April 28, 2026.
972. Helstrom G Sanchez. Letter received April 28, 2026.
973. Yahveh Carrillo. Letter received April 28, 2026.
974. Juan Carlos Garnica Montes. Letter received April 28, 2026.
975. William Ojeda. Letter received April 28, 2026.
976. Librado Ortiz. Letter received April 28, 2026.
977. Omar Ali Salinas. Letter received April 28, 2026.
978. Leonel Chavez Salas. Letter received April 28, 2026.
979. Tatiana Gutierrez. Letter received April 28, 2026.
980. Carlos Ivan Romero Ramos. Letter received April 28, 2026.
981. Moises Moreno. Letter received April 28, 2026.
982. Antonio Cruz Magdalena. Letter received April 28, 2026.
983. Rosa Arenas Benitez. Letter received April 28, 2026.
984. Fabian Cruz. Letter received April 28, 2026.
985. Leonel Orozco. Letter received April 28, 2026.
986. Leonel Sanchez Barbosa. Letter received April 28, 2026.
987. Orsai Gonzalez Vazquez. Letter received April 28, 2026.
988. Nicolas Vega. Letter received April 28, 2026.
989. Jorge Hernandez Navarrete. Letter received April 28, 2026.
990. Ivan Regalado. Letter received April 28, 2026.
991. Victor Manuel Suarez Zepeda. Letter received April 28, 2026.
992. Victor Maldonado. Letter received April 28, 2026.
993. Juan Aviles. Letter received April 28, 2026.
994. Mario Mancilla Hetnandez. Letter received April 28, 2026.
995. Saloman Arrieta. Letter received April 28, 2026.
996. Erik Chavez. Letter received April 28, 2026.
997. Isaias Martinez Parada. Letter received April 28, 2026.
998. Elias Hernandez. Letter received April 28, 2026.
999. Braulio Medina. Letter received April 28, 2026.
1000. Antonio Capi. Letter received April 28, 2026.
1001. Miguel Sanchez. Letter received April 28, 2026.
1002. Jesus Mireles. Letter received April 28, 2026.
1003. Jesus O Gomez. Letter received April 28, 2026.
1004. Lindsey Lindor. Letter received April 28, 2026.
1005. David Diaz. Letter received April 28, 2026.

1006. Miguel Arreola. Letter received April 28, 2026.
1007. Alejandra Anguiano. Letter received April 28, 2026.
1008. Cristian Castillo. Letter received April 28, 2026.
1009. Hector Rosales. Letter received April 28, 2026.
1010. Teague Picht. Letter received April 28, 2026.
1011. Blanca Garcia. Letter received April 28, 2026.
1012. Eduardo Nochebuena Zaragoza. Letter received April 28, 2026.
1013. Antonio Ramos. Letter received April 28, 2026.
1014. Hugo Sanchez Arenas. Letter received April 28, 2026.
1015. Berenice Huescas. Letter received April 28, 2026.
1016. Kurtis Wulf. Letter received April 28, 2026.
1017. Jesus Galindo Hernandez. Letter received April 28, 2026.
1018. Miguel Urrutia Calvo. Letter received April 28, 2026.
1019. Karen Campos. Letter received April 28, 2026.
1020. Ramos Jaimez. Letter received April 28, 2026.
1021. Mitch Koehl. Letter received April 28, 2026.
1022. Carlos Portillo. Letter received April 28, 2026.
1023. Jose Borjas Gonzales. Letter received April 28, 2026.
1024. Valente Fuentes. Letter received April 28, 2026.
1025. Miguel Cruz. Letter received April 28, 2026.
1026. Kyle Fehr. Letter received April 28, 2026.
1027. Dylan Reese. Letter received April 28, 2026.
1028. Oscar Neri. Letter received April 28, 2026.
1029. Oscar Ceyala. Letter received April 28, 2026.
1030. Lucio Santiago. Letter received April 28, 2026.
1031. Alton Ekren. Letter received April 28, 2026.
1032. Christopher Ruiz. Letter received April 28, 2026.
1033. Misael Carrasco. Letter received April 28, 2026.
1034. Victor Morales. Letter received April 28, 2026.
1035. Carlos Alba Mora. Letter received April 28, 2026.
1036. Susan Medrano. Letter received April 28, 2026.
1037. Daniel Camacho Ramirez. Letter received April 28, 2026.
1038. Fernando Chapa. Letter received April 28, 2026.
1039. Miguel Rodriguez. Letter received April 28, 2026.
1040. Heribier Ramos. Letter received April 28, 2026.
1041. Hilary Reeves. Letter received April 28, 2026.
1042. Benjamin Juarez Cervantes. Letter received April 28, 2016.
1043. Amber Ramey. Letter received April 28, 2026.
1044. Robert Valnes. Letter received April 29, 2026.

1045. Dustin Hollermann. Letter received April 29, 2026.
1046. Jared Wohlers. Letter received April 29, 2026.
1047. Luis C Hernandez Valenzuela. Letter received April 29, 2026.
1048. Alberto Ochoa. Letter received April 29, 2026.
1049. Helstrom Sanchez. Letter received April 29, 2026.
1050. Gordon Dalseide. Letter received April 29, 2026.
1051. Lucas Anderson. Letter received April 29, 2026.
1052. Ford Thunderbird. Letter received April 29, 2026.
1053. David Hauge. Letter received April 29, 2026.
1054. Nicole Wagner. Letter received April 29, 2026.
1055. Laura Lee. Letter received April 29, 2026.
1056. David Kortan. Letter received April 30, 2026.
1057. Ann Williams. Letter received April 30, 2026.
1058. Greg Solberg. Letter received April 30, 2026.
1059. Carrie Slater Duffy. Letter received April 30, 2026.
1060. Rebecca Tryon. Letter received April 30, 2026.
1061. Tom Rosen, Rosen's Diversified Inc. Letter received April 30, 2026.
1062. Nancy Hinrichs. Letter received April 30, 2026.
1063. Jerry Nohl. Letter received April 30, 2026.
1064. Kayla Parkin. Letter received May 01, 2026.
1065. Linus Meyer. Letter received May 01, 2026.
1066. Robert Schlobohm. Letter received May 01, 2026.
1067. Nathan Kestner, Minnesota Department of Natural Resources. Letter received May 01, 2026.
1068. Jill Holslin. Letter received May 01, 2026.
1069. Sonja Trom Eayrs. Letter received May 01, 2026.
1070. Philip Strelow. Letter received May 01, 2026.
1071. John Fischer-Merritt. Letter received May 01, 2026.
1072. Ricardo Camargo. Letter received May 01, 2026.
1073. Jennifer Maleitzke, RDO Equipment Co. Letter received May 01, 2026.
1074. Cathy Solvie. Letter received May 01, 2026.
1075. Nathan Hrnicek. Letter received May 01, 2026.
1076. Reyna Estrada. Letter received May 02, 2026.
1077. Tyler Bueng. Letter received May 02, 2026.
1078. Josie Hollermann. Letter received May 02, 2026.
1079. Suzanne Swanson. Letter received May 02, 2026.
1080. Athena Kildegaard. Letter received May 03, 2026.
1081. Peter Dolan. Letter received May 03, 2026.
1082. Mark Satre. Letter received May 03, 2026.
1083. Susan Kulberg. Letter received May 04, 2026.

1084. Exal Villalbos. Letter received May 04, 2026.
1085. Christian Baez Tellez. Letter received May 04, 2026.
1086. Jose A Vasquez. Letter received May 04, 2026.
1087. Victorino Serrato Martinez. Letter received May 04, 2026.
1088. Diego Saldana Morales. Letter received May 04, 2026.
1089. J. Cesor Chavez. Letter received May 04, 2026.
1090. Luis C. Hernandez. Letter received May 04, 2026.
1091. Humberto Meyer Fuentes. Letter received May 04, 2026.
1092. Anonymous anonymous. Letter received May 04, 2026.
1093. Anonymous anonymous. Letter received May 04, 2026.
1094. Anonymous anonymous. Letter received May 04, 2026.
1095. Marilo Rodriguez. Letter received May 04, 2026.
1096. Hugo Gonzalez. Letter received May 04, 2026.
1097. Jackson Walsh. Letter received May 04, 2026.
1098. Dustin Walsh. Letter received May 04, 2026.
1099. Jeanne Norrgard. Letter received May 04, 2026.
1100. Connie Benson. Letter received May 04, 2026.
1101. Marcus Vaqueu. Letter received May 04, 2026.
1102. Terri Hawkinson. Letter received May 04, 2026.
1103. Heriblez n/a. Letter received May 04, 2026.
1104. Nathan Compart. Letter received May 04, 2026.
1105. Alejandra Anguiano. Letter received May 04, 2026.
1106. David Diaz. Letter received May 04, 2026.
1107. Adam Koehl. Letter received May 04, 2026.
1108. Ash Rose. Letter received May 04, 2026.
1109. Kyle Klausing. Letter received May 04, 2026.
1110. brian wojtalewicz. Letter received May 04, 2026.
1111. Chad Davison. Letter received May 04, 2026.
1112. Diana Oliwaus. Letter received May 04, 2026.
1113. Lynn Hu. Letter received May 04, 2026.
1114. Barbara Kill. Letter received May 04, 2026.
1115. Brenda Boever. Letter received May 04, 2026.
1116. Shawna Conroy. Letter received May 04, 2026.
1117. Barbara Hyk-Zimmer. Letter received May 05, 2026.
1118. Nelson Jorgenson. Letter received May 05, 2026.
1119. Herbert Davis. Letter received May 05, 2026.
1120. Billy X Curmano. Letter received May 05, 2026.
1121. Kay Slama. Letter received May 05, 2026.
1122. Susan Scherer. Letter received May 05, 2026.

1123. Diane Baum. Letter received May 05, 2026.
1124. Ferolyn Angell. Letter received May 05, 2026.
1125. Em Senten. Letter received May 05, 2026.
1126. Lori Hinrichsen. Letter received May 05, 2026.
1127. Tommy Houdek, Wild Rice Electric Cooperative, Inc.. Letter received May 05, 2026.
1128. Robert Dana. Letter received May 05, 2026.
1129. Ismad Cruz. Letter received May 05, 2026.
1130. Jason Yoss. Letter received May 05, 2026.
1131. Julie Kill. Letter received May 05, 2026.
1132. Janine Wojtalewicz. Letter received May 05, 2026.
1133. Kelly Skaurud. Letter received May 05, 2026.
1134. Taylor Gibson. Letter received May 05, 2026.
1135. Amanda Holslin, Holslin Family Farms. Letter received May 05, 2026.
1136. Jay Sheets. Letter received May 05, 2026.
1137. David Soehren. Letter received May 05, 2026.
1138. Melissa Bakker Roach. Letter received May 06, 2026.
1139. Amy Werk. Letter received May 06, 2026.
1140. Jeanne Johnson. Letter received May 06, 2026.
1141. Adam Zelltwanger. Letter received May 06, 2026.
1142. Landon Koehl. Letter received May 06, 2026.
1143. Lucas Koehl. Letter received May 06, 2026.
1144. Baldomero Penaloza. Letter received May 06, 2026.
1145. Osvaldo Penaloza Gomez. Letter received May 06, 2026.
1146. Anthony Anker. Letter received May 06, 2026.
1147. Tyler Thiel. Letter received May 06, 2026.
1148. Javier P Torillo. Letter received May 06, 2026.
1149. Francisco Guadarrama Capitaine. Letter received May 06, 2026.
1150. Jodi DeCamp. Letter received May 06, 2026.
1151. Cameron Adams. Letter received May 06, 2026.
1152. Kevin Stallman. Letter received May 06, 2026.
1153. Dustin Nelson. Letter received May 06, 2026.
1154. Heidi Wellnitz. Letter received May 06, 2026.
1155. Matt Wellnitz. Letter received May 06, 2026.
1156. Lowell Moser. Letter received May 06, 2026.
1157. Rob Needham. Letter received May 06, 2026.
1158. Mike Wade, Wild Rice Electric Cooperative . Letter received May 06, 2026.
1159. Felipe Jaimes Aviles. Letter received May 06, 2026.
1160. Sam Bradshaw. Letter received May 06, 2026.
1161. Diego Velazquez Sanchez. Letter received May 06, 2026.

1162. Martha Cristina Lopez H. Letter received May 06, 2026.
1163. Paulina Velazquez. Letter received May 06, 2026.
1164. Phillip Earle. Letter received May 06, 2026.
1165. James Morais. Letter received May 06, 2026.
1166. Taylor Flemming. Letter received May 06, 2026.
1167. Tony Tillma, Valley Dairy Supply. Letter received May 06, 2026.
1168. Gerhard Prinsloo. Letter received May 06, 2026.
1169. Rodrigo n/a. Letter received May 06, 2026.
1170. Brett Peterson. Letter received May 06, 2026.
1171. SG Prinsloo. Letter received May 06, 2026.
1172. Nancy Fabiola Acevedo. Letter received May 06, 2026.
1173. Marco Grubinoew. Letter received May 06, 2026.
1174. Victoria Dalager. Letter received May 06, 2026.
1175. Anonymous Anonymous. Letter received May 06, 2026.
1176. Anonymous Anonymous. Letter received May 06, 2026.
1177. Mathew Miller. Letter received May 06, 2026.
1178. Anonymous Anonymous. Letter received May 06, 2026.
1179. Anonymous Anonymous. Letter received May 06, 2026.
1180. Luis Carmona. Letter received May 06, 2026.
1181. Janet Espinoza. Letter received May 06, 2026.
1182. Susana Corona. Letter received May 06, 2026.
1183. Rodney McCollum. Letter received May 06, 2026.
1184. Rames Jaimez. Letter received May 06, 2026.
1185. Jose luis Martinez. Letter received May 06, 2026.
1186. Filemon Cervantez. Letter received May 06, 2026.
1187. Anonymous Anonymous. Letter received May 06, 2026.
1188. Ratael Sevilla. Letter received May 06, 2026.
1189. Christian Cabrera. Letter received May 06, 2026.
1190. Juan Pablo Alvarez. Letter received May 06, 2026.
1191. Don Wienhold. Letter received May 06, 2026.
1192. Jorge Mehel. Letter received May 06, 2026.
1193. Michael Anderson. Letter received May 06, 2026.
1194. Martin M. Ruano. Letter received May 06, 2026.
1195. brian wojtalewicz. Letter received May 06, 2026.
1196. Nancy Malcomson. Letter received May 06, 2026.
1197. Stuart Knappmiller. Letter received May 06, 2026.
1198. Margaret Kuchenreuther. Letter received May 06, 2026.
1199. Daniel Cona. Letter received May 06, 2026.
1200. Alberto Garcia. Letter received May 06, 2026.

1201. Veronica Bonilla. Letter received May 06, 2026.
1202. Cole Watzke. Letter received May 06, 2026.
1203. Reynaldo Gomez Espinoza. Letter received May 06, 2026.
1204. Roben Hernandez. Letter received May 06, 2026.
1205. Marcelo R Gonzalez. Letter received May 06, 2026.
1206. Hugo Gabriel Ruiz. Letter received May 06, 2026.
1207. Angeles Salem Hernandez. Letter received May 06, 2026.
1208. Leslie Garrido. Letter received May 06, 2026.
1209. Sergio Vazquez. Letter received May 06, 2026.
1210. Alejandra Vazquez. Letter received May 06, 2026.
1211. Isa Garrido. Letter received May 06, 2026.
1212. Adrian Garrido. Letter received May 06, 2026.
1213. Mariana Garrido. Letter received May 06, 2026.
1214. Josh Hollen. Letter received May 06, 2026.
1215. Gerardo Catalan. Letter received May 06, 2026.
1216. Alejandro Gonzalez. Letter received May 06, 2026.
1217. Eric Joos. Letter received May 06, 2026.
1218. Anonymous Anonymous. Letter received May 06, 2026.
1219. Zachary Koehl. Letter received May 06, 2026.
1220. Tyler Reese. Letter received May 06, 2026.
1221. Anonymous Anonymous. Letter received May 06, 2026.
1222. Timoteo Alejandro Mtnez. Letter received May 06, 2026.
1223. Monserat Marquez. Letter received May 06, 2026.
1224. Eduardo Holhebuena Zaraboza. Letter received May 06, 2026.
1225. Jesus Suarez Camucho. Letter received May 06, 2026.
1226. Chrstina Lanzagorta Silva. Letter received May 06, 2026.
1227. Josue Roberto Moreno Soriano. Letter received May 06, 2026.
1228. Cristian n/a. Letter received May 06, 2026.
1229. Jose Borjus. Letter received May 06, 2026.
1230. Casey Thorson. Letter received May 06, 2026.
1231. Karen Camos. Letter received May 06, 2026.
1232. Blanca Garcia. Letter received May 06, 2026.
1233. Carlos Angel Alba Mora. Letter received May 06, 2026.
1234. Andres Barrios Hverra. Letter received May 06, 2026.
1235. Yonatan Ordonez. Letter received May 06, 2026.
1236. Evelyn Serna. Letter received May 06, 2026.
1237. Jason Pielt. Letter received May 06, 2026.
1238. Concerned Citizen. Letter received May 06, 2026.
1239. Justin Englebert. Letter received May 06, 2026.

1240. Don B.. Letter received May 06, 2026.
1241. Yohnny Serna Vite. Letter received May 06, 2026.
1242. Ricardo Camrgu. Letter received May 06, 2026.
1243. Joaquin Ortega Rerez. Letter received May 06, 2026.
1244. Diego Serva. Letter received May 06, 2026.
1245. Alan Stokke, Prairie Pest Control. Letter received May 06, 2026.
1246. Randy Thymian. Letter received May 06, 2026.
1247. Brett Sletta, Prairie Pest Control. Letter received May 06, 2026.
1248. Dick Metzger. Letter received May 06, 2026.
1249. Jordan Staples. Letter received May 06, 2026.
1250. Brad Visser. Letter received May 06, 2026.
1251. Marcos Lazarro. Letter received May 06, 2026.
1252. Amanda Bilek, Minnesota Corn Growers Association. Letter received May 06, 2026.
1253. Amando Chagoua. Letter received May 06, 2026.
1254. Madeline Maxeiner. Letter received May 06, 2026.
1255. Rosalind Alexson. Letter received May 06, 2026.
1256. Brad Lewison. Letter received May 06, 2026.
1257. Randal Gorder. Letter received May 06, 2026.
1258. Andrew Israels-Swenson. Letter received May 06, 2026.
1259. Anna Kilian. Letter received May 06, 2026.
1260. Gary Dukes. Letter received May 06, 2026.
1261. Martha Koehl. Letter received May 06, 2026.
1262. Ben Weiland. Letter received May 06, 2026.
1263. Logan Tosel. Letter received May 06, 2026.
1264. David Jungst. Letter received May 06, 2026.
1265. Laura Aldrich-Wolfe. Letter received May 06, 2026.
1266. Oscar Galan Trejo. Letter received May 07, 2026.
1267. Kari Visser. Letter received May 07, 2026.
1268. Julia Murillo. Letter received May 07, 2026.
1269. Bernardo Laines Alonzo. Letter received May 07, 2026.
1270. Marc Stevens. Letter received May 07, 2026.
1271. Dustin Hollermann. Letter received May 07, 2026.
1272. Megan Horsager. Letter received May 07, 2026.
1273. Daniel Granados. Letter received May 07, 2026.
1274. Jim Birkemeyer, R & J Broadcasting, LLC.. Letter received May 07, 2026.
1275. Kelsey Olson, CURE . Letter received May 07, 2026.
1276. Gary Wertish, Minnesota Farmers Union. Letter received May 07, 2026.
1277. William Pelowski. Letter received May 07, 2026.
1278. Beth Slocum. Letter received May 07, 2026.

1279. Kristin Lamberty. Letter received May 07, 2026.
1280. Ron Visser. Letter received May 07, 2026.
1281. Aloriberto Vite. Letter received May 07, 2026.
1282. Jose Luis Quinter. Letter received May 07, 2026.
1283. Jose Luis Martinez. Letter received May 07, 2026.
1284. John H Beste. Letter received May 07, 2026.
1285. Lee Ann Hall. Letter received May 07, 2026.
1286. Jaylon Nichols. Letter received May 07, 2026.
1287. Brady Janzen, Riverview, LLP. Letter received May 07, 2026.
1288. Blaine Hill. Letter received May 07, 2026.
1289. Eric Lindberg, Minnesota Center for Environmental Advocacy. Letter received May 07, 2026.
1290. Priscilla Wood. Letter received May 07, 2026.
1291. Stephanie Gausman. Letter received May 07, 2026.
1292. Char Zinda. Letter received May 07, 2026.
1293. Jamalea Martelle. Letter received May 07, 2026.
1294. Peter Kennedy. Letter received May 07, 2026.
1295. Johanna Knorr. Letter received May 07, 2026.
1296. Travis Moser. Letter received May 07, 2026.
1297. Ronald Visser. Letter received May 07, 2026.
1298. A concerned Minnesota resident. Letter received May 07, 2026.
1299. Logan Visser. Letter received May 07, 2026.
1300. Max Lundgren. Letter received May 07, 2026.
1301. Glen Visser. Letter received May 07, 2026.
1302. Sandra Fernow. Letter received May 07, 2026.
1303. Sam Visser. Letter received May 07, 2026.
1304. Joe Stroman. Letter received May 07, 2026.
1305. Rick Metzger. Letter received May 07, 2026.
1306. Jeff Beckman. Letter received May 07, 2026.
1307. Erica Boyum. Letter received May 07, 2026.
1308. Peter Louwagie. Letter received May 07, 2026.
1309. Alisha Livengood. Letter received May 07, 2026.
1310. Rebecca Pedersen. Letter received May 07, 2026.
1311. Willis Mattison, Izaak Walton League of America - Prairie Woods Chapter - Detroit Lakes, Mn. Letter received May 07, 2026.
1312. Ethan Bruer. Letter received May 07, 2026.
1313. Brett Boyum. Letter received May 07, 2026.
1314. Kody Livengood. Letter received May 07, 2026.
1315. Josh VanDerPol. Letter received May 07, 2026.
1316. Mike Odello. Letter received May 06, 2026.

1317. Kim Larson. Letter received February 11, 2026.
1318. Eric Klindt. Letter received March 12, 2026.
1319. Thomas Claussen. Letter received March 13, 2026.
1320. Susan Frenzel. Letter received March 17, 2026.
1321. Sue Frenzel. Letter received March 20, 2026.
1322. Thomas Probst. Letter received April 02, 2026.
1323. Amy Kephart. Letter received April 02, 2026.
1324. Rita Holland. Letter received April 02, 2026.
1325. Heather Rykus. Letter received April 02, 2026.
1326. Julia Pearson. Letter received April 02, 2026.
1327. Laura Klein. Letter received April 02, 2026.
1328. Heidi Harder. Letter received April 02, 2026.
1329. Thomas Kalahar. Letter received April 03, 2026.
1330. Kevin Van Winkle. Letter received April 03, 2026.
1331. Bob Lefebvre. Letter received April 03, 2026.
1332. Francis Casey. Letter received April 04, 2026.
1333. Darlene Aragon. Letter received April 04, 2026.
1334. Ferolyn Angell. Letter received April 04, 2026.
1335. Marv Post. Letter received April 05, 2026.
1336. Kristine Hamm. Letter received April 05, 2026.
1337. Robert Finley. Letter received April 06, 2026.
1338. Jeanne Norrgard. Letter received April 06, 2026.
1339. Shannon Nieland. Letter received April 08, 2026.
1340. Patricia Cole. Letter received April 08, 2026.
1341. Jacqueline Colby. Letter received April 08, 2026.
1342. TJ Hennen. Letter received April 08, 2026.
1343. Audrey Arner. Letter received April 08, 2026.
1344. Rose & Dan Merphy. Letter received April 08, 2026.
1345. Kim Larson. Letter received April 08, 2026.
1346. Diane Baum. Letter received April 08, 2026.
1347. Kevin Meixel. Letter received April 09, 2026.
1348. Nancy Thorson. Letter received April 09, 2026.
1349. Blake Criswell, GotWhey LLC. Letter received April 09, 2026.
1350. Lynetter Kayser. Letter received April 09, 2026.
1351. Mitchell Debuhr. Letter received April 10, 2026.
1352. Tracey Eliason. Letter received April 13, 2026.
1353. Brady Koehl. Letter received April 14, 2026.
1354. Steve Olinger. Letter received April 27, 2026.
1355. Douglas Lande. Letter received April 28, 2026.

1356. Francisco Guadarrama Capitaine. Letter received April 28, 2026.
1357. Rebecca Ramos. Letter received April 28, 2026.
1358. Diane Baum. Letter received April 29, 2026.
1359. Todd Charnetzke. Letter received April 29, 2026.
1360. Samantha Kramer. Letter received April 29, 2026.
1361. Jerry Seibel. Letter received April 29, 2026.
1362. Dick Cheney. Letter received April 29, 2026.
1363. Lilia Mendoza Acosta. Letter received April 30, 2026.
1364. Michael Smith. Letter received May 02, 2026.
1365. Hunter Bohn. Letter received May 05, 2026.
1366. Federico Cano Nepauseno. Letter received May 05, 2026.
1367. David Hauge. Letter received May 06, 2026.
1368. David Israels-Swenson. Letter received May 06, 2026.
1369. Gary Dukes. Letter received May 06, 2026.
1370. David Jungst. Letter received May 06, 2026.
1371. Dave Vipond, H2 Land Stewards. Letter received May 06, 2026.
1372. Gary Wertish, Minnesota Farmers Union. Letter received May 07, 2026.
1373. Eric Lindberg, Minnesota Center for Environmental Advocacy. Letter received May 07, 2026.
1374. Travis Moser. Letter received May 07, 2026.
1375. Ronald Visser. Letter received May 07, 2026.
1376. Josh VanDerPol. Letter received May 07, 2026.

Appendix B-1: Responses to comments on the EAW

Comment Group	Comment	Response
1	Commenters are requesting an Environmental Impact Statement (EIS) be completed for the Project.	The Commissioner of the MPCA will make the determination on the need for an EIS after carefully reviewing all the information in the EAW, written public comments, and the Response to Comments. Upon reviewing all the available information, the Commissioner determines if the Project has the potential for significant environmental effects following the criteria specified in Minn. R. 4410.1700 subp. 7. The Commissioner issues Findings of Fact, Conclusions of Law, and Order to support either a positive declaration on the need for an EIS, or a negative declaration on the need for an EIS.
2	Commenters are requesting an EIS be completed for the Project due to potential impacts to water quality.	The Commissioner of the MPCA will make the determination on the need for an EIS after carefully reviewing all the information in the EAW, written public comments, and the Response to Comments. Upon reviewing all the available information, the Commissioner determines if the Project has the potential for significant environmental effects following the criteria specified in Minn. R. 4410.1700 subp. 7. The Commissioner issues Findings of Fact, Conclusions of Law, and Order to support either a positive declaration on the need for an EIS, or a negative declaration on the need for an EIS.
3	Commenters are requesting an EIS be completed for the Project due to potential impacts to water quantity.	The Commissioner of the MPCA will make the determination on the need for an EIS after carefully reviewing all the information in the EAW, written public comments, and the Response to Comments. Upon reviewing all the available information, the Commissioner determines if the Project has the potential for significant environmental effects following the criteria specified in Minn. R. 4410.1700 subp. 7. The Commissioner issues Findings of Fact, Conclusions of Law, and Order to support either a positive declaration on the need for an EIS, or a negative declaration on the need for an EIS.
4	Commenters are requesting an EIS be completed for the Project due to potential impacts to air quality.	The Commissioner of the MPCA will make the determination on the need for an EIS after carefully reviewing all the information in the EAW, written public comments, and the Response to Comments. Upon reviewing all the available information, the Commissioner determines if the Project has the potential for significant environmental effects following the criteria specified in Minn. R. 4410.1700 subp. 7. The Commissioner issues Findings of Fact, Conclusions of Law, and Order to support either a positive declaration on the need for an EIS, or a negative declaration on the need for an EIS.
5	Commenters are requesting an EIS be completed for the Project due to the potential impact from greenhouse gas emissions.	The Commissioner of the MPCA will make the determination on the need for an EIS after carefully reviewing all the information in the EAW, written public comments, and the Response to Comments. Upon reviewing all the available information, the Commissioner determines if the Project has the potential for significant environmental effects following the criteria specified in Minn. R. 4410.1700

Comment Group	Comment	Response
		subp. 7. The Commissioner issues Findings of Fact, Conclusions of Law, and Order to support either a positive declaration on the need for an EIS, or a negative declaration on the need for an EIS.
6	Commenters are requesting an EIS be completed for the Project due to potential impacts to land and soil.	The Commissioner of the MPCA will make the determination on the need for an EIS after carefully reviewing all the information in the EAW, written public comments, and the Response to Comments. Upon reviewing all the available information, the Commissioner determines if the Project has the potential for significant environmental effects following the criteria specified in Minn. R. 4410.1700 subp. 7. The Commissioner issues Findings of Fact, Conclusions of Law, and Order to support either a positive declaration on the need for an EIS, or a negative declaration on the need for an EIS.
7	Commenters are requesting an EIS be completed for the Project due to potential impacts to wildlife.	The Commissioner of the MPCA will make the determination on the need for an EIS after carefully reviewing all the information in the EAW, written public comments, and the Response to Comments. Upon reviewing all the available information, the Commissioner determines if the Project has the potential for significant environmental effects following the criteria specified in Minn. R. 4410.1700 subp. 7. The Commissioner issues Findings of Fact, Conclusions of Law, and Order to support either a positive declaration on the need for an EIS, or a negative declaration on the need for an EIS.
8	Commenters are requesting an EIS be completed for the Project due to potential impacts on local roads.	The Commissioner of the MPCA will make the determination on the need for an EIS after carefully reviewing all the information in the EAW, written public comments, and the Response to Comments. Upon reviewing all the available information, the Commissioner determines if the Project has the potential for significant environmental effects following the criteria specified in Minn. R. 4410.1700 subp. 7. The Commissioner issues Findings of Fact, Conclusions of Law, and Order to support either a positive declaration on the need for an EIS, or a negative declaration on the need for an EIS.
9	Commenters are requesting an EIS be completed for the Project due to potential impacts from leaks.	The Commissioner of the MPCA will make the determination on the need for an EIS after carefully reviewing all the information in the EAW, written public comments, and the Response to Comments. Upon reviewing all the available information, the Commissioner determines if the Project has the potential for significant environmental effects following the criteria specified in Minn. R. 4410.1700 subp. 7. The Commissioner issues Findings of Fact, Conclusions of Law, and Order to support either a positive declaration on the need for an EIS, or a negative declaration on the need for an EIS.
10	Commenters are requesting an EIS be completed for the Project due to potential impacts on human health.	The Commissioner of the MPCA will make the determination on the need for an EIS after carefully reviewing all the information in the EAW, written public comments, and the Response to Comments. Upon reviewing all the available information, the Commissioner determines if the Project has the potential for significant environmental effects following the criteria specified in Minn. R. 4410.1700 subp. 7. The Commissioner issues Findings of Fact, Conclusions of Law, and Order to support either a positive declaration on the need for an EIS, or a negative declaration on the need for an EIS.
11	Commenters are requesting an EIS be completed for the Project due to potential	The Commissioner of the MPCA will make the determination on the need for an EIS after carefully reviewing all the information in the EAW, written public comments, and the Response to Comments.

Comment Group	Comment	Response
	cumulative impacts from the project and other existing feedlots.	Upon reviewing all the available information, the Commissioner determines if the Project has the potential for significant environmental effects following the criteria specified in Minn. R. 4410.1700 subp. 7. The Commissioner issues Findings of Fact, Conclusions of Law, and Order to support either a positive declaration on the need for an EIS, or a negative declaration on the need for an EIS.
12	Commenters are requesting an EIS be completed for the Project to assess potential impacts to small independent dairy farms.	The comment is out of scope for the EAW as it does not substantially inform the decision on the need for an EIS per the evaluation criteria in Minn. R. 4410.1700 subp. 7.
13	Commenters are requesting an EIS be completed for the Project to assess potential impacts to the local community.	The comment is out of scope for the EAW as it does not substantially inform the decision on the need for an EIS per the evaluation criteria in Minn. R. 4410.1700 subp. 7.
14	Commenters are requesting an EIS be completed for the Project to assess potential socio-economic impacts.	The comment is out of scope for the EAW as it does not substantially inform the decision on the need for an EIS per the evaluation criteria in Minn. R. 4410.1700 subp. 7.
15	Commenters are requesting an EIS be completed for the Project due to the large size/scope of the Project.	The comment is out of scope for the EAW as it does not substantially inform the decision on the need for an EIS per the evaluation criteria in Minn. R. 4410.1700 subp. 7.
16	Commenters note that there have been no EISs completed for an animal feedlot or that when the MPCA has ordered an EIS the project was withdrawn.	The comment is out of scope for the EAW as it does not substantially inform the decision on the need for an EIS per the evaluation criteria in Minn. R. 4410.1700 subp. 7.
17	Commenters request the MPCA to order an EIS due to a past history of spills at some of Riverview's existing dairies.	The comment is out of scope for the EAW as it does not substantially inform the decision on the need for an EIS per the evaluation criteria in Minn. R. 4410.1700 subp. 7.
18	Commenters are requesting that the EAW/EIS should be prepared by an independent third party.	The comment is out of scope for the EAW as it does not substantially inform the decision on the need for an EIS per the evaluation criteria in Minn. R. 4410.1700 subp. 7.
19	Commenters are suggesting several statewide policy changes related to environmental review and regulation of feedlots in Minnesota.	The comment is out of scope for the EAW as it does not substantially inform the decision on the need for an EIS per the evaluation criteria in Minn. R. 4410.1700 subp. 7.
20	Commenters do not believe an EIS is necessary for the Project.	The Commissioner of the MPCA will make the determination on the need for an EIS after carefully reviewing all the information in the EAW, written public comments, and the Response to Comments.

Comment Group	Comment	Response
		Upon reviewing all the available information, the Commissioner determines if the Project has the potential for significant environmental effects following the criteria specified in Minn. R. 4410.1700 subp. 7. The Commissioner issues Findings of Fact, Conclusions of Law, and Order to support either a positive declaration on the need for an EIS, or a negative declaration on the need for an EIS.
21	Commenter reminds MPCA of the criteria to be used when determining if there is the potential to cause significant environmental effects.	The Commissioner of the MPCA will make the determination on the need for an EIS after carefully reviewing all the information in the EAW, written public comments, and the Response to Comments. Upon reviewing all the available information, the Commissioner determines if the Project has the potential for significant environmental effects following the criteria specified in Minn. R. 4410.1700 subp. 7. The Commissioner issues Findings of Fact, Conclusions of Law, and Order to support either a positive declaration on the need for an EIS, or a negative declaration on the need for an EIS.
22	Commenters note to the MPCA, the space for the Public Meeting was too small to accommodate everyone that planned to attend and that some people were turned away from the meeting.	The MPCA's public meeting was held at a venue near the Project location, to enable more local people to attend and not force people to travel one hour plus to a larger venue.
23	Commenters state all of Riverview's feedlot operations should be included in the cumulative impacts analysis.	Environmental review is limited to the proposed project. Existing facilities, unless a phased action, are exempt from further environmental review. Existing facilities can be included in a cumulative impacts analysis, but information requested is limited to "could be reasonably obtained."
24	Commenters argue the "Environmentally Relevant Area" is vastly undersized and does not include a cumulative climate analysis.	The Environmentally Relevant Area (ERA) can vary depending on the environmental topic of consideration such as groundwater extraction vs. manure application vs. cumulative climate analysis. For some environmental topics the ERA is defined within the EAW form, for others the MPCA decides on what constitutes the ERA but must also take into consideration information that "could be reasonably obtained."
25	Commenter is making a legal argument that the including of Rumensin in the EAW irrelevant and vague.	The inclusion of possible feed additives like Rumensin is a suggestion of possible ways is part of the acceptable response under EAW item 18.B.2 to identifying methods for reducing CO_2e.
26	Commenters argue an EAW is insufficient to provide adequate analysis for a project of this size.	MPCA is obligated to follow the process detailed in Minn. R. 4410. Currently, for feedlots an EAW is what is required. The Commissioner of the MPCA will make the determination on the need for an EIS after carefully reviewing all the information in the EAW, written public comments, and the Response to Comments. Upon reviewing all the available information, the Commissioner determines if the Project has the potential for significant environmental effects following the criteria specified in Minn. R. 4410.1700 subp. 7. The Commissioner issues Findings of Fact, Conclusions of Law, and Order to support either a positive declaration on the need for an EIS, or a negative declaration on the need for an EIS.

Comment Group	Comment	Response
27	Commenters request the MPCA do a more thorough environmental review due to the massive size/scope of the Project.	MPCA is following the process detailed in Minn. R. 4410, which MPCA is legally obligated to do.
28	Commenters state there must be a requirement for a socioeconomic review of the Project.	The comment is out of scope for the EAW as it does not substantially inform the decision on the need for an EIS per the evaluation criteria in Minn. R. 4410.1700 subp. 7.
29	Commenters state the MPCA must conduct a full, thorough, industrial scale review of the Project.	MPCA is following the process detailed in the existing Minn. R. 4410, which MPCA is legally obligated to do.
30	Commenters argue there should be an analysis of alternatives in the EAW.	An EAW evaluates "the potential for significant environmental effect" on the Project as proposed. If the MPCA determines there is no potential for significant environmental effects from the Project, then there is no need for an alternatives analysis. If the MPCA determines that there is potential for significant environmental effects from the project, an Environmental Impact Statement (EIS) would then be ordered, and an analysis of alternatives would be included in the EIS.
31	Commenters argue that if Riverview has nothing to hide, they should just do the EIS and prove it.	The comment is out of scope for the EAW as it does not substantially inform the decision on the need for an EIS per the evaluation criteria in Minn. R. 4410.1700 subp. 7.
32	Comments are related to the existing environmental review process currently being followed by MPCA to review the Project.	The comment is out of scope for the EAW as it does not substantially inform the decision on the need for an EIS per the evaluation criteria in Minn. R. 4410.1700 subp. 7.
33	Commenters request the MPCA deny the project.	Environmental review is not intended to be an approval or denial for a project. Rather the intent of environmental review is to gather information related to the environmental impacts of the project and determine whether those impacts are significant.
34	Commenters state it is irresponsible of the MPCA to advance permits without a full understanding of groundwater and water-quality risks.	No governmental unit, including the Minnesota Pollution Control Agency (MPCA) and Minnesota Department of Natural Resources (DNR), may issue permits approving the Project until the environmental review process is completed in accordance with Minn. R. 4410.3100, subp. 1. Groundwater: The EAW found that no karst features, exposed bedrock, limited unconsolidated soils, soils developed in bedrock, or sand and sand plain soils are present at the existing facility, manure storage, or manure application sites that would represent elevated groundwater vulnerability. The EAW identifies potential groundwater contamination pathways including seepage from liquid manure storage areas (LMSAs), nutrient leaching from manure application fields, and stormwater contacting

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		manure or feed storage areas before reaching groundwater or surface water. The EAW concludes these potential impacts can be mitigated through existing regulatory requirements and permit conditions, including NPDES permit requirements, the Nutrient Management Plan, concrete and clay-lined manure storage structures, increased clay liner thickness from two to five feet, perimeter drain tile systems surrounding LMSAs, compliance with Minnesota Rule 7020, and manure application restrictions. The Project also identifies more than 3,000 additional acres as contingency acreage for manure application. Water Quality: The EAW identifies several potential pathways for impacts to surface water quality, including nutrient runoff from manure application to fields as well as stormwater runoff from feed and manure storage areas and during construction. The EAW notes heavy rainfall events may increase runoff. To address the risk to surface water quality identified in the EAW, the Proposer is subject to conditions found in the Individual NPDES Feedlot Permit and nutrient management plan requirements, setbacks and buffers from protected waters, nutrient management planning based on agronomic rates, manure injection or incorporation practices, stormwater management infrastructure, covered or engineered manure storage facilities, and a prohibition on direct discharges to waters of the state. Cumulative Effects: The EAW states that cumulative potential effects for feedlot projects are generally associated with overlapping manure application and excessive groundwater withdrawals within the same Environmentally Relevant Area (ERA). The EAW concludes that cumulative impacts to groundwater and surface water can be addressed through compliance with the Individual NPDES Feedlot Permit, DNR water appropriation permit conditions, nutrient management requirements, setbacks, stormwater management practices, engineering controls, and the prohibition on direct discharges from the facility.
35	Commenter requests MPCA to review this permit with extreme caution, it seems these big dairies only wreck our environment.	The comment is out of scope for the EAW as it does not substantially inform the decision on the need for an EIS per the evaluation criteria in Minn. R. 4410.1700 subp. 7.
36	Commenter requests that the MPCA hold a public meeting regarding the Project.	MPCA held a public meeting for the Project on April 28, 2026, in Morris, MN.
37	Commenter states the MPCA rules do not align with BMP's for synthetic fertilizer and fertilizer/manure application.	The comment is out of scope for the Feedlot permit.

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38	Commenters are inquiring if MPCA has authority to hold permits until Environmental Review is complete.	Minn. S. 116D.04 subp. 6 and Minn. R. 4410.3100 prohibit final decisions on permits and approvals for projects subject to environmental review, until the review is complete.
39	Commenters asserted the proposed Project is being reviewed and permitted under feedlot rules and permit requirements that the EPA has already determined are inadequate to protect water quality. They argued that EPA directed the MPCA to revise its feedlot regulatory program and permits, but those improvements have not yet been implemented. As a result, the Project would proceed under an outdated regulatory framework before the strengthened rules and permit requirements are in place.	Revision of Minnesota Rules Chapter 7020 is at the beginning stages of the rulemaking process and is expected to extend multiple years into the future. The current 7020 rules are still in effect until the rulemaking process is complete. This facility is being permitted as an individual NPDES feedlot permit. As such this facility would be subject to all 7020 general conditions in addition to requirements that are more stringent than the general permit. These include additional requirements for Liquid Manure Storage areas, permanent manure stockpiles, stormwater runoff, feed storage, land application of manure, and Operation/Maintenance (OM) standards.
40	Commenter states, "Enforcing the Air Emission Plan requirement would also align with the Minnesota Environmental Rights Act (MERA). MERA, one of Minnesota's bedrock environmental laws, was passed in 1971 "to create and maintain within the state conditions under which human beings and nature can exist in productive harmony in order that present and future generations may enjoy clean air and water, productive land, and other natural resources with which this state has been endowed." MERA allows Minnesota residents to bring civil actions "against any person, for the protection of the air, water, land, or other natural resources located within the state, whether publicly or privately owned, from pollution, impairment, or destruction." Minnesota	This comment is out of scope of this Environmental Review as it focuses on the Minnesota Environmental Rights Act. As part of the Proposers permit application, the applicant affirmed that they will employ the Air Emissions Plan as described in Minn. Rule 7020.0505 supb4.B (1) and in the application.

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	residents may also challenge “any environmental quality standard, limitation, rule, order, license, stipulation agreement, or permit [as] inadequate to protect the air, water, land, or other natural resources located within the state from pollution, impairment, or destruction.”	
41	Commenters state Riverview packed the house with employees at the public meeting held by the MPCA on April 28, 2026, in Morris.	The comment is out of scope for the EAW as it does not substantially inform the decision on the need for an EIS per the evaluation criteria in Minn. R. 4410.1700 subp. 7.
42	Commenter requests ongoing monitoring be required for the project.	The comment is out of scope for the EAW as it does not substantially inform the decision on the need for an EIS per the evaluation criteria in Minn. R. 4410.1700 subp. 7.
43	Commenter thanks the MPCA for the EIS! They are trying to get more of them in Wisconsin as well as strong ordinances.	The comment is out of scope for the EAW as it does not substantially inform the decision on the need for an EIS per the evaluation criteria in Minn. R. 4410.1700 subp. 7.
44	Commenter states that Riverview is exercising an overreach of power and needs to be investigated.	The comment is out of scope for the EAW as it does not substantially inform the decision on the need for an EIS per the evaluation criteria in Minn. R. 4410.1700 subp. 7.
45	Commenter states, "Administrative rules include any “agency statement of general applicability and future effect” adopted to implement or make specific the law the agency administers. If a state agency wishes to create an administrative rule, it must engage in a rulemaking process that includes notice published in the State Register, a statement of need and reasonableness, opportunity for written and oral public comment, and frequently independent review by an administrative law judge. State agencies are prohibited from enforcing a “policy, guideline, bulletin, criterion, manual, standard, or similar	The comment is out of scope for the EAW as it does not substantially inform the decision on the need for an EIS per the evaluation criteria in Minn. R. 4410.1700 subp. 7.

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	pronouncement" as though it were a duly adopted rule. To separate lawful guidance documents from unpromulgated rules, Minnesota courts examine whether agency documents offer an "interpretation of a rule [that] corresponds with its plain meaning."	
46	Commenter notes, all the previous operations previously determined to need an EIS were significantly smaller than West River's proposed operation.	The comment is out of scope for the EAW as it does not substantially inform the decision on the need for an EIS per the evaluation criteria in Minn. R. 4410.1700 subp. 7.
47	Commenters request that sustainable practices such as no-till, and cover crops be required.	The comment is out of scope for the EAW as it does not substantially inform the decision on the need for an EIS per the evaluation criteria in Minn. R. 4410.1700 subp. 7.
48	Commenters note there is an expectation and responsibility of the MPCA to protect Minnesota's people and environment.	The comment is out of scope for the EAW as it does not substantially inform the decision on the need for an EIS per the evaluation criteria in Minn. R. 4410.1700 subp. 7.
49	Commenter requests the EPA do an in-depth examination before MPCA decides on whether to issue a permit.	The comment is out of scope for the EAW as it does not substantially inform the decision on the need for an EIS per the evaluation criteria in Minn. R. 4410.1700 subp. 7.
50	Commenter states the EAW is merely assurance by the proposer that all is well.	While much of the information in the EAW is obtained from the Proposer, the content and accuracy of the EAW is the responsibility of the Responsible Governmental Unit (RGU) per Minn. R. 4410.1400 A, "The RGU shall be responsible for the completeness and accuracy of all information." For the West River Dairy EAW, the MPCA is the RGU as designated by Minn. R. 4410.4300 Subp. 29. Minn. R. 4410.1000 Subp.1 states "The EAW serves primarily to: A. aid in the determination of whether an EIS is needed for a proposed project; and B. serve as a basis to begin the scoping process for an EIS."
51	Commenter suggests the MPCA is not giving the Project legitimate approval, betraying the trust of the public and weakening Minnesota.	The comment is out of scope for the EAW as it does not substantially inform the decision on the need for an EIS per the evaluation criteria in Minn. R. 4410.1700 subp. 7.
52	Commenter alleges the Minnesota River Basin is currently overrun with manure from CAFO's and that the MPCA continues to permit them.	The comment is out of scope for the EAW as it does not substantially inform the decision on the need for an EIS per the evaluation criteria in Minn. R. 4410.1700 subp. 7.

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53	Commenter states if the MPCA fails to do a thorough study, it will expose a history of mismanaged environmental review by the MPCA.	The comment is out of scope for the EAW as it does not substantially inform the decision on the need for an EIS per the evaluation criteria in Minn. R. 4410.1700 subp. 7.
54	Commenter states, "The thousands of documented pleas the MPCA has received from Minnesota residents to honor entitled protections under MEPA may finally command the attention they have always deserved."	The comment is out of scope for the EAW as it does not substantially inform the decision on the need for an EIS per the evaluation criteria in Minn. R. 4410.1700 subp. 7.
55	Commenter states, "MPCA must enforce policy that protects our planet and people. "Only when the last tree has been cut down, the last fish caught, and the last stream poisoned, will you realize you cannot eat money."	The comment is out of scope for the EAW as it does not substantially inform the decision on the need for an EIS per the evaluation criteria in Minn. R. 4410.1700 subp. 7.
56	Commenter requests the MPCA look into the opposition that Riverview has received in other states.	The comment is out of scope for the EAW as it does not substantially inform the decision on the need for an EIS per the evaluation criteria in Minn. R. 4410.1700 subp. 7.
57	Commenter states, "I can't believe that the policy of the state of Minnesota is going to permit the largest feedlot expansion in a single geographic area without more fully exploring the already existing environmental condition of the area."	The comment is out of scope for the EAW as it does not substantially inform the decision on the need for an EIS per the evaluation criteria in Minn. R. 4410.1700 subp. 7.
58	Commenter states, "Not requiring one [an EIS] makes a mockery of all that has been done previously to protect our land and water resources from degradation."	The comment is out of scope for the EAW as it does not substantially inform the decision on the need for an EIS per the evaluation criteria in Minn. R. 4410.1700 subp. 7.
59	Commenter states Riverview should be ethically reviewed for their proposed actions.	The comment is out of scope for the EAW as it does not substantially inform the decision on the need for an EIS per the evaluation criteria in Minn. R. 4410.1700 subp. 7.

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60	Commenter states that Minnesota has been spotty enforcing existing environmental laws.	The comment is out of scope for the EAW as it does not substantially inform the decision on the need for an EIS per the evaluation criteria in Minn. R. 4410.1700 subp. 7.
61	Commenter wants to know what will be done to ensure that Riverview will follow the requirements of their permit.	The comment is out of scope for the EAW as it does not substantially inform the decision on the need for an EIS per the evaluation criteria in Minn. R. 4410.1700 subp. 7. The MPCA is the regulatory governmental unit for NPDES general permitted facilities. NPDES general permitted facilities are inspected on a regular basis by MPCA feedlot staff based on resources available. Typically, NPDES general permitted facilities are inspected once every five years, more frequently if appropriate based on inspection results, activities taking place at the feedlot site (i.e. construction), or complaints received. NPDES general permitted feedlot facilities are also required to submit annual reports to the MPCA regarding their feedlot operations and manure applications. These annual reports also serve as means of monitoring NPDES general permitted facilities.
62	Commenter requests Minnesota require Riverview to ship their manure to other states.	The comment is out of scope for the EAW as it does not substantially inform the decision on the need for an EIS per the evaluation criteria in Minn. R. 4410.1700 subp. 7.
63	Commenter claims MPCA cannot issue the Individual NPDES Permit to West River Dairy because it fails to address GHG Emissions.	Currently, there are no federal or Minnesota thresholds of greenhouse Gas significance for determining the impacts of Greenhouse Gas emissions from an individual project on global climate change. There are also no Minnesota or National Ambient Air Quality Standards (NAAQS) for Greenhouse Gas emissions. The Project Proposers application materials and information provided in the EAW included measures that the Project Proposer implements to reduce GHG emissions from the site. MPCA staff reviewed the Project application materials and found them to meet Minn. R. Ch. 7020 requirements and NPDES Permit requirements.
64	Commenter claims, "Exempting Riverview From Addressing GHG Emissions Based On MPCA's Air Emissions Plan Template Would Reflect Unlawful And Unpromulgated Rulemaking."	The comment is out of scope for the Feedlot permit.
65	Commenter notes, nationally permitting and inspection rates of CAFOs are inconsistent and declining.	The comment is out of scope for the EAW as it does not substantially inform the decision on the need for an EIS per the evaluation criteria in Minn. R. 4410.1700 subp. 7. The MPCA is the regulatory governmental unit for NPDES general permitted facilities. NPDES general permitted facilities are inspected on a regular basis by MPCA feedlot staff based on resources

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		available. Typically, NPDES general permitted facilities are inspected once every five years, more frequently if appropriate based on inspection results, activities taking place at the feedlot site (i.e. construction), or complaints received. NPDES general permitted feedlot facilities are also required to submit annual reports to the MPCA regarding their feedlot operations and manure applications. These annual reports also serve as means of monitoring NPDES general permitted facilities.
66	Commenter states, "State preemption laws in many jurisdictions block local governments from imposing stricter standards than the state minimum, creating what researchers call "regulatory vacuums" that leave communities with no meaningful recourse. [Moran, 2022]"	The comment is out of scope for the EAW as it does not substantially inform the decision on the need for an EIS per the evaluation criteria in Minn. R. 4410.1700 subp. 7. This comment is out of scope for the Feedlot Permit.
67	Commenter states, "Minnesota has never permitted a facility of this scale. It has no track record with a livestock operation of 26,397 animal units, no established monitoring infrastructure calibrated to impacts of this magnitude, no regulatory precedent for enforcing against a facility that dwarfs anything that has come before. The Environmental Impact Study is not just about understanding the facility's environmental impacts it is about determining whether Minnesota's regulatory framework is even equipped to manage them, and what additional protections would be required before a permit could be responsibly granted."	The MPCA is the regulatory governmental unit for NPDES general permitted facilities. NPDES general permitted facilities are inspected on a regular basis by MPCA feedlot staff based on resources available. Typically, NPDES general permitted facilities are inspected once every five years, more frequently if appropriate based on inspection results, activities taking place at the feedlot site (i.e. construction), or complaints received. NPDES general permitted feedlot facilities are also required to submit annual reports to the MPCA regarding their feedlot operations and manure applications. These annual reports also serve as means of monitoring NPDES general permitted facilities.
68	Commenter requests the MPCA, "Ensure that manure management plans account for extreme weather events and long-term soil nutrient loading."	Several practices are required by the Feedlot Permit to prevent nutrient runoff that include application at agronomic rates to not exceed expected crop nitrogen needs, testing for soil phosphorus, application timing, planting cover crops, and setbacks from waterways. The Proposer will comply with manure application requirements set forth by the Feedlot Permit that are intended to protect waters of the state. The Nutrient Management Plan addresses the timing of manure application and sets forth requirements and best management practices for application, including not incorporating manure within 24 hours of any 1/2 inch or greater rainfall event.

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69	Commenter requests the MPCA, "Provide meaningful opportunities for public participation and community input before any final approval."	MPCA held a public comment period from February 10 - May 7, 2026. In addition, a public meeting was held on April 28, 2026, in Morris.
70	Commenter appreciates and respects the process of getting these permits.	Comment noted.
71	Commenter notes, " If a project would house 1,000 or more animal units, a feedlot applicant may apply for an independent SDS permit, or it may apply for a federal NPDES permit that incorporates Minnesota's SDS permit requirements." and "the proposed rule requires owners having 1,000 animal units or more to develop and implement an Air Emission Plan (part 7020.0505, subp. 4, item B, subitem 1.)"	Comment noted. It should also be noted that neither NPDES Permits nor SDS Permits contain restrictions/thresholds relating to the maximum number of animal units that a feedlot facility can be permitted for.
72	Comments concerned about animal disease because of the Project.	The comment is out of scope for the EAW as it does not substantially inform the decision on the need for an EIS per the evaluation criteria in Minn. R. 4410.1700 subp. 7.
73	Commenters expressed concern about health of the animals.	The comment is out of scope for the EAW as it does not substantially inform the decision on the need for an EIS per the evaluation criteria in Minn. R. 4410.1700 subp. 7.
74	Commenters expressed concern about animal welfare related to the Project.	The comment is out of scope for the EAW as it does not substantially inform the decision on the need for an EIS per the evaluation criteria in Minn. R. 4410.1700 subp. 7.
75	Commenters are concerned about blue-green algae (cyanobacteria) blooms in the summer months.	Blue-green algae blooms can be toxic. The blooms are associated with excess nutrients, typically phosphorus, in the affected water body. The excess nutrients are generally attributed to agriculture runoff from cropland; however, this is not the only source. The Project will have an MPCA approved nutrient management plan that addresses phosphorus application rates in certain circumstances where there is elevated risk of phosphorous moving off the landscape into the water.
76	Commenters are concerned about the impact to wildlife and wildlife habitat by the Project.	No existing wildlife habitat will be converted to cropland and only cropland will be converted for the expansion building site by the Project. The main impact to wildlife is impacts to the wildlife habitat. Wildlife habitat can be impacted runoff of agricultural land. The building site must collect and control all stormwater runoff from the site. Additionally, the Project has an MPCA approved nutrient management plan that includes restrictions intended to limit the impact of runoff from cropland receiving manure from impacting existing wildlife habitat.

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77	Commenters are concerned about how mortalities at the Project will be handled.	The Project is required to have an approved mortality management plan as part of the Feedlot Permit. The mortality management plan must be in compliance with applicable MPCA and Board of Animal Health regulations.
78	Commenters are concerned about how disposal of carcasses if there is a mass mortality event.	The Proposer is required to follow applicable MPCA and Board of Animal Health regulations when handling carcasses from a mass mortality event. Proposer is required to notify the Minnesota Duty Officer if such an event were to happen. The Minnesota Duty Officer will in turn notify all appropriate agencies to respond, including the MPCA and Board of Animal Health.
79	Commenter is concerned about oversight of the non-milk producing calves.	The comment is out of scope for the EAW as it does not substantially inform the decision on the need for an EIS per the evaluation criteria in Minn. R. 4410.1700 subp. 7. The Comment is also beyond the scope of applicable feedlot regulations (U.S.C. 1251, 40 CFR pts. 52, 122, 123, 127, 412, Minn. Stat. Ch. 115 and 116, Minn. R. Ch. 7001, 7009, 7020, 7053, 7060, and 7090), and Individual NPDES Feedlot Permit requirements the Project is required to meet. The Proposer does not raise calves at the project location.
80	Commenters are concerned about the cumulative impact on air quality from the Project.	Air modeling was completed for the Project which included all feedlots within a 3-mile by 3-mile modeling domain. All feedlots greater than 50 animal units within the modeling domain are included in the modeling exercise. Additionally, background values are included in the modeling exercise. Background values are calculated from monitoring data collected in Minnesota. All residences within the modeling domain are modeled as discrete receptors and predicted modeling results at each discrete receptor are included in the Air Quality Modeling Report. Air modeling for feedlots includes hydrogen sulfide, ammonia, and odor.
81	Commenters are concerned about the Project's impact on air quality.	Air modeling was completed for the Project which included all feedlots within a 3-mile by 3-mile modeling domain. All feedlots greater than 50 animal units within the modeling domain are included in the modeling exercise. Additionally, background values are included in the modeling exercise. Background values are calculated from monitoring data collected in Minnesota. Air modeling for feedlots includes hydrogen sulfide, ammonia, and odor. The maximum predicted property hydrogen sulfide concentration is 29.44 parts per billion which is below the ambient standards. The maximum property line ammonia concentration is 2,009 µg/m3 which is below the acute inhalation Health Risk Value (iHRV). Total calculated greenhouse gas emissions from the Project are 72,210 tons/year.
82	Commenter is concerned about how the Project will keep the air clean and fresh for the neighbors.	The Proposer is subject to all permit requirements, including Minnesota Individual Feedlot Permit (attachment 22) which requires an Air Emission Plan that includes methods to mitigate odors and a Manure Management Plan (attachment 23).

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83	Commenters are concerned about the impacts of odor generated the Project.	The maximum hourly odor concentrations along the Facility's property lines were below the "moderate" odor threshold of 244 OU, except for one hourly exceedance along the near-south property line. The maximum odor concentration for the near south property line was 260 OU. The calculated hourly odor concentration at any property-line receptor was less than or equal to the "faint" odor threshold of 83 OU at least 99.67 percent of the time.
84	Commenters are concerned about the health effects from the methane emissions from the Project.	The comment is out of scope for the EAW as it does not substantially inform the decision on the need for an EIS per the evaluation criteria in Minn. R. 4410.1700 subp. 7.
85	Commenters are concerned about the health effects from the hydrogen sulfide emissions from the Project.	The Project was modeled for hydrogen sulfide emissions. Modeling was used to evaluate the emissions related to the Minnesota Department of Health's (MDH) - inhalation Health Risk Values (iHRV). The modeled predictions at nearest neighboring residences did not exceed the sub-chronic iHRV.
86	Commenters are concerned about the health effects from the ammonia emissions from the Project.	The Project was modeled for ammonia emissions. Modeling was used to evaluate emissions related to the MDHs - iHRVs. The modeled predictions at the property line and nearest residences did not exceed the Acute iHRV. The modeled predictions at the nearest neighbors did not exceed the Chronic iHRV.
87	Commenters are concerned about the health effects from the particulate matter emissions from the Project.	While dairies do produce particulate matter emissions, they are not considered to be a problem at sites with total confinement barns as is proposed by the Project. Past modeling for particulate emissions at feedlots did not show violations of the particulate matter standards.
88	Commenters are concerned about the health effects from the air emissions from the Project.	The Project was modeled for the two primary hazardous air pollutant emissions from feedlots, hydrogen sulfide and ammonia. Modeling results were compared against the iHRVs. Modeled results did not exceed the iHRVs.
89	Commenter notes that the Air Emissions Plan does not commit the company to employing any of the identified odor mitigation measures.	The Proposer is subject to all requirements within the Air Emission Plan.
90	Commenter refers to the methods for controlling hydrogen sulfide emissions in the Air Emission Plan.	Hydrogen sulfide emissions from feedlots have been identified an issue of concern. MPCA has done enforcement on several feedlots in the past for violating Minnesota's Ambient Air Quality Standard for hydrogen sulfide. Common to all those cases was the existence of an uncovered manure storage basin or pit. Putting an impermeable cover on the basins or pits has shown to be the most effective method of controlling hydrogen sulfide emissions. The Proposer has impermeable covers on most of its manure storage basins and straw covers on the remaining basins. The straw covers are typically on smaller settling basins prior to the liquid portion going into the larger covered basins.

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91	Commenter notes, "The Air Emission Plan does not incorporate, attach, or reference the GHG mitigation measures identified in this project's EAW. As a result, neither Riverview's permit application, nor the resulting draft permit, contains any discussion of "methods and practices that will be used to minimize air emissions" associated with the facility's projected 72,210 tons of annual CO_2e emissions."	The focus of air emissions from feedlots are on H2S and odor, with ammonia also included in the air modeling that was conducted for this EAW. MPCA staff reviewed the Project application materials and found them to meet Minn. R. ch. 7020 requirements and NPDES Permit requirements. The Proposer will implement measures to minimize methane production produced by enteric fermentation through dietary manipulation. Additionally, separating the manure solids from the liquid portion of the manure will reduce methane produced from anaerobic digestion occurring in the liquid manure storage basins. There are no state or federal thresholds for greenhouse gases. Additionally, through the EAW process the MPCA found the Project, as proposed, does not have the potential for significant environmental effects based on the type, extent, and reversibility of impacts related to emissions of Greenhouse Gas emissions, which are reasonably expected to occur.
92	Commenter states, "If MPCA's template form is used to demonstrate compliance with Minnesota Rule 7020.0505, subp. 4(B)(1), the agency would be enforcing an unpromulgated rule. First, the form contradicts the Feedlot Rules' plain meaning by wrongly restricting the Rules' scope. Subpart 4 of Minnesota Rule 7020.0505 requires an Air Emission Plan that addresses "emissions resulting from animal feedlot or manure storage area operations." Those emissions include GHGs. By interpreting the rule to omit GHG emissions, contrary to the rule's plain text, MPCA's form falls outside the bounds of lawful interpretation."	There are no federal or Minnesota thresholds of greenhouse gas significance for enforcing greenhouse gas emissions from an individual project on global climate change.
93	Commenter states, "Absent complaints or exceedances, the template form does not require feedlot applicants to commit to any air emission reduction strategies. This approach is inconsistent with the Feedlot Rules' directive to describe emission reduction measures that 'will be used'."	Currently, there are no federal or Minnesota thresholds of greenhouse gas significance for determining the impacts of greenhouse gas emissions from an individual project on global climate change. There are also no Minnesota or National Ambient Air Quality Standards (NAAQS) for greenhouse gas emissions. The Project Proposers application materials and information provided in the EAW included measures that the Project Proposer implements to reduce GHG emissions from the site. MPCA staff reviewed the Project application materials and found them to meet Minn. R. Ch. 7020 requirements and NPDES Permit requirements. Additionally, through the EAW process the MPCA found the Project, as proposed, does not have the potential for significant environmental

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		effects based on the type, extent, and reversibility of impacts related to emissions of greenhouse gas emissions, which are reasonably expected to occur.
94	Commenter wants to know, "Where does all that methane end up?"	Methane emissions are released into the atmosphere. Calculated methane emissions as a result of enteric fermentation and barn and manure storage from the 11,000 animals is 2,397 tons/year. Emissions from stockpiled manure, such as methane can be released into the atmosphere. Manure processed through the anaerobic digester produces renewable natural gas.
95	Commenter states that, "questionable track record of West River Dairy in other states, the environmental & social impacts of the air pollution must be considered."	The comment is out of scope for the EAW as it does not substantially inform the decision on the need for an EIS per the evaluation criteria in Minn. R. 4410.1700 subp. 7.
96	Commenter asks how far the wind will carry the feed dust generated at the facility?	Dry feedstuffs for the cattle will be stored inside a commodity shed, reducing dust from fine particles. Feedstuffs that are stored outside are forages, which are high in moisture content and are unlikely to create dust. Additionally, covers placed over the forage piles help prevent dust. Most feed-mixing will occur inside a building.
97	Commenter is concerned about dust from township and county roads.	The item 17.C in the EAW addresses dust control within the proposed project area, and mitigation strategies and control measures. Dust emissions will be monitored to ensure they do not exceed 20% opacity and are not visible beyond the property lines. The Project will pave traffic area on the Project site with asphalt or concrete. Non-traffic areas will be planted with grass to control dust and erosion. Dry feedstuffs for the cattle will be stored inside a commodity shed, reducing dust while most feed-mixing will occur inside.
98	Commenters are concerned that the EAW does not evaluate the cumulative GHG Emissions.	Climate change because of greenhouse gas emissions is a well-documented existing cumulative impact occurring on a global scale. Due to the global nature of climate change, it is impossible to establish a reasonable Environmentally Relevant Area from which to calculate cumulative GHG emissions. The design of the Project takes into consideration increased precipitation in the design of its stormwater controls and manure storage structure. The Proposer will implement measures to minimize methane production produced by enteric fermentation through dietary manipulation. Additionally, separating the manure solids from the liquid portion of the manure will reduce methane produced from anaerobic digestion occurring in the liquid manure storage basins. There are no state or federal thresholds for greenhouse gases.
99	Commenters state that the GHG calculation should also include the existing cows at the site.	The existing cows have been at the existing facility for more than three years and therefore are exempt from environmental review (Minn. R. 4410.4300, Subp. 1). GHG calculations for the existing facility are in Appendix C – EAW Errata.
100	Comments are related to increasing extreme weather events.	Several practices are required by the Feedlot Permit to prevent runoff, including manure application requirements and restrictions based on application timing and predicated rainfall events and

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		sensitive features in or near where manure application is planned. Additionally, the design for the proposed LMSA at the site includes additional freeboard capacity should an extreme rain event occur.
101	Commenter states that a marginal change in emission rates will translate into a substantial increase in emissions over time.	The comment is out of scope for the EAW as it does not substantially inform the decision on the need for an EIS per the evaluation criteria in Minn. R. 4410.1700 subp. 7.
102	Commenter states, "The MPCA must ensure that nutrient management plans are not only technically sufficient on paper but enforceable and resilient in practice and that they align with the state's climate goals, specifically: initiative 2.3.2, manage fertilizer and manure to reduce emissions; and 2.4.1 manage agricultural landscapes to minimize nitrogen runoff and pollution. The proposed mitigations for manure management, which include applying manure fertilizer on fields that are in operation and considering rates of application, still introduce increased manure and therefore N_2O into the soil, water, and atmosphere."	Several practices are required by the Feedlot Permit to prevent nutrient runoff that include application at agronomic rates to not exceed expected crop nitrogen needs, testing for soil phosphorus, application timing, planting cover crops, and setbacks from waterways. The Proposer will comply with manure application requirements set forth by the Feedlot Permit that are intended to protect waters of the state.
103	Commenters note that the project will increase GHG Emissions and thereby contribute to climate change.	Using the latest emissions and approved GHG calculator it is estimated that the Project will contribute 72,210 tons per year of CO_2e.
104	Commenters contend that the GHG calculations are likely underestimated or uncertain.	MPCA's calculator provides a reasonable, standardized representation of the project's likely emissions related to enteric fermentation and manure management. Since its development, the MPCA Feedlot tool has been the standard tool for feedlots when calculating GHG emissions.
105	Commenter notes that, "Riverview's EAW acknowledges that ongoing climate change is expected to increase average annual temperatures."	Comment noted.
106	Commenter states, "We need to fight climate change in all ways, including in our food production systems."	The comment is out of scope for the EAW as it does not substantially inform the decision on the need for an EIS per the evaluation criteria in Minn. R. 4410.1700 subp. 7.

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107	Commenter states, "You are correct, our climate is counting on us."	The comment is out of scope for the EAW as it does not substantially inform the decision on the need for an EIS per the evaluation criteria in Minn. R. 4410.1700 subp. 7.
108	Commenter states, "Another problem with the EAW is that it relies only on a 100-year global warming potential (GWP100) value. Even though under GWP100, methane is converted to CO_2e emissions using a factor of 28 (meaning 1 ton of methane is treated as having the same warming impact as 28 tons of CO_2 over a 100-year period), this approach can still obscure the near-term climate impacts of the Expansion Project's emissions. Given that methane is a short-lived but highly potent GHG, the analysis should also present emissions using a 20-year global warming potential (GWP20), which better reflects the Expansion Project's 30-year operational lifetime and the acute warming effects of methane during that period. "	GWP 100 is the standard value used in nearly every regulatory and reporting framework, including EPA's GHG inventories. MPCA accepts the use of GWP 100 values.
109	Commenter contends the EAW omits scope 3 emissions from the GHG calculations and is ignoring at least half of the Project's true GHG emissions.	The GHG emissions included in the EAW have been properly scoped. The downstream emissions are classified as scope 1 because the land where alfalfa and manure are applied are under the control of Riverview Dairy.
110	Commenter states, "the EAW does not quantify the total annual GHG emissions generated from feed production but does quantify a specific reduction (or carbon sink credit) related to growing feed".	The EAW cannot assume feed production would not occur even without the expansion project.
111	Commenter states, "the upstream reduction from avoided synthetic fertilizer manufacturing (-9,038 tons) and the carbon sink credit for converting land to alfalfa feed (-2,662 tons) are both included in the	Land utilized for manure application and alfalfa growth are under the operation of the Proposer and thus properly identified as scope 1.

Comment Group	Comment	Response
	total as scope 1 adjustments. Such misleading and erroneous calculation methods result in significant asymmetry."	
112	Commenter notes, "Fully assessing the GHG emissions of the Expansion Project is especially important because the agriculture sector is the second largest source of GHG emissions in Minnesota, responsible for approximately 25% of the State's net emissions. "	The comment is out of scope for the EAW as it does not substantially inform the decision on the need for an EIS per the evaluation criteria in Minn. R. 4410.1700 subp. 7.
113	Commenter contends the EAW should include a full lifecycle GHG emissions analysis.	The calculation methodologies used to determine the GHG emissions are based on vetted tools, emission factors, and methodologies. The purpose of EAW item 18 is not to conduct a lifecycle analysis, but to quantify the emissions that the Project proposer has control over. Only emissions that are directly under the proposers' control are included.
114	Commenter argues the mitigation strategies in the EAW are inadequate.	The quantification of two strategies in EAW item 18.B.2 plus the additional unquantified options satisfies the EAW prompt.
115	Commenter argues that a number of alternatives to those proposed were not considered as mitigation strategies to GHG emissions.	The comment is out of scope for the EAW as it does not substantially inform the decision on the need for an EIS per the evaluation criteria in Minn. R. 4410.1700 subp. 7.
116	Commenter questions the use of cropland conversion to alfalfa as a mitigation strategy and its inclusion as Scope 1.	MPCA's calculator provides a reasonable, standardized representation of the Project's likely emissions related to enteric fermentation and manure management. Since its development, the MPCA Feedlot tool has been the standard tool for feedlots when calculating GHG emissions. Land utilized for manure applications and alfalfa growth are under the operation of the Proposer and thus are properly identified as scope 1.
117	Comment questions the methodologies used to determine GHG reductions based on ammonia replacement by manure.	The calculation methodologies used to determine the GHG emissions are based on vetted tools, emission factors, and methodologies.
118	Commenter notes, "The EAW fails to provide any research on potential emissions reductions from the crossbred Holstein-Jersey cows that will be used in the Expansion Project."	The quantification of two strategies in EAW item 18.B.2 plus the additional unquantified options satisfies the requirements of the EAW.

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119	Comment states that even though manure can replace the use of synthetic fertilizer, it also increases the risk of nitrous oxide emissions from soils under specific conditions.	Manure application rates shall be controlled so the estimated nitrogen available to crops from all nitrogen sources (including commercial fertilizer) does not exceed expected annual crop nitrogen needs for non-legumes and expected nitrogen removal for legumes based on the most recent recommendations of the MES and the MPCA fact sheets "Manure Nitrogen Rates For Corn Production (wq-f8-18)" and "Manure Management For Corn On Irrigated Sandy Soils (wq-f8-52)". Manure application will also be restricted based on time of year, BMP use, perennial crop use, groundwater vulnerability, winter conditions, as well as other restrictions required by the NPDES permit and nutrient management plan to reduce nitrogen runoff or groundwater contamination.
120	Comments are related to Minnesota's climate goals and how the Project does not support those goals.	The quantification of two strategies in EAW item 18.B.2 plus the additional unquantified options addresses how the Project supports the Minnesota Next Generation Energy Act goals.
121	Commenter would like to know the impact to the public more than doubled truck traffic from CO_2 emissions.	Vehicle emissions will account for 1,626 tons/year of CO_2.
122	Commenter is concerned that the warmer temperatures in February and March will result in loss of all the manure nitrogen unless treated with a nitrogen stabilizer.	The Proposer shall comply with all permit requirements of land application of manure.
123	Commenters want to know if the dairy has sufficiently accounted for extreme precipitation events?	The stormwater basins are sized more than 20% larger than the minimum requirement. Each stormwater basin will have a maintenance plan as part of the Storm Water Pollution Prevent Plan (SWPPP).
124	Commenter wants to know if there was a reported manure overflow from the pit when Morris was hit with 16 inches of rain?	The comment is out of scope for the EAW as it does not substantially inform the decision on the need for an EIS per the evaluation criteria in Minn. R. 4410.1700 subp. 7.
125	Commenters are concerned about increased likelihood of overflows from the manure storage basins due to increased frequency of extreme weather events.	The design for the proposed LMSA at the site includes additional freeboard capacity should an extreme rain event occur. Additionally, the LMSAs will have a synthetic cover, which will allow West River Dairy to remove stormwater from those basins without manure contamination and preserve available liquid manure storage capacity.
126	Commenter states the emissions from additional vehicle traffic were not included in the GHG emissions.	Vehicle emissions from construction equipment (1,915 tons/year) and additional Ag equipment (1,626 tons/year) have been accounted for within the EAW in attachment 21.

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127	Commenter states that GHG emissions associated with the moving and application of manure were not included in the EAW.	Vehicle emissions from additional Ag equipment (1,626 tons/year) have been accounted for within the EAW in attachment 21. Liquid manure is pumped through pipelines.
128	Commenter notes, "The project is not proposed for a pristine, isolated island, it will be situated in an already degraded environment, part of which is caused by the existing feedlot that is being expanded. And degradation by the landscape having been converted to agriculture is evidence of past effects. If the air and water in the vicinity are not clean and the native ecosystems are not fully functioning, this project's impacts must be added to these "past and present" actions and then added to the impacts of reasonably foreseeable actions."	The comment is out of scope for the EAW as it does not substantially inform the decision on the need for an EIS per the evaluation criteria in Minn. R. 4410.1700 subp. 7.
129	Commenters are suggesting that alternatives to the Project as proposed be considered.	The comment is out of scope for the EAW as it does not substantially inform the decision on the need for an EIS per the evaluation criteria in Minn. R. 4410.1700 subp. 7.
130	Commenter is concerned about concentrating all the nutrients in mass storage in one location.	Liquid Manure Storage Areas (LMSA) and Dry Manure Storage are the locations where manure is stored on the feedlot facility site. The individual NPDES feedlot Permit and manure management plan incorporates manure storage, transfer, and land application requirements that exceed those in the NPDES General Feedlot Permit, including 5 feet of compacted clay liner of LMSAs, synthetic covers and installation of a perimeter drain-tile system will be at an elevation below the liner of each of the three LMSAs to control seasonal sub-surface saturation, and operation and monitoring and reporting requirements pertaining to freeboard of the LMSA. Manure from cattle in the free-stall barn will be collected twice daily using a self-propelled vacuum wagon. Solid manure will be stored on a concrete pad. Solid and liquid manure transferred to area farmers for use as fertilizer will be applied in accordance with Feedlot Permit requirements. The Proposer will install stormwater basins and modify the contour of the site to direct stormwater to stormwater basins.
131	Commenters are concerned about the impact of consolidating this amount of livestock in one place.	The comment is out of scope for the EAW as it does not substantially inform the decision on the need for an EIS per the evaluation criteria in Minn. R. 4410.1700 subp. 7.

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132	Commenters do not believe one person or company should have this many animals in one place.	The comment is out of scope for the EAW as it does not substantially inform the decision on the need for an EIS per the evaluation criteria in Minn. R. 4410.1700 subp. 7.
133	Commenters believe the scale of the Project is too large.	The comment is out of scope for the EAW as it does not substantially inform the decision on the need for an EIS per the evaluation criteria in Minn. R. 4410.1700 subp. 7.
134	Commenters state that the Project is twice as big as any current operations in the state, and its environmental harm would be enormous.	The comment is out of scope for the EAW as it does not substantially inform the decision on the need for an EIS per the evaluation criteria in Minn. R. 4410.1700 subp. 7.
135	Commenters are concerned about the creation of biohazards at the Project.	The cows will be housed in a cross-ventilated, total-confinement, free-stall barn with clay-lined basins with impermeable covers to collect and store manure and wastewater. Any contaminated stormwater runoff will not leave the Project site. The Proposer will use onsite earthen materials (clay) to construct manure storage facilities, stormwater basins, and water storage basins. The updated Feedlot Permit incorporates manure storage guidelines through the NPDES General Feedlot Permit, which prevents surface and groundwater pollution. Manure will be land applied at agronomic rates in accordance with Minn. R.7020 and the Feedlot Permit. For acreage converting from commercial fertilizer to manure from the Project, there will be more oversight and regulation of nutrient application than currently exists. The American Meteorological Society/ Environmental Protection Agency Regulatory Model (AERMOD) that was conducted for this Project found that it will not create exceedances of the Minnesota Ambient Air Quality Standard or Sub-chronic Inhalation Health Risk Value (iHRV) for Hydrogen Sulfide (H_2S). AERMOD also predicted that the Project would not create exceedances of the Acute or Chronic iHRV for Ammonia (NH_3). The air modeling was conducted and the permit applied for to ensure that human health and the environment are protected from the activities of the Project.
136	Commenters are concerned the EAW did not consider the cumulative impacts of other feedlots in the area, watershed, geographic area.	The EAW did consider the cumulative impacts of other feedlots in the area where it was reasonable to do so at a scale that is appropriate.
137	Commenters are suggesting how the MPCA should do its job in relation to the decision on the need for an EIS for the Project.	The Commissioner of the MPCA will make the determination on the need for an EIS after carefully reviewing all the information in the EAW, written public comments, and the Response to Comments. Upon reviewing all the available information, the Commissioner determines if the Project has the potential for significant environmental effects following the criteria specified in Minn. R. 4410.1700 subp. 7. The Commissioner issues Findings of Fact, Conclusions of Law, and Order to support either a positive declaration on the need for an EIS, or a negative declaration on the need for an EIS.

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138	Commenter suggests, "Landscaping with trees, shrubs, pollinator friendly plants near constructed ponds could provide aesthetic mitigation for the adverse effects of the enormous built infrastructure proposed in this project while providing a modicum of natural habitat for birds, insects and many other forms of important wildlife. As described above, this entire region has had its wildlife populations of all kinds, decimated by loss of these types of habitats."	MPCA will forward suggestions on to Proposer.
139	Commenter stated, "The most meaningful objections concerned the statement made by former MPCA staff that the existing regulations are not strict enough to protect the environment."	The comment is out of scope for the EAW as it does not substantially inform the decision on the need for an EIS per the evaluation criteria in Minn. R. 4410.1700 subp. 7.
140	Commenter complains about the amount of flies.	Existing activities will help to minimize pests such as flies which include covering liquid manure storage areas with impermeable synthetic covers, and other activities as laid out in the Air Emissions Plan (attachment 22). The Proposer also actively employs good-housekeeping practices, such as frequent collection of manure and prompt clean-up of any spilled feed and removal of manure, spilled water, and water will be collected with a vacuum truck in the scrape alleys which can help to minimize fly breading grounds. These practices reduce the presence of flies. Animal housing at the project will be a "cross-ventilated" barn. This style of ventilation is known for maintaining a steady breeze through the barn, which is great for animal comfort, and it also effectively reduces the presence of flies.
141	Commenter is concerned about the recent flooding.	The comment is out of scope for the EAW as it does not substantially inform the decision on the need for an EIS per the evaluation criteria in Minn. R. 4410.1700 subp. 7.
142	Commenter states the "EAW describes purposeful avoidance of potential mitigation offered by “green infrastructure” as part of intentional project design."	Thank you for the comment.
143	Commenter states, "We're headed for global famine by the end of the century if	The comment is out of scope for the EAW as it does not substantially inform the decision on the need for an EIS per the evaluation criteria in Minn. R. 4410.1700 subp. 7.

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	we keep allowing industries like this to trash our only planet."	
144	Commenter states, "I am very concerned about the harmful effects of industrial dairying by Riverview, LLP."	The comment is out of scope for the EAW as it does not substantially inform the decision on the need for an EIS per the evaluation criteria in Minn. R. 4410.1700 subp. 7.
145	Commenter states, "Being an organic home Gardner for over 50 years I know the importance of toxins!"	The comment is out of scope for the EAW as it does not substantially inform the decision on the need for an EIS per the evaluation criteria in Minn. R. 4410.1700 subp. 7.
146	Commenters note that the Project will increase pollution.	The comment is out of scope for the EAW as it does not substantially inform the decision on the need for an EIS per the evaluation criteria in Minn. R. 4410.1700 subp. 7.
147	Commenter states, "the EAW documents are filled with concerns about water allotment, catch basins, and manure proximity to bodies of water."	The EAW is a brief document prepared in worksheet format designed to rapidly assess the environmental effects which may be associated with a proposed project. The EAW serves primarily to aid in the determination of whether an EIS is needed for a proposed project; and serve as a basis to begin the scoping process for an EIS.
148	Commenters state that this "kind of farming" is bad for the environment and communities.	The comment is out of scope for the EAW as it does not substantially inform the decision on the need for an EIS per the evaluation criteria in Minn. R. 4410.1700 subp. 7.
149	Commenter states, "It's well known that leaks, and contamination will occur, it's more a matter of when not if."	The Liquid Manure Storage Area liners are permitted and regulated under the individual NPDES feedlot permit associated with this facility. A monthly examination of the monitoring port or drain tile outlet for water flow and signs of discoloration or odor in any water flowing in the drain tile. A weekly visual inspection of the LMSA and any devices channeling manure-contaminated runoff to the LMSA to assess conformance to the approved plans and the Feedlot Permit. The LMSA design requirements in rule and the Feedlot Permit, along with enhanced liner thickness (5 feet) will reduce theoretical seepage and provide greater groundwater protection.
150	Commenter states, "Can we even hold Riverview LLP accountable in any case of environment damage in the future? If we cannot guarantee the accountability, then we must not let Riverview LLP have this opportunity to abuse the environment."	The comment is out of scope for the EAW as it does not substantially inform the decision on the need for an EIS per the evaluation criteria in Minn. R. 4410.1700 subp. 7.
151	Commenter states, "Citizens have the right to determine the magnitude of how this	The comment is out of scope for the EAW as it does not substantially inform the decision on the need for an EIS per the evaluation criteria in Minn. R. 4410.1700 subp. 7.

Comment Group	Comment	Response
	new feedlot would introduce a nuisance onto the land."	
152	Commenter states, "Large numbers of live stock mean less crop diversity."	The comment is out of scope for the EAW as it does not substantially inform the decision on the need for an EIS per the evaluation criteria in Minn. R. 4410.1700 subp. 7.
153	Commenters are concerned that the large facility will result in increased nitrate contamination.	The Project is required to follow Minn. R. Ch. 7020 and Feedlot Permit requirements relating to application of nutrients (manure) generated from the Project in combination with other nutrient sources. Potential sources of N include commercial fertilizer, manure applied during the current crop year, manure applied during the previous crop year, irrigation water, and legumes grown during previous years. The Project's nutrient management plan describes how manure in combination with other nutrient sources will be applied at agronomic rates. N rates must be limited so that the estimated plant-available nitrogen (N) from all N sources does not exceed the expected crop N needs for non-legume crops or the expected N removal for legume crops. To further minimize the potential for nitrate leaching into the groundwater, the Feedlot Permit requires the Project implement N BMPs based on the timing of manure application and field location. Potential BMPs requirements include application to actively growing crops, planting cover crops, use of a nitrapyrin-based nitrogen stabilizing product, delaying application until soil temperature has reached 50 degrees or less for two consecutive days, crop rotations that include growing perennial crops 2 years during any 5-year period and reduced rate split N applications.
154	Commenter states, "the EAW does not demonstrate that the Expansion Project's manure can be applied at agronomic rates each year without increasing nitrous oxide or transport-related emissions, and runoff risk and other pollution."	Minn. R. Ch. 7020 and the Individual NPDES Permit contains specific requirements relating the application of manure. The requirements found in rule and the permit are designed to provide protection to Minnesota surface and groundwater. The MPCA staff reviewed the Project application materials and found them to meet Minn. R. Ch. 7020 requirements and NPDES Permit requirements. Please also see response to comment group 119.
155	Commenters are concerned about past violations by Riverview.	The comment is out of scope for the EAW as it does not substantially inform the decision on the need for an EIS per the evaluation criteria in Minn. R. 4410.1700 subp. 7.
156	Commenter states, "EAW does not properly characterize past, present and future environmental conditions of the environmentally relevant area."	The comment is out of scope for the EAW as it does not substantially inform the decision on the need for an EIS per the evaluation criteria in Minn. R. 4410.1700 subp. 7.
157	Commenter makes the following assertion: Translation of science to policy.	The comment is out of scope for the EAW as it does not substantially inform the decision on the need for an EIS per the evaluation criteria in Minn. R. 4410.1700 subp. 7.

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	Requirements for issuing permits for CAFOs should include increased protections for health and the environment including the following: • CAFOs should be sited and issued permits on the basis of total animal density allowed in a given watershed as determined by the carrying capacity. • Environmental impact statements should be mandated for all new CAFOs. These should include environmental health, social justice, and socioeconomic issues. • Decisions to issue permits for CAFOs should be considered in public meeting and decided at the local level. • CAFOs should be regulated using standards applied to general industry based on the level of emissions and type of waste handling. • Permits for manure storage basins should require bonding for performance and remediation. • The current state of knowledge of community impacts of CAFOs warrants support for the American Public Health Association recommendation for a moratorium on all new CAFO construction."	The Comment is also beyond the scope of applicable feedlot regulations (U.S.C. 1251, 40 CFR pts. 52, 122, 123, 127, 412, Minn. Stat. Ch. 115 and 116, Minn. R. Ch. 7001, 7009, 7020, 7053, 7060, and 7090), and Individual NPDES Feedlot Permit requirements the Project is required to meet.
158	Commenter states, "I grew up on a small dairy farm in southeastern Ottertail County. Our profits were fair and competitive."	The comment is out of scope for the EAW as it does not substantially inform the decision on the need for an EIS per the evaluation criteria in Minn. R. 4410.1700 subp. 7.
159	Commenters discuss good stewardship and sustainability of farming.	The comment is out of scope for the EAW as it does not substantially inform the decision on the need for an EIS per the evaluation criteria in Minn. R. 4410.1700 subp. 7.

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160	Commenters are concerned about future spills.	The comment is out of scope for the EAW as it does not substantially inform the decision on the need for an EIS per the evaluation criteria in Minn. R. 4410.1700 subp. 7.
161	Commenter suggests MPCA should "Bring back the sea of grass, save the soil and the pollinators."	The comment is out of scope for the EAW as it does not substantially inform the decision on the need for an EIS per the evaluation criteria in Minn. R. 4410.1700 subp. 7.
162	Commenters contend that livestock needs to be more spread out across the state into smaller dairies.	The comment is out of scope for the EAW as it does not substantially inform the decision on the need for an EIS per the evaluation criteria in Minn. R. 4410.1700 subp. 7.
163	Commenters are concerned the Project will threaten biodiversity.	The DNR conducted a search of the Natural Heritage Information System (NHIS) for the Project site and identified no ecologically significant areas or state-listed Endangered or Threatened species documented within the vicinity of the Project site. The Prairie Mimosa (Desanthus illionoensis), which is a State-listed special concern species in the vicinity of the Project site, would not be a suitable area for survival in the Project site. The DNR noted that they do not believe the Project will affect any known occurrences of rare features, including any State-listed species, rare plant communities, or other sensitive ecological resources. Three areas with Moderate Biodiversity Significance ranking near the manure areas and Seven areas with Below Biodiversity Significance ranking near the manure areas were found by the DNR. To avoid any potential impacts to these mapped areas, the Proposer reviewed the above listed areas and if there was overlap, they either amended field boundaries to avoid the above identified features or removed the entire field from consideration.
164	Commenter states, "If current trends continue—prioritizing short-term production over ecological limits—we risk accelerating climate instability."	The comment is out of scope for the EAW as it does not substantially inform the decision on the need for an EIS per the evaluation criteria in Minn. R. 4410.1700 subp. 7.
165	Commenters are concerned the Project will threaten the ecosystem.	The Project site, the Project waterline route, and the proposed Project manure application sites are all located on agricultural production land. Since row-crop production land is not identified as suitable habitat for any known fish, wildlife, plant communities, rare features, and ecosystems, no projected negative effects from those areas were identified. The only portion of the Project not in row-crop production is the portion of the Project waterline where the Off-Site Well/APEC Well is located, which is currently in agricultural production pastureland. After the underground water line is installed, the disturbed area will be restored to its current condition. Ecosystems are not expected to be directly affected by the Project.
166	Commenters are concerned about the ecological impacts of the Project.	Please see response to comment group 163 and comment group 165.

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167	Commenters state that the Project is a threat to the environment.	The comment is out of scope for the EAW as it does not substantially inform the decision on the need for an EIS per the evaluation criteria in Minn. R. 4410.1700 subp. 7.
168	Commenter claims, "they destroy farm land with no care."	The comment is out of scope for the EAW as it does not substantially inform the decision on the need for an EIS per the evaluation criteria in Minn. R. 4410.1700 subp. 7.
169	Commenters are concerned about the Projects impact on the flora and fauna in the area.	The Small White Lady's Slipper (Cypripedium candidum) has been documented near a proposed manure application area. This species can be found in mesic native prairies and wet prairies; it cannot grow in habitats on land used for livestock grazing or crop production. In addition, the Prairie Mimosa (Desmanthus illinoensis) has been documented near a proposed manure application area. This species can be found in mesic native prairie and on sandy lake shores. The DNR recommends avoiding areas with suitable habitat for these two species in the proposed manure application areas. However, the Project only includes manure application to land that is in crop production, and that is not considered suitable habitat for either species. The DNR had no records of any federally listed species within one mile of the manure application areas. Please also see responses to comment groups 163 and 165.
170	Commenters are concerned the Project will threaten the safety of our food supply.	The comment is out of scope for the EAW as it does not substantially inform the decision on the need for an EIS per the evaluation criteria in Minn. R. 4410.1700 subp. 7.
171	Commenter states, "CAFOs pose well known and documented environmental risk as a result of destruction of grazing land."	The comment is out of scope for the EAW as it does not substantially inform the decision on the need for an EIS per the evaluation criteria in Minn. R. 4410.1700 subp. 7.
172	Commenters are concerned about the loss of habitat.	The Elktoe mussel (Alasmidonta marginata) was documented in a portion of the Pomme de Terre River in 2007. Although its status near the manure application areas is unknown, mussels are particularly vulnerable to deterioration in water quality. The Project will operate with an MPCA-approved Manure Management Plan (MMP), which regulates manure application and requires following BMPs such as agronomic rates and setbacks from surface waters to avoid adverse impacts and minimize runoff from the field. The IPaC identified no federally protected endangered species or critical habitats within the Project site. The Northern Long-Eared Bat (Myotis septentrionalis) is a federally endangered species identified in the vicinity of the Project waterline route and Project manure application area. There are no critical habitats designated for this species, and the Project is unlikely to affect its habitat, as the waterline route installation will cause short-term disturbances with no tree removal. The U.S. Fish and Wildlife Service site Information for Planning and Consultation (IPaC) identified the presence of Bald Eagles (Haliaeetus leucocephalus) in the vicinity of the Project. No nests were observed as of 2023 and the closest trees capable of being utilized for nest sites are 2,300 feet away in the Waterfowl Production Area south of Project site and the manure application area. Please also see responses to comment groups 163, 165. and 169.

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173	Commenters are concerned about the threat to wildlife.	DNR identified (EAW attachment 7a) that no state-listed endangered species have been documented in the vicinity of the Project and that they do not believe the Project will affect any known occurrences of rare features, including any State-listed species, rare plant communities, or other sensitive ecological resources for the Project waterline route.
174	Commenters note there a number of waterfowl and wildlife production areas in the area.	Fish and wildlife resources are limited at the Project site; however, natural resources are available near the Project. These include: Gorder Lake, 0.86 miles north of the Project; Landers Waterfowl Production Area, 0.5 miles south of the Project; the Bill Freeman Wildlife Management Area, 0.26 miles west of the Off-Site Well/APEC Well; and the Pomme de Terre River, 3.84 miles east of the Project and 0.11 miles east of the Off-Site Well/APEC Well. Efforts to avoid fish and wildlife resources for this Project are included in the manure application sites (Manure Management Plan). Please also see response to comment group 165.
175	Commenter is concerned about the cumulative of all the animal units in the county and watershed will increase the threat to protected wildlife.	DNR identified (EAW attachment 7a) that no state-listed endangered species have been documented in the vicinity of the project and that they do not believe the Project will affect any known occurrences of rare features, including any State-listed species, rare plant communities, or other sensitive ecological resources for the Project waterline route.
176	Commenters state the Project is a threat to our land.	The comment is out of scope for the EAW as it does not substantially inform the decision on the need for an EIS per the evaluation criteria in Minn. R. 4410.1700 subp. 7.
177	Commenter is concerned about the impact the Project will have on appropriate land use.	The Project as proposed is consistent with current local zoning regulations. Land use and zoning are done at the local level in Minnesota. Changes to zoning laws must be done at the county or township level.
178	Commenters are concerned about the impact on the landscape.	The comment is out of scope for the EAW as it does not substantially inform the decision on the need for an EIS per the evaluation criteria in Minn. R. 4410.1700 subp. 7.
179	Commenter is concerned marginal farmland will be farmed more intensely out of convenience for large equipment to be used.	The comment is out of scope for the EAW as it does not substantially inform the decision on the need for an EIS per the evaluation criteria in Minn. R. 4410.1700 subp. 7.
180	Commenters are concerned about the threat to our natural resources.	The comment is out of scope for the EAW as it does not substantially inform the decision on the need for an EIS per the evaluation criteria in Minn. R. 4410.1700 subp. 7.
181	Commenters state the Project will create environmental conditions that will devastate the living conditions for surrounding properties.	The potential air emissions expected from the proposed project were modeled. H_2S concentration is 29.44 parts per billion which is below the ambient standards. NH_3 concentration is 2,009 µg/m3 which is below the acute levels. GHG total emissions are 72,210 tons/year (there are no federal or state threshold levels for GHG emissions). The Proposer is subject to all permit requirements, including those in the Minnesota Individual Feedlot Permit (EAW attachment 22) which will require

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		an Air Emission Plan that includes methods to mitigate odors and a Manure Management Plan (EAW attachment 23). Minnesota Department of Transportation data indicates that Annual Average Daily Traffic (AADT) near the Project on Stevens County Road 8 is 520 vehicles. The Project would increase current traffic counts by an estimated total of 45 vehicles per day. Therefore, the traffic on Stevens County Road 8 would increase by up to 8.7%, and the potential for traffic congestion is considered low. No improvements to County Road 8 are considered necessary to accommodate this increase in traffic. Feeding activities, which would be peak noise times, typically take place during the morning and early afternoon. The noise level was measured with a sound level meter along the property lines during peak operation time at the Existing Facility. The highest noise level recorded was 48.5 decibels, which is equivalent to the noise in a library and below the most stringent noise standards (NAC 1). For the benefit of wildlife and the reduction of insect attraction, the Proposer will consider a previous DNR recommended best management practice of choosing downward-facing and shielded fixtures to prevent light pollution. The Proposer will cover the liquid manure storage areas (facilities 101, 102, & 106) with impermeable synthetic covers, and pump liquid manure through pipelines.
182	Commenters are concerned about the threat to the Pomme de Terre River.	The Project Site and the Off-Site Well/APEC Well are within the Pomme de Terre River Watershed. There are no lakes, streams, wetlands, or intermittent streams at the Project site. There are no aquatic invasive species or impaired waters within one mile of the Project site. Surface water from the Project will flow south/east to County Tile 30, which runs across the south side of the Project site. County Tile 30 outlets into two unnamed creeks (WID 070200002-551 and 07020002-552),13 which then flows to the Pomme de Terre River (WID 07020002-501), and then eventually to the Minnesota River (WID 070200001-552). The Off-Site Well/APEC Well is approximately 500 feet west of the Pomme de Terre River. The Project site is designed to capture and reuse most or all of stormwater runoff, largely eliminating the untreated runoff that currently leaves the property. In addition, Best Management Practices (BMPs) will be adhered to with this Project to limit the potential for nitrate impacts on water resources including manure will be applied at agronomic rates, supplying only the nitrogen (N) needed by the crop to be grown. The Proposer will use the MPCA's Nutrient Management tool to calculate the amount of nitrogen that can be safely applied to each of their application fields. This tool considers manure N levels, the type of crop to be grown, and previous manure application (residual N levels) to indicate how many gallons per acre may be applied. The Proposer will also follow the state or county setbacks from ditches, lakes, tile intakes, and wells, to prevent nutrient runoff into those features and other waterbodies. The Project will replace cropland with impervious surface, grass/landscaping, and stormwater basins. The addition of stormwater basins will balance stormwater flow by collecting and filtering the water before release. Additionally, the impervious surface will include feed storage and solid manure storage areas. The Project will direct runoff from the feed storage and solid manure storage areas to an LMSA for land application.

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		Ultimately, the calculated runoff for the Project site will decrease to 106 MGY and the post-treatment runoff sediment and nutrient amounts will decrease to 0.05 tons/acre of sediment annually (EAW attachment 24). Water that is not recaptured would be discharged to the county tile system after passing through a stormwater basin with natural filtration. The water discharge rate would follow agronomic rates and would not be higher than it would be without the dairy.
183	Commenters are concerned the Project will threaten the soil quality in Stevens County.	Several practices are required by the Feedlot Permit to prevent nutrient runoff that include application at agronomic rates to not exceed expected crop nitrogen needs, testing for soil phosphorus, application timing, planting cover crops, and setbacks from waterways. The Proposer will comply with manure application requirements set forth by the Feedlot Permit.
184	Commenter states, "The ecological setting for this massive, multifaceted food (milk) industry enterprise is one that has, over many decades, been incrementally degraded to such an impoverished level that the beneficial functions (services) original ecosystems once provided have been all but obliterated." ... "This EAW hints at what the area used to be and in subtle ways justifies the projects contribution to the ecological destruction by explaining that the land is now only used for agriculture and therefore there is little measurable impact on the parts which remain in their “natural” state."	The comment is out of scope for the EAW as it does not substantially inform the decision on the need for an EIS per the evaluation criteria in Minn. R. 4410.1700 subp. 7.
185	Commenter states, "This dairy and it's feed suppliers will use huge farm equipment, which means bigger fields, and more erosion."	The comment is out of scope for the EAW as it does not substantially inform the decision on the need for an EIS per the evaluation criteria in Minn. R. 4410.1700 subp. 7.
186	Commenters are concerned the Project will alter cropping practices as to cause an increase in wind erosion from the cropland.	The comment is out of scope for the EAW as it does not substantially inform the decision on the need for an EIS per the evaluation criteria in Minn. R. 4410.1700 subp. 7.
187	Commenter states, "Such harms should be quantified to weigh against our state's stated emissions and environmental	The comment is out of scope for the EAW as it does not substantially inform the decision on the need for an EIS per the evaluation criteria in Minn. R. 4410.1700 subp. 7.

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	protection goals prior to considering the project for approval."	
188	Commenter states, "We need full transparency and accountability in this permitting process."	MPCA held a public comment period from February 10 - May 7, 2026. In addition, a public meeting was held on April 28, 2026, in Morris.
189	Commenter notes the Project is located in a vulnerable area.	The comment is out of scope for the EAW as it does not substantially inform the decision on the need for an EIS per the evaluation criteria in Minn. R. 4410.1700 subp. 7.
190	Commenters ask if the aquifer has been thoroughly studied?	The Project will use an off-site well (UN# 740629, APEC/Off-Site Well), approximately three miles southeast of the Project. The APEC/Off-Site Well is appropriated for the withdrawal of 452 million gallons per year (MGY) total, 226 MGY for APEC and 226 MGY for livestock watering (Proposer) as outlined in existing MN DNR Permit #2008-0230. The appropriation was established based on the results of a seven-day aquifer pump test that identified sufficient water in the water-table aquifer and confirmed that the aquifer is hydraulically connected to the Pomme De Terre River. Water Appropriation Permit 2008-0230 is not eligible for transfer to the Proposer. This permit was issued for a different project that was never developed. West River Dairy has applied for a new water appropriation from this same well (developed for permit 2008-0230), but it is a new application for a new permit. If authorized, a new appropriation permit would replace and modify permit 2008-0230, which will be terminated. DNR consulted with Riverview on the use of this well and confirmed that an additional aquifer test would not be needed from the well provided the new application proposed equal or lesser annual quantities and instantaneous pump rates to what was authorized in permit 2008-0230. DNR is evaluating the proposed use of that well against statutory and rule requirements. The Proposer has applied for a new water appropriation from the APEC/Off-Site Well for 226 MGY for livestock watering. MN DNR is completing a re-evaluation of stream flow in the Pomme de Terre River, and if a permit is authorized, it would be expected to include permit conditions based on stream flow. The Proposer will comply with all DNR pumping restrictions for the APEC/Off-Site Well.
191	Commenters are concerned about advancing permits for the Project with old or incomplete information on the Aquifer.	A new aquifer test for the Off-Site Well/APEC Well was waived by the DNR since the Proposer will abide by the following parameters: Pumping will occur from only the Off-Site Well/APEC Well, no more than 226 MGY is to be used at a rate not to exceed 1,000 gpm, pumping is subject to restrictions up to and including cessation of pumping depending on the flow conditions of the Pomme de Terre River and the Proposer will construct water storage basins to store a contingency supply of water. This contingency will allow flexibility if pumping restrictions of the Off-Site Well/APEC Well are ever required during low-flow periods. The Proposer has designed the facility to direct an average of 90 MGY of clean run-off from the project as another water source contingency.

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192	Commenters state the EAW does not describe how the existing permitted wells will be integrated with the well proposed to be used for the expansion.	The Project will use an off-site well (UN# 740629, APEC/Off-Site Well), approximately three miles southeast of the Project. The APEC/Off-Site Well is appropriated for the withdrawal of 452 million gallons per year (MGY) total, 226 MGY for APEC and 226 MGY for livestock watering (Proposer) as outlined in existing MN DNR Permit #2008-0230. The appropriation was established based on the results of a seven-day aquifer pump test that identified sufficient water in the water-table aquifer and confirmed that the aquifer is hydraulically connected to the Pomme De Terre River. Water Appropriation Permit 2008-0230 is not eligible for transfer to the Proposer. This permit was issued for a different project that was never developed. West River Dairy has applied for a new water appropriation from this same well (developed for permit 2008-0230), but it is a new application for a new permit. If authorized, a new appropriation permit would replace and modify permit 2008-0230, which will be terminated. DNR consulted with Riverview on the use of this well and confirmed that an additional aquifer test would not be needed from the well provided the new application proposed equal or lesser annual quantities and instantaneous pump rates to what was authorized in permit 2008-0230. DNR is evaluating the proposed use of that well against statutory and rule requirements. The Proposer has applied for a new water appropriation from the APEC/Off-Site Well for 226 MGY for livestock watering. MN DNR is completing a re-evaluation of stream flow in the Pomme de Terre River, and if a permit is authorized, it would be expected to include permit conditions based on stream flow. The Proposer will comply with all DNR pumping restrictions for the APEC/Off-Site Well.
193	Commenters are concerned about groundwater and drinking water getting contaminated by manure.	The Liquid Manure Storage Area liners are permitted and regulated under the individual NPDES feedlot permit associated with this facility. A monthly examination of the monitoring port or drain tile outlet for water flow and signs of discoloration or odor in any water flowing in the drain tile. A weekly visual inspection of the LMSA and any devices channeling manure-contaminated runoff to the LMSA to assess conformance to the approved plans and this Permit. Several practices are required by the Feedlot Permit to prevent nutrient runoff that include application at agronomic rates to not exceed expected crop nitrogen needs, testing for soil phosphorus, application timing, planting cover crops, and setbacks from waterways. The Proposer will comply with manure application requirements set forth by the Feedlot Permit that are intended to protect waters of the state. The Minnesota Department of Health (MDH) Well Management Program oversees public and private wells in Minnesota. The MDH's "Owner's Guide to Wells" states that the homeowner is responsible for regularly testing their well water. This includes laboratory analysis for bacteria annually and nitrate-nitrogen (nitrate) testing every other year. Please visit MDH's website for more information on well testing and health related questions.

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194	Comments are related to an issue of over pumping water in Arizona by Riverview.	The comment is out of scope for the EAW as it does not substantially inform the decision on the need for an EIS per the evaluation criteria in Minn. R. 4410.1700 subp. 7.
195	Commenters are concerned about the volume of water being used and how it will affect their wells.	The primary source of water will be an existing Off-Site Well/APEC Well as well as two water storage basins to serve as a contingency (facilities 501 and 502) in the event groundwater availability is disrupted. For groundwater extraction, the Proposer has chosen to use an off-site well screened in a different aquifer than the wells utilized by the existing facility. The basins will be filled with well water outside restricted periods. The water storage basins will also store an average of 90 MGY of collected stormwater per year, reducing reliance on a single water source. The Proposer has applied for a new water appropriation from this same Off-Site Well/APEC Well (developed for permit 2008-0230), but it is a new application for a new permit. If authorized, a new appropriation permit would replace and modify permit 2008-0230, which will be terminated. Additionally, although the on-site wells and the off-site well are screened in different aquifers, DNR's analysis shows that the shallow and deep aquifers in this area are hydraulically connected and function as a single groundwater system with limited water availability. Consequently, the proposed wells do not provide a diversified groundwater source. Because of these hydraulic connections, cumulative existing and proposed water appropriations will be evaluated during the DNR's water appropriation permitting process.
196	Commenters are concerned the DNR has not completed the Geologic Atlas for Stevens County which would include a hydrologic survey.	The comment is out of scope for the EAW as it does not substantially inform the decision on the need for an EIS per the evaluation criteria in Minn. R. 4410.1700 subp. 7.
197	Commenters would like to know where the water comes from?	Please see response to comment group 195.
198	Commenter wants to know what aquifer will be used for the off-site well?	The groundwater source for the Project will be an Off-Site Well/APEC Well, approximately three miles southeast of the Project. The Off-Site Well/APEC Well is near the Pomme de Terre River valley and is screened in a Quaternary Water Table Aquifer (QWTA), while the wells for the existing facility are screened in the Quaternary Buried Artesian Aquifer (QBAA) beneath the Project site. For groundwater extraction, the Proposer has chosen to use an off-site well screened in a different aquifer than the wells utilized by the Existing Facility. Water Appropriation Permit 2008-0230 is not eligible for transfer to the Proposer. This permit was issued for a different project that was never developed. West River Dairy has applied for a new water appropriation from this same Off-Site Well/APEC (developed for permit 2008-0230), but it is a new application for a new permit. If authorized, a new appropriation permit would replace and modify permit 2008-0230, which will be terminated. Groundwater availability is moderate to limited in this area. As identified in permit 2008-0230, the groundwater appropriation from this well can directly impact the river and is subject to

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		existing permit conditions based on the river flow. MN DNR is completing a re-evaluation of stream flow in the Pomme de Terre River, and if a permit is authorized, it would be expected to include permit conditions based on stream flow. Conditions would be modified from those currently included with 2008-0230, including restrictions on the ability to appropriate water during summer months. Additionally, DNR will evaluate the impacts of water appropriation on rare features in the Pomme de Terre River downstream of the appropriation site. Additionally, although the on-site wells and the off-site well are screened in different aquifers, DNR's analysis shows that the shallow and deep aquifers in this area are hydraulically connected and function as a single groundwater system with limited water availability. Consequently, the proposed wells do not provide a diversified groundwater source. Because of these hydraulic connections, cumulative existing and proposed water appropriations will be evaluated during the DNR's water appropriation permitting process.
199	Commenters want to know if the Project will be using water from the Sioux Aquifer?	No, the groundwater source for the Project will be an Off-Site Well/APEC Well, approximately three miles southeast of the Project. The Off-Site Well/APEC Well is near the Pomme de Terre River valley and is screened in a Quaternary Water Table Aquifer (QWTA), while the wells for the existing facility are screened in the Quaternary Buried Artesian Aquifer (QBAA) beneath the Project site.
200	Commenter wants to know what will happen if the off-site well is connected to the Sioux Aquifer?	The comment is out of scope for the EAW as it does not substantially inform the decision on the need for an EIS per the evaluation criteria in Minn. R. 4410.1700 subp. 7.
201	Commenter wants to know if wells in the area have been monitored for depth and quality?	There is one well (UN#: 768109) within the Project footprint that is 138 feet deep and screened in a buried quaternary (confined) artesian aquifer. This well has an existing DNR water appropriation (DNR Permit #2009-0492) for both irrigation and livestock watering. Nine domestic wells and four commercial wells have been identified within one mile of the Project site. Four commercial wells and one domestic well (UN#: 682246, 6822488, 731318, 757860, & 836244) are at the existing facility. The remaining domestic wells are at rural farmsteads. There are no public water supply wells within or adjacent to the Project or any manure application areas. As outlined in the Aquifer Test Report for the Off-Site Well/APEC Well, a well survey was completed for all wells within 1.5 miles of the Off-Site Well/APEC Well. In addition, the Minnesota Department of Health (MDH) Well Management Program oversees public and private wells in Minnesota. The MDH's "Owner's Guide to Wells" states that the homeowner is responsible for regularly testing their well water. This includes laboratory analysis for bacteria annually and nitrate-nitrogen (nitrate) testing every other year. Please visit MDH's website for more information on well testing and health related questions.
202	Commenter states, "A project of this scope demands careful and exacting review of cumulative impacts, including existing	The Environmentally Relevant Area (ERA) for the Project has been delineated to ensure that environmental effects from other projects do not overlap. The ERA is defined as the oversized Project Boundary, all identified manure application fields designated for the Project and Existing Facility, and

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	animal units of all operations within the county and watershed, the increased demand on area water resources with potential threats to existing wells."	a one-mile radius surrounding the Off-Site Well/APEC Well. This generously sized ERA will keep other project-related environmental effects from overlapping with those from the Project, thereby avoiding the potential for cumulative potential effects. Cumulative potential effects for feedlot projects would generally be related to overlapping manure application and excess water usage within the same Environmentally Relevant Area (ERA) by other similar projects. The Proposer established an ERA which includes sufficient manure acres for the Project and the existing facility and has over 3,000 additional acres extra to account for possible unknowns. These designated manure acres are not only established in this EAW, but they will also be reported in the Manure Management Plan that is submitted to the MPCA. For groundwater extraction, the Proposer has chosen to use an Off-Site Well/APEC Well screened in a different aquifer than the wells utilized by the existing facility. Water Appropriation Permit 2008-0230 is not eligible for transfer to the Proposer. This permit was issued for a different project that was never developed. The Proposer has applied for a new water appropriation from this same well (developed for permit 2008-0230), but it is a new application for a new permit. If authorized, a new appropriation permit would replace and modify permit 2008-0230, which will be terminated. DNR consulted with the Riverview on the use of this well and confirmed that an additional aquifer test would not be needed from the well provided the new application proposed equal or lesser annual quantities and instantaneous pump rates to what was authorized in permit 2008-0230. DNR is evaluating the proposed use of that well against statutory and rule requirements.
203	Commenter asks, "How about that aquifer under us from the Gulf of Mexico to the Canadian border? Is it drawn down beyond use yet?"	The comment is out of scope for the EAW as it does not substantially inform the decision on the need for an EIS per the evaluation criteria in Minn. R. 4410.1700 subp. 7.
204	Commenter states, "75% of Minnesotans rely on groundwater for their source of drinking water."	The comment is out of scope for the EAW as it does not substantially inform the decision on the need for an EIS per the evaluation criteria in Minn. R. 4410.1700 subp. 7.
205	Commenter states, "the research documents that groundwater contamination from intensive livestock farming can have legacy effects with lag times exceeding 20 years. [Kim et al., 2021] The full consequences of today's permitting decisions may not fully appear in Minnesota's water supply for two decades. By the time the harm is visible, the facility will be entrenched, the contamination will	The Liquid Manure Storage Area liners are permitted and regulated under the individual NPDES feedlot permit associated with this facility. A monthly examination of the monitoring port or drain tile outlet for water flow and signs of discoloration or odor in any water flowing in the drain tile. A weekly visual inspection of the LMSA and any devices channeling manure-contaminated runoff to the LMSA to assess conformance to the approved plans and this Permit. Several practices are required by the Feedlot Permit to prevent nutrient runoff that include application at agronomic rates to not exceed expected crop nitrogen needs, testing for soil phosphorus, application timing, planting cover crops, and setbacks from waterways. The Proposer

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	be established, and the opportunity to prevent it will be gone."	will comply with manure application requirements set forth by the Feedlot Permit that are intended to protect waters of the state. There are no Drinking Water Supply Management Areas (DWSMAs) or Source Water Protection Areas (SWPAs) near the Project or the manure application fields. The Groundwater Contamination Susceptibility in Minnesota report estimates the potential for groundwater pollution. In June 2016, the DNR updated this evaluation. The report uses a matrix for determining a sensitivity rating of the water table ranging from very high to very low based on aquifer material, recharge potential, soil materials, and vadose zone materials. After review of the published information related to pollution sensitivity potential the Project and its manure application fields are primarily in an area designated as having a low sensitivity to groundwater pollution. Specifically, of the 16,669 manure acres designated for the proposed Project, only 425 acres are within sensitive areas that have fall fertilizer application restrictions.
206	Commenter states that when his dad applied anhydrous ammonia to his neighbor's cornfields it polluted their well water.	The comment is out of scope for the EAW as it does not substantially inform the decision on the need for an EIS per the evaluation criteria in Minn. R. 4410.1700 subp. 7.
207	Commenter asks, "What do we do when the aquifer is gone, or polluted?"	The comment is out of scope for the EAW as it does not substantially inform the decision on the need for an EIS per the evaluation criteria in Minn. R. 4410.1700 subp. 7.
208	Commenter notes the EAW does not provide calculations to demonstrate that the on-site water storage basins are appropriately sized.	Unlike stormwater basins, the water storage basins will be designed for long-term water storage. The water source for the water storage basins will come from the off-site well and stormwater runoff collected from other areas of the Project. The site is designed so that no stormwater runoff will naturally enter the water storage basins. Facility 503 will house the pumping equipment necessary to transfer water from the water storage basins to the appropriate facilities. The total size of the water storage basins and pump building will be approximately 21.6 acres with a combined design capacity of 157 million gallons of water and are designed to hold a 9-month contingency water supply in the event the well pumping is restricted for extended periods. The Project is designed to direct run-off water from the Project site to the water storage basins for reuse. The Proposer conservatively calculates that they will be able to collect and reuse an average of 90 million gallons per year (MGY) of stormwater runoff from the Project site. This backup source of clean water has proven effective as a mitigation tool at similar facilities operated by the Proposer.
209	Commenter states, "With climate change data [from] the past 30 years we know not	Climate projections suggest big rains will continue increasing into the future. Therefore, there may be a decrease in area irrigation well usage due to more moisture received from rain and increased stormwater. The groundwater source for the Project will be an Off-Site Well/APEC Well,

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	[to] expect aquifers to recharge, or for water sources to become more plentiful."	approximately three miles southeast of the Project as well as two water storage basins to serve as a contingency (facilities 501 and 502) in the event groundwater availability is disrupted. The Off-Site Well/APEC Well is near the Pomme de Terre River valley and is screened in a Quaternary Water Table Aquifer (QWTA), while the wells for the existing facility are screened in the Quaternary Buried Artesian Aquifer (QBAA) beneath the Project site. For groundwater extraction, the Proposer has chosen to use an off-site well screened in a different aquifer than the wells utilized by the Existing Facility. As a contingency measure for seasonal fluctuations and/or potential pumping restrictions, two water storage basins (Facilities 501 and 502), will be constructed as part of the Project. The basins will be filled with well water outside restricted periods. The water storage basins will also store an average of 90 MGY of collected stormwater per year, reducing reliance on a single water source. Moreover, groundwater use is highly regulated by the MN DNR through its Water Appropriation Permit process. MN DNR is completing a re-evaluation of stream flow in the Pomme de Terre River, and if a permit is authorized, it would be expected to include permit conditions based on stream flow. Conditions would be modified from those currently included with 2008-0230, including restrictions on the ability to appropriate water during summer months. Additionally, DNR will evaluate the impacts of water appropriation on rare features in the Pomme de Terre River downstream of the appropriation site. Please also see response to comment group 208.
210	Commenter asks, "What will happen if there is a drought?"	In Table 4: Historic Climate Trends in the EAW, it states that the historic trend for maximum number of consecutive days without rain during the growing season in Stevens County has averaged 15.6 days since 1995. The future projection for maximum number of consecutive days without rain during the growing season in Stevens County is expected to increase by 1.6 days. The Project's water source for the water storage basins will come from the off-site well and stormwater runoff collected from other areas of the Project. The site is designed so that no stormwater runoff will naturally enter the water storage basins. The Proposer conservatively calculates that they will be able to collect and reuse an average of 90 million gallons per year (MGY) of stormwater runoff from the Project site. This backup source of clean water has proven effective as a mitigation tool at similar facilities operated by the Proposer. In addition, the Aquifer Test Report from the 7-day aquifer pump test for the Project includes pumping conditions which were recommended by the DNR to protect the river in the event of drought or low surface-water flows. The Proposer will follow the DNR-identified restrictions on pumping levels and/or cessation of pumping based on the measured flow conditions of the Pomme de Terre River.
211	Comments are related to water usage by Data Centers.	The comment is out of scope for the EAW as it does not substantially inform the decision on the need for an EIS per the evaluation criteria in Minn. R. 4410.1700 subp. 7.
212	Commenter relates actions taken by Riverview at Dollymont Dairy.	The comment is out of scope for the EAW as it does not substantially inform the decision on the need for an EIS per the evaluation criteria in Minn. R. 4410.1700 subp. 7.

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213	Commenter states, the ethanol plant in Morris gets water directly from the city instead of the wells it used.	The ethanol plant in Morris (DENCO II) is not the same ethanol plant (APEC) that initially drilled and permitted the well that West River Dairy proposes to use. The APEC Ethanol Plant was not constructed.
214	Comments are related to the wells at the existing site.	The comment is out of scope for the EAW as it does not substantially inform the decision on the need for an EIS per the evaluation criteria in Minn. R. 4410.1700 subp. 7.
215	Commenter believes that allowing the Project to go forward will be a huge experiment in aquifer depletion.	The comment is out of scope for the EAW as it does not substantially inform the decision on the need for an EIS per the evaluation criteria in Minn. R. 4410.1700 subp. 7.
216	Commenter states, "the EAW does not address the impact altered hydrology has on river flow and thus whether the flow-based permit conditions will protect natural resources."	The Minnesota DNR is the authority for water appropriation permitting, and as part of the process is completing a re-evaluation of stream flow in the Pomme de Terre River to inform decision making. If a permit is authorized, it would be expected to include permit conditions based on stream flow. Conditions would be modified from those currently included with 2008-0230, including restrictions on the ability to appropriate water during summer months. Additionally, DNR will evaluate the impacts of water appropriation on rare features in the Pomme de Terre River downstream of the appropriation site.
217	Commenter asks, “How much additional water will be?”	The existing facility uses approximately 95 million gallons per year (MGY). The Project will add 226 MGY, for a total of 321 MGY.
218	Comments state that CAFOs will have an impact on groundwater supply and quality.	The comment is out of scope for the EAW as it does not substantially inform the decision on the need for an EIS per the evaluation criteria in Minn. R. 4410.1700 subp. 7.
219	Commenter is concerned that if the aquifer is contaminated that it will in turn contaminate lakes.	The comment is out of scope for the EAW as it does not substantially inform the decision on the need for an EIS per the evaluation criteria in Minn. R. 4410.1700 subp. 7.
220	Commenter states, "I fear a massive dairy of this size will only increase water consumption."	The Project will use an off-site well (UN# 740629, APEC/Off-Site Well), approximately three miles southeast of the Project. The APEC/Off-Site Well is an existing well originally constructed for an ethanol plant (APEC) (not constructed). The APEC/Off-Site Well is appropriated for the withdrawal of 452 million gallons per year (MGY) total, 226 MGY for APEC and 226 MGY for livestock watering (Proposer) as outlined in existing MN DNR Permit #2008-0230. The appropriation was established based on the results of a seven-day aquifer pump test that identified sufficient water in the water-table aquifer and confirmed that the aquifer is hydraulically connected to the Pomme De Terre River. As recommended in the Aquifer Test Report, pumping conditions were imposed by the DNR to protect the river in the event of drought or low surface-water flows. This permit was issued for a different project that was never developed. Water Appropriation Permit 2008-0230 is not eligible for

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		transfer to the Proposer. The Proposer has applied for a new water appropriation from the APEC/Off-Site Well for 226 MGY for livestock watering. MN DNR is completing a re-evaluation of stream flow in the Pomme de Terre River, and if a permit is authorized, it would be expected to include permit conditions based on stream flow. The Proposer will comply with all DNR pumping restrictions for the APEC/Off-Site Well. In addition, the Proposer will collect stormwater with water storage basins located onsite (Facilities 501 and 502) which will account for 157 MGY. The Proposer will also collect and reuse 90 MGY of stormwater from Project runoff directed to water storage basins to be used for livestock watering.
221	Commenter states that it appears there is increased irrigation in the area.	Please see response to comment group 220.
222	Commenter states there are new irrigation wells near the off-site well that were installed after the 2007 aquifer test was completed.	West River Dairy has applied for a new water appropriation for the Project to use the APEC/Off-Site Well (developed for permit 2008-0230), but it is a new application for a new permit. If authorized, a new appropriation permit would replace and modify permit 2008-0230, which will be terminated. DNR consulted with Riverview on the use of this well and confirmed that an additional aquifer test would not be needed from the well provided the new application proposed equal or lesser annual quantities and instantaneous pump rates to what was authorized in permit 2008-0230. DNR is evaluating the proposed use of that well against statutory and rule requirements.
223	Commenter states, "The MPCAs own site lists 1800 old, unpermitted, mostly unlined solid waste dump sites that are contaminating our groundwater, with 43 construction and demolition dump sites being monitored only as of 2010 showing arsenic, boron and manganese at levels beyond human and environmental standards and mitigation efforts are not helping. That's only 43 out of 1800 that are even monitored?"	The comment is out of scope for the EAW as it does not substantially inform the decision on the need for an EIS per the evaluation criteria in Minn. R. 4410.1700 subp. 7.
224	Commenters want to know who pays if wells go dry or become contaminated?	The Project will use an off-site well (UN# 740629, APEC/Off-Site Well), approximately three miles southeast of the Project. The APEC/Off-Site Well is an existing well originally constructed for an ethanol plant (APEC) (not constructed). The APEC/Off-Site Well is appropriated for the withdrawal of 452 million gallons per year (MGY) total, 226 MGY for APEC and 226 MGY for livestock watering (Proposer) as outlined in existing MN DNR Permit #2008-0230. This permit was issued for a different project that was never developed. Water Appropriation Permit 2008-0230 is not eligible for transfer

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		to the Proposer. The Proposer has applied for a new water appropriation from the APEC/Off-Site Well for 226 MGY for livestock watering. MN DNR is completing a re-evaluation of stream flow in the Pomme de Terre River, and if a permit is authorized, it would be expected to include permit conditions based on stream flow. The Proposer will comply with all DNR pumping restrictions for the APEC/Off-Site Well. In addition, the Proposer will collect stormwater with water storage basins located onsite (Facilities 501 and 502) which will account for 157 MGY. The Proposer will also collect and reuse 90 MGY of stormwater from Project runoff directed to water storage basins to be used for livestock watering. A DNR water appropriation permit is required for any individual, business, or entity that withdraws large volumes of surface water or groundwater. It ensures that high-volume water use is sustainable, does not harm the environment, and does not conflict with other users. The water appropriation permit for this Project will serve to limit pumping so it does not dry up nearby lakes, streams, or aquifers.
225	Commenter believes there needs to be intensive water well testing by an independent testing company before Project is approved.	The Proposer consulted with DNR on the use of the APEC/Off-Site Well and confirmed that an additional aquifer test would not be needed from the well provided the new application proposed equal or lesser annual quantities and instantaneous pump rates to what was authorized in permit 2008-0230. Although the on-site wells and the off-site well are screened in different aquifers, DNR's analysis shows that the shallow and deep aquifers in this area are hydraulically connected and function as a single groundwater system with limited water availability. Consequently, the proposed wells do not provide a diversified groundwater source. Because of these hydraulic connections, cumulative existing and proposed water appropriations will be evaluated during the DNR's water appropriation permitting process. Please also see response to comment group 220.
226	Commenter requests "that the MPCA: 2. Require rigorous groundwater monitoring and publicly accessible reporting."	Minn. R. Ch. 7020 and the Individual NPDES Permit contains specific requirements for locating, constructing, and operating feedlot facilities in Minnesota. The requirements found in rule and the permit are designed to provide protection for Minnesota groundwater. Permit application information included engineered design plans, construction specifications, construction testing and operation and maintenance plans for proposed manure storage areas at the site. The Permit requires the Permittee to conduct weekly inspections of manure storage areas monthly inspections of manure storage area perimeter tiles and reporting of any spills or discharges. Additionally, the Projects proposed earthen lined manure storage areas will be constructed with compacted clay liners that are three feet thicker than required by rule.
227	Commenters ask MPCA to protect Minnesota's groundwater.	The comment is out of scope for the EAW as it does not substantially inform the decision on the need for an EIS per the evaluation criteria in Minn. R. 4410.1700 subp. 7.

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228	Commenter makes unfounded allegations about past employment of current MPCA Commissioner.	The comment is out of scope for the EAW as it does not substantially inform the decision on the need for an EIS per the evaluation criteria in Minn. R. 4410.1700 subp. 7.
229	Commenter pleads with MPCA to take our mission seriously and be proactive.	The comment is out of scope for the EAW as it does not substantially inform the decision on the need for an EIS per the evaluation criteria in Minn. R. 4410.1700 subp. 7.
230	Commenter is concerned about people in town not being able to afford to treat their water from the city.	The comment is out of scope for the EAW as it does not substantially inform the decision on the need for an EIS per the evaluation criteria in Minn. R. 4410.1700 subp. 7.
231	Commenter states water is not a renewable resource.	The comment is out of scope for the EAW as it does not substantially inform the decision on the need for an EIS per the evaluation criteria in Minn. R. 4410.1700 subp. 7.
232	Commenters have read articles about groundwater issues in other states.	The comment is out of scope for the EAW as it does not substantially inform the decision on the need for an EIS per the evaluation criteria in Minn. R. 4410.1700 subp. 7.
233	Commenter asks how much Riverview pays for their water.	The comment is out of scope for the EAW as it does not substantially inform the decision on the need for an EIS per the evaluation criteria in Minn. R. 4410.1700 subp. 7.
234	Commenter states the groundwater near dairy operations has been found to contain PFAS.	The comment is out of scope for the EAW as it does not substantially inform the decision on the need for an EIS per the evaluation criteria in Minn. R. 4410.1700 subp. 7.
235	Commenter wants to know, "Are we willing to empty our already limited aquifers in the name of a mega corporation over our own residents?"	The comment is out of scope for the EAW as it does not substantially inform the decision on the need for an EIS per the evaluation criteria in Minn. R. 4410.1700 subp. 7.
236	Commenter states there is no information in the EAW relating to recharge rates.	MN DNR is completing a re-evaluation of stream flow in the Pomme de Terre River, and if a water appropriation permit is authorized, it would be expected to include permit conditions based on stream flow. Conditions would be modified from those currently included with 2008-0230, including restrictions on the ability to appropriate water during summer months.
237	Commenter wants to know if Riverview, "Can they treat and reuse the treated water instead of using fresh water?"	The comment is out of scope for the EAW as it does not substantially inform the decision on the need for an EIS per the evaluation criteria in Minn. R. 4410.1700 subp. 7.
238	Commenter states, "The Driftless Area in SE MN (in places like Lewiston, where Rush Creek is) has a "Swiss cheese" geology, which is why we have cold water spring	The comment is out of scope for the EAW as it does not substantially inform the decision on the need for an EIS per the evaluation criteria in Minn. R. 4410.1700 subp. 7.

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	creeks in the area. Water from the surface can reach the aquifer in 0-3 days."	
239	Commenter states, "We also have polluted ground water that have also been impacted by these "accidents"."	The comment is out of scope for the EAW as it does not substantially inform the decision on the need for an EIS per the evaluation criteria in Minn. R. 4410.1700 subp. 7.
240	Commenter states, "The degradation of the ground water are externalities that are invariably left for the community or state to deal with."	The comment is out of scope for the EAW as it does not substantially inform the decision on the need for an EIS per the evaluation criteria in Minn. R. 4410.1700 subp. 7.
241	Commenter suggests MPCA get comments from the Soil Water and Conservation District (SWCD) on the EAW.	The local SWCD always receives a copy of the Notice of Availability for the EAW along with a copy of the EAW and may comment on the EAW.
242	Commenter, a citizen of Winona County, sympathizes with the people near Morris.	The comment is out of scope for the EAW as it does not substantially inform the decision on the need for an EIS per the evaluation criteria in Minn. R. 4410.1700 subp. 7.
243	Commenter states, "they use massive amounts of fertilizers and other chemicals to grow the feed for these cattle."	The comment is out of scope for the EAW as it does not substantially inform the decision on the need for an EIS per the evaluation criteria in Minn. R. 4410.1700 subp. 7.
244	Commenter states the MPCA must require Riverview to install synthetic liners with leak detection.	All LMSAs will be lined with no less than 60” of compacted clay. The risk of contamination to groundwater quality due to the LMSAs is low given the clay-lined design for the Project exceeds the required soil seepage standard. Based on geotechnical review of boring logs the clay soils encountered on sites are suitable for use in liner material. A perimeter drain-tile system will be installed at an elevation below the liner of each of the three proposed earthen LMSAs to control seasonal sub-surface saturation as outlined in the Minnesota NPDES Individual Feedlot Permit (Feedlot Permit) application. Tile inspection ports will be installed near the LMSAs to enable inspection of the tile system. After construction, the Permit requires that the Proposer inspect the tile system on a monthly basis to ensure the drain-tile system is functioning correctly and to look for signs of discoloration or odor that may indicate an issue with the liner. Note LMSAs will be designed with enhanced clay liner thickness, and geology doesn’t warrant synthetic liners as per rule.
245	Commenter states, "More and more farm land is being tiled which quickly drains rain water off the field so it is no longer seeping into the ground to replenish the ground water."	The comment is out of scope for the EAW as it does not substantially inform the decision on the need for an EIS per the evaluation criteria in Minn. R. 4410.1700 subp. 7.

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246	Commenter states, "as a Registered Professional Engineer, I believe this project—which would become the largest livestock farm in state history—poses unacceptable risks to our groundwater."	The comment is out of scope for the EAW as it does not substantially inform the decision on the need for an EIS per the evaluation criteria in Minn. R. 4410.1700 subp. 7.
247	Commenter states, "this does not benefit other water users."	The comment is out of scope for the EAW as it does not substantially inform the decision on the need for an EIS per the evaluation criteria in Minn. R. 4410.1700 subp. 7.
248	Commenter states, "I think a full environmental review is warranted to evaluate the potential noise pollution."	An Environmental Assessment Worksheet was completed for the Project. Project construction will create a temporary increase in noise and dust, mostly due to earthwork activities, delivery truck traffic, and construction equipment operating on unpaved surfaces. The nearest sensitive receptor is a rural residence 920 feet north of the Project. MPCA guidance on noise states that when a distance is doubled, the sound level decreases by six decibels (Distance Attenuation). Therefore, the noise from the Project at the nearest sensitive receptor would be near zero decibels and well below the most stringent MN noise standards. The Project is designed to operate with features that reduce noise. The manure vacuum and skid loaders are operated within the freestall barn (Facility 201). Front-end loaders and feed mixing wagons are primarily operated inside the commodity shed (Facility 207) and the freestall barn, with a small portion of feed preparation happening on the outdoor feed storage area (Facility 206). Equipment for milking and manure handling is within enclosed structures (Facilities 203 and 204, respectively).
249	Commenters are concerned about the increase in noise in the community.	Project construction will create a temporary increase in noise and dust, mostly due to earthwork activities, delivery truck traffic, and construction equipment operating on unpaved surfaces. The nearest sensitive receptor is a rural residence 920 feet north of the Project. MPCA guidance on noise states that when a distance is doubled, the sound level decreases by six decibels (Distance Attenuation). Therefore, the noise from the Project at the nearest sensitive receptor would be near zero decibels and well below the most stringent MN noise standards. The Project is designed to operate with features that reduce noise. The manure vacuum and skid loaders are operated within the freestall barn (Facility 201). Front-end loaders and feed mixing wagons are primarily operated inside the commodity shed (Facility 207) and the freestall barn, with a small portion of feed preparation happening on the outdoor feed storage area (Facility 206). Equipment for milking and manure handling is within enclosed structures (Facilities 203 and 204, respectively).
250	Commenter asks, "What will the impact to the public be in more than doubled truck traffic—traffic noise?"	Project construction will create a temporary increase in noise and dust, mostly due to earthwork activities, delivery truck traffic, and construction equipment operating on unpaved surfaces. The nearest sensitive receptor is a rural residence 920 feet north of the Project. MPCA guidance on noise states that when a distance is doubled, the sound level decreases by six decibels (Distance

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		Attenuation). Therefore, the noise from the Project at the nearest sensitive receptor would be near zero decibels and well below the most stringent MN noise standards. The Project is designed to operate with features that reduce noise. The manure vacuum and skid loaders are operated within the freestall barn (Facility 201). Front-end loaders and feed mixing wagons are primarily operated inside the commodity shed (Facility 207) and the freestall barn, with a small portion of feed preparation happening on the outdoor feed storage area (Facility 206). Equipment for milking and manure handling is within enclosed structures (Facilities 203 and 204, respectively).
251	Comment states there needs to be more baseline monitoring before the Project is constructed.	Prior to obtaining the DNR Water Appropriation Permit for the Facility, an aquifer test was completed, including continuous pumping of the Off-Site Well/APEC Well at 1,093 gallons per minute (gpm) for seven days while monitoring water levels in new observation wells, existing observation and potable wells, and nearby surface water levels. Based on the results of this aquifer test, the water-table aquifer used by the Off-Site Well/APEC Well was found to provide ample water, be hydraulically connected to the Pomme de Terre River, and that river flows need to be considered. The Aquifer Test Report included an assessment of potential impacts to surface-water features, including the historical examination of the Pomme de Terre River flows. Therefore, the DNR Water Appropriation Permit (2008-0230), includes a condition to reduce or restrict well pumping based on Pomme de Terre River flow. In addition, the Project will have an MPCA approved nutrient management plan that addresses phosphorus application rates in certain circumstances where there is elevated risk of phosphorous moving off the landscape into the water.
252	Commenters are concerned the basins are "leaking" manure and will impact surface waters.	The cows will be housed in a free-stall barn and will use clay-lined basins with impermeable covers to collect and store manure and wastewater. The manure storage basins will have covers to prevent stormwater from entering and causing overflow. Installation of a perimeter drain-tile system will be at an elevation below the liner of each of the three Liquid Manure Storage Areas (LMSAs) to control seasonal sub-surface saturation included in the Minnesota NPDES Individual Feedlot Permit. The Proposer will install an inspection port near the LMSAs to enable monthly visual inspections. After construction, the Proposer will ensure the drain-tile system is functioning correctly for each LMSA and look for signs of discoloration or odor that may indicate an issue with the liner. In addition, grading at the Project site will direct clean stormwater away from manure storage areas and feedstock storage areas and toward stormwater basins, where the water will be collected and treated before released back to the existing watershed at a controlled rate. Solid and liquid manure transferred to area farmers for use as fertilizer will be applied in accordance with Feedlot Permit requirements which protect the impact of pollution to surface waters.
253	Commenters are concerned the basins are "leaking" manure and will impact surface waters.	The comment is out of scope for the EAW as it does not substantially inform the decision on the need for an EIS per the evaluation criteria in Minn. R. 4410.1700 subp. 7.

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		In relation to the Feedlot Permit, please see response to comment group 252.
254	Commenter states the EAW needs to, "12.B.1.c. If the wastewater discharge is to surface water, identify the wastewater treatment methods and identify discharge points and proposed effluent limitations to mitigate impacts. Discuss any effects to surface or groundwater from wastewater discharges, taking into consideration how current Minnesota climate trends and anticipated climate change in the general location of the project may influence the effects."	Residential wastewater from the facilities at the Project site will be treated by mound systems (septic tanks). All septic tanks (SSTSs) for will be pumped annually by Engebretson Pumping (MPCA Maintainer License #3265), based in the region. After the SSTSs are constructed per MN Rules 7080, the areas around them will be landscaped to divert any excess stormwater away which will prolong the life of each system. The risk of contamination of groundwater quality due to the Liquid Manure Storage Areas (LMSAs) is low due to the engineered concrete structures and clay-lined design for the Project. LMSAs at the Project site will exceed the required soil seepage standard, and LMSA clay-liner thickness will be increased from two feet to five feet. The Proposer may encounter shallow groundwater during construction of the LMSAs, so they will install a perimeter drain-tile system at an elevation that is lower than the liner within the LMSA to reduce external groundwater pressure on the walls and to control seasonal subsurface saturation near the LMSAs. The Project will reduce contamination risk from manure application to groundwater quality by following proper land application practices. The Proposer will follow requirements of Minn. R. 7020 and the MMP in the Feedlot Permit for manure application.
255	Commenters state there needs to be more cumulative impacts analysis from runoff from the site as well as the leaching from the manure basins.	The Project site is designed to capture and reuse most or all of stormwater runoff, largely eliminating the untreated runoff that currently leaves the property. The Proposer will comply with manure application procedures put in place to prevent runoff and impacts to waterbodies. Please also see responses to comment groups 252 and 274.
256	Commenters state there needs to be more cumulative impacts analysis related to manure/nutrient runoff from land application of manure.	Information about all the NMPs in the area impacted by the project is not "reasonably obtained information". Generally, MPCA relies on existing water quality data to determine if there is a cumulative impact. NOTE: Due to the number of identified impairments in the area we can assume there is a cumulative impact. However, the Proposer is complying with the evaluation criteria laid out in 4410.1700 Subp. 7.B. to minimize impacts. The feedlot permit requirements which include the individual NPDES permit and nutrient management plan reduce the likelihood of cumulative impacts on the watershed as the NPDES permit does not allow discharge from land application. Instead, the feedlot permit establishes conditions that reduce the likelihood of runoff, including a requirement to inject or immediately incorporate manure when there is a greater than 50 percent probability of 0.5 inches or more of rainfall within 24 hours after application (outside winter conditions), unless applied under an emergency. The inspection requirements—conducted daily during application, at completion, and within 24 hours after qualifying rainfall events within 14 days of application—are designed to identify any discharge at downgradient field edges, tile intakes,

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		ditches, or other conveyances. Required response and reporting of any observed discharge reduces the potential for unaddressed releases to contribute to cumulative effects in the watershed.
257	Commenter, MN DNR, has received and is reviewing a Dam Safety Permit application, 2026-0133, associated with the water storage ponds identified in item 9 of the EAW. This permit application was received on January 29, 2026.	Thank you for the comment.
258	Commenter notes that the impacts from the Project are to tributaries of the Mississippi River and thus contribute to the dead zone in the Gulf of Mexico.	The comment is out of scope for the EAW as it does not substantially inform the decision on the need for an EIS per the evaluation criteria in Minn. R. 4410.1700 subp. 7.
259	Commenter states, "I am concerned about the contaminants already in that river that, although they meet EPA guidelines, as was mentioned last night, those guidelines are out of date in regards to the current health concerns this river poses."	The comment is out of scope for the EAW as it does not substantially inform the decision on the need for an EIS per the evaluation criteria in Minn. R. 4410.1700 subp. 7.
260	Commenter states, "I am extremely concerned about the run off from the lot entering local water ways. We will need emergency plans in case of natural disasters should this gain approval."	The Project's Feedlot Permit application materials include an Emergency Response plan. If a spill or discharge occurs, the Permittee is responsible for containment and cleanup, as well as notifying the State Duty Officer.
261	Commenter states, "These rivers and waterways are crucial to the Midwest in being used to feed a nation."	The comment is out of scope for the EAW as it does not substantially inform the decision on the need for an EIS per the evaluation criteria in Minn. R. 4410.1700 subp. 7.
262	Commenter states, "It just takes a few flooding events per year to spread feces into waterways."	The comment is out of scope for the EAW as it does not substantially inform the decision on the need for an EIS per the evaluation criteria in Minn. R. 4410.1700 subp. 7.
263	Commenters want to know how long before they have to endure low quality waterways and lakes and have to install and	The comment is out of scope for the EAW as it does not substantially inform the decision on the need for an EIS per the evaluation criteria in Minn. R. 4410.1700 subp. 7.

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	operate a costly treatment system for their well."	
264	Commenters state that CAFOs degrade rivers and streams.	The comment is out of scope for the EAW as it does not substantially inform the decision on the need for an EIS per the evaluation criteria in Minn. R. 4410.1700 subp. 7.
265	Commenters are concerned about the impact the Project will have on recreation and tourism in the area - especially as it relates to lakes and streams in the area.	The comment is out of scope for the EAW as it does not substantially inform the decision on the need for an EIS per the evaluation criteria in Minn. R. 4410.1700 subp. 7.
266	Commenters note there are a number of listed impaired waters in the area including the Pomme de Terre River.	The Project Site and the Off-Site Well/APEC Well are within the Pomme de Terre River Watershed. There are no lakes, streams, wetlands, or intermittent streams at the Project site. There are no impaired waters within one mile of the Project site. All the manure application sites are also within the Pomme de Terre River Watershed. There are several lakes, wetlands, and streams adjacent to the manure application sites, with seven total identified as being on the current 303d impaired waters list. Several practices are required by the Feedlot Permit to prevent nutrient runoff that include application at agronomic rates to not exceed expected crop nitrogen needs, testing for soil phosphorus, application timing, planting cover crops, and setbacks from waterways. The Proposer will comply with manure application requirements set forth by the Feedlot Permit that are intended to protect waters of the state.
267	Commenter states, "I spent thirteen years living in Iowa prior to moving to Minnesota. Most of Iowa's animal agriculture operations are CAFOs, and regulation is minimal. As a result, most of Iowa's rivers and streams are aggressively polluted, many as a result of uncontained manure run-off. I do not want to see the same thing happen here."	The comment is out of scope for the EAW as it does not substantially inform the decision on the need for an EIS per the evaluation criteria in Minn. R. 4410.1700 subp. 7.
268	Commenter states, "I am extremely concerned about the runoff from the lot entering local water ways. We will need mitigation strategies detailed should this gain approval."	The Project will manage runoff in accordance with the Stormwater Pollution Prevention Plan (SWPPP) plan included with the Feedlot Permit application. The Feedlot Permit includes stormwater requirements for the treatment of construction stormwater when one or more acres of soil is disturbed and permanent treatment of stormwater when one acre or more of new impervious surface is created. The construction stormwater requirements will ensure that additional stormwater created by the Project will not degrade the water quality of the surrounding area. After construction is complete, the surface water runoff prior to any discharge from the Project will be controlled by

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		three permanent stormwater basins for volume control and have two water storage basins that will store stormwater and contingency groundwater at the Project site. Since all stormwater is contained on the Project, impacts to nearby lands are not expected. Best Management Practices (BMPs) include: (1) Stormwater will generally not come into contact with feed, animals, manure, or bedding. Any contaminated runoff will not leave the Project site and (2) the feed piles will be covered with impermeable plastic on an asphalt feed pad to minimize rainwater contact with the feed. Stormwater from the feed pad and solid manure storage areas will flow to Facility 106 (Feed Storage Pad) and be contained in a Liquid Manure Storage Area (LMSA) preventing it from entering local waterways.
269	Commenter states, "A report in EAW minimizes future low flow probability in Pomme de Terre River and is misleading and inconsistent with climate trends stated elsewhere."	The report referenced is one of many pieces of information included in the EAW, and all available information presented is evaluated to determine applicability to any decision. The DNR is re-evaluating the flow in the Pomme de Terre River as a part of their review of the water appropriation permit, and if a permit is authorized it is anticipated conditions would be included based on stream flow, including restrictions on appropriating water during the summer months. Additionally, DNR will evaluate the impacts of water appropriation on rare features in the Pomme de Terre River downstream of the appropriation site.
270	Commenter states, "Managing and land-applying hundreds of millions of gallons of manure each year presents meaningful risks to nearby waterways if storage systems fail."	Several practices are required by the Feedlot Permit to prevent nutrient runoff that include application at agronomic rates to not exceed expected crop nitrogen needs, testing for soil phosphorus, application timing, planting cover crops, and setbacks from waterways. The Proposer will comply with manure application requirements set forth by the Feedlot Permit that are intended to protect waters of the state. The Project will reduce contamination risk from manure application to groundwater quality by following proper land application practices. The Proposer will follow requirements of Minn. R. 7020 and the MMP in the Feedlot Permit for manure application. Once the Project is operational and manure is being generated and transferred to farmers, the manure recipients will be required to follow the Feedlot Permit rules for land application of manure that requires: “field receiving manure shall be sampled and tested in the upper six inches for soil phosphorus at least once every four years”. Where field phosphorous tests levels are above 21 ppm Bray 1 or 16 ppm and have surface water within 300 feet, the Feedlot Permit requires that manure recipients apply manure at a rate and frequency that phosphorous applied does not exceed phosphorous removal during a six-year period or that there be a vegetated buffer along lakes, streams, or other waterways.
271	Commenters note there is documented evidence of historical levels of flooding in the area where the Pomme de Terre and Chippewa rivers united.	The comment is out of scope for the EAW as it does not substantially inform the decision on the need for an EIS per the evaluation criteria in Minn. R. 4410.1700 subp. 7.

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272	Commenters are concerned about the impact from nutrient/manure runoff to nearby surface waters.	Please see responses to comment groups 252 and 274.
273	Commenter states, "Facilities of this magnitude in other states have literally displaced material human populations through their depletion of surface water bodies."	The comment is out of scope for the EAW as it does not substantially inform the decision on the need for an EIS per the evaluation criteria in Minn. R. 4410.1700 subp. 7.
274	Commenter states, "Managing and land-applying hundreds of millions of gallons of manure each year presents meaningful risks to nearby waterways if nutrients are over-applied."	Several practices are required by the Feedlot Permit to prevent nutrient runoff that include application at agronomic rates to not exceed expected crop nitrogen needs, testing for soil phosphorus, application timing, planting cover crops, and setbacks from waterways. The Proposer will comply with manure application requirements set forth by the Feedlot Permit that are intended to protect waters of the state. The Project will reduce contamination risk from manure application to groundwater quality by following proper land application practices. The Proposer will follow requirements of Minn. R. 7020 and the MMP in the Feedlot Permit for manure application. Once the Project is operational and manure is being generated and transferred to farmers, the manure recipients will be required to follow the Feedlot Permit rules for land application of manure that requires: “field receiving manure shall be sampled and tested in the upper six inches for soil phosphorus at least once every four years”. Where field phosphorous tests levels are above 21 ppm Bray 1 or 16 ppm and have surface water within 300 feet, the Feedlot Permit requires that manure recipients apply manure at a rate and frequency that phosphorous applied does not exceed phosphorous removal during a six-year period or that there be a vegetated buffer along lakes, streams, or other waterways.
275	Commenter states, "at least one problem is evident from the EAW materials that were made available. Riverview plans to install a drain tile system to “control seasonal subsurface saturation” near the 35.2 acres of liquid manure storage basins where Riverview proposes to store nearly 150 million gallons of additional liquid manure. This subsurface water will be diverted to one of the on-site storage basins and then released directly into the environment via a	To control potential seasonal subsurface saturation near the LMSAs, a drain-tile system will be installed around the perimeter of the LMSAs at an elevation below the LMSA liners as outlined in the Minnesota NPDES Individual Feedlot Permit (Feedlot Permit) application (Attachment 22). The clean seasonal subsurface water from the perimeter tile system will drain into a nearby stormwater basin, where it combines with Project stormwater. Clean stormwater does not encounter manure or feed storage areas. The Proposer will install an inspection port near the LMSAs to enable monthly visual inspections. After construction, the Proposer will ensure the drain-tile system is functioning correctly for each LMSA and look for signs of discoloration or odor that may indicate an issue with the liner. The clean

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	series of drainage ditches that ultimately flow to the Pomme de Terre River. "	seasonal subsurface water from the perimeter tile system will drain into a nearby stormwater basin, where it combines with Project stormwater.
276	Commenters are concerned about the impact the Project will have on the Pomme de Terre River.	Please see responses to comment groups 182, 251, and 266.
277	Commenters noted the Project is near the Pomme de Terre River and only 20-25 miles upstream from the confluence with the Minnesota River.	The comment is out of scope for the EAW as it does not substantially inform the decision on the need for an EIS per the evaluation criteria in Minn. R. 4410.1700 subp. 7.
278	Commenter states, "These rivers and waterways are crucial to the Midwest in being used to move goods."	The comment is out of scope for the EAW as it does not substantially inform the decision on the need for an EIS per the evaluation criteria in Minn. R. 4410.1700 subp. 7.
279	Commenter states, "These rivers and waterways are crucial to the Midwest in being used to provide jobs."	The comment is out of scope for the EAW as it does not substantially inform the decision on the need for an EIS per the evaluation criteria in Minn. R. 4410.1700 subp. 7.
280	Commenter states, "Surface water pollution: Runoff from feed storage areas increases the risk of phosphorus and nitrogen loading into nearby rivers, streams, and wetlands. This contributes to algal blooms, fish kills, and long-term ecosystem degradation."	The comment is out of scope for the EAW as it does not substantially inform the decision on the need for an EIS per the evaluation criteria in Minn. R. 4410.1700 subp. 7. For the Feedlot Permit, all runoff from feed storage is collected and land applied.
281	Commenter states, "Surface water pollution: Runoff from manure storage increases the risk of phosphorus and nitrogen loading into nearby rivers, streams, and wetlands. This contributes to algal blooms, fish kills, and long-term ecosystem degradation."	The only potential runoff from manure storage is from the stockpile of separated solids that will be land applied. The Project will direct runoff from the feed storage and solid manure storage areas to an LMSA for land application.
282	Comments are related to a fish kill that occurred in southeast Minnesota along Rush Creek.	The comment is out of scope for the EAW as it does not substantially inform the decision on the need for an EIS per the evaluation criteria in Minn. R. 4410.1700 subp. 7.

Comment Group	Comment	Response
283	Commenter is concerned that the Project is in a sandy area and that sandy soils are where surface waters can quickly reach the aquifer, similar to the karst region in southeast Minnesota.	Stevens County is not in a sandplains setting. In addition, karst topography is not known to exist within the vicinity of the Project or the manure application acres. The Project site geology consists of a layer of lean clay topsoil and fill soils underlain by various alluvial deposits with clay till present at depth. The surficial fill/topsoil layer organic lean clay, silty clay, sandy lean clay and lean clay. The main geologic deposit encountered at the Project site consisted of sandy lean clay, glacial till. From the soil borings and laboratory testing from the American Engineering Testing report, these sandy lean clay, fat clay, and lean clay soils are suitable for dike and liner construction of the proposed LMSA ponds. Please also see responses to comment groups 102, 149, and 182.
284	Commenter states, "What controls will you put on these open sewer lines to prevent it ending up in ground water or in the Mississippi River?"	Responding under the assumption that 'open sewer lines' is referring to the stormwater, then The Project will manage runoff in accordance with the Stormwater Pollution Prevention Plan (SWPPP) plan included with the Feedlot Permit application. Each stormwater basins are sized more than 20% larger than the minimum requirement. Since all stormwater is contained on the Project, impacts to nearby lands are not expected. Best Management Practices (BMPs) include: (1) Stormwater will generally not come into contact with feed, animals, manure, or bedding. Any contaminated runoff will not leave the Project site and (2) the feed piles will be covered with impermeable plastic on an asphalt feed pad to minimize rainwater contact with the feed. Stormwater from the feed pad and solid manure storage areas will flow to Facility 106 (Feed Storage Pad) and be contained in a Liquid Manure Storage Area (LMSA) preventing it from entering local waterways.
285	Commentors are concerned about spills from the site contaminating surface waters.	The comment is out of scope for the EAW as it does not substantially inform the decision on the need for an EIS per the evaluation criteria in Minn. R. 4410.1700 subp. 7.
286	Commenter states, "Rainwater run-off from roofs is another source of displaced water. With numerous huge buildings to house animals on that scale there will be ecosystem impacts from rainwater run-off."	The Proposer will install stormwater basins and modify the contour of the site to direct stormwater to stormwater basins. The Project will include physical landscape modifications, including removing topsoil and grading the site to meet the stormwater management plan.
287	Commenter is concerned why "clean" stormwater needs to be treated.	The process is similar to the required capture of precipitation in stormwater basins; however, instead of releasing the captured water, stormwater is used to offset the water pumped for cow consumption. This storm water is being collected to be used as a backup water supply, which is why it needs to be treated.
288	Commenter states, "Of note, Commenters are limited in their ability to assess impacts that would result from Riverview's stormwater management because the facility's Stormwater Pollution Prevention	The Proposer's application materials included a SWPPP for the project. The Permit public notice for the Project indicates; "A draft permit is available for review on the MPCA Public Notices webpage at https://www.pca.state.mn.us/get-engaged/public-comments. Additional materials relating to the issuance of this permit are available for inspection by appointment at any MPCA office

Comment Group	Comment	Response
	Plan was not included in materials made available for public comment."	(https://www.pca.state.mn.us/about-mpca/contact-us) between the hours of 8:00 a.m. and 4:30 p.m., Monday through Friday. The MPCA will mail or email a copy of the draft permit upon request."
289	Commenters are concerned the Project is a major threat to surface waters.	The comment is out of scope for the EAW as it does not substantially inform the decision on the need for an EIS per the evaluation criteria in Minn. R. 4410.1700 subp. 7.
290	Commenters are concerned the Project is a major threat to the local watershed.	The comment is out of scope for the EAW as it does not substantially inform the decision on the need for an EIS per the evaluation criteria in Minn. R. 4410.1700 subp. 7.
291	Commenter states the Project is on sensitive ground due to the presence of wetlands to the south of the site.	The Project site is designed to capture and reuse most or all of stormwater runoff, largely eliminating the untreated runoff that currently leaves the property.
292	Commenters state some of the land is tiled and request that the MPCA do an analysis of the tile lines.	The comment is out of scope for the EAW as it does not substantially inform the decision on the need for an EIS per the evaluation criteria in Minn. R. 4410.1700 subp. 7.
293	Commenter states, "Compliance with TMDL goals for areas surface waters are not acknowledged" in the EAW.	A Total Maximum Daily Load (TMDL) study identifies pollutants causing impairment and how much of those pollutants can enter the waterbody while still meeting water quality standards. Several practices are required by the Feedlot Permit to prevent nutrient runoff that include application at agronomic rates to not exceed expected crop nitrogen needs, testing for soil phosphorus, application timing, planting cover crops, and setbacks from waterways. The Proposer will comply with manure application requirements set forth by the Feedlot Permit that are intended to protect waters of the state.
294	Commenters are concerned the Project will make lakes and streams swimmable and unfishable due to blue-green (toxic) algae blooms.	Nutrient overloads have been known to cause harmful algal blooms to surface waters. Manure will be applied at agronomic rates, supplying only the nitrogen (N) needed by the crop to be grown. The Proposer will use the MPCA's Nutrient Management tool to calculate the amount of nitrogen that can be safely applied to each of their application fields. This tool considers manure N levels, the type of crop to be grown, and previous manure application (residual N levels) to indicate how many gallons per acre may be applied. The Proposer will also follow the state or county setbacks from ditches, lakes, tile intakes, and wells, to prevent nutrient runoff into those features. To prevent surface water contamination and control potential seasonal subsurface saturation near the Liquid Manure Storage Areas (LMSAs), a drain-tile system will be installed around the perimeter of the LMSAs at an elevation below the LMSA liners. The clean seasonal subsurface water from the perimeter tile system will drain into a nearby stormwater basin, where it combines with Project stormwater. The proposed Project will include the retention, filtering, treatment and/or reuse of surface water runoff that would otherwise be directed downstream by existing drainage. Please also see response for comment group 268, and 330.

Comment Group	Comment	Response
295	Commenters make general statements about putting a high value on Minnesota's lakes and streams.	The Project will manage runoff in accordance with the Stormwater Pollution Prevention Plan (SWPPP) plan included with the Feedlot Permit application. Each stormwater basin is sized more than 20% larger than the minimum requirement. Since all stormwater is contained on the Project, impacts to nearby lands are not expected. Best Management Practices (BMPs) include: (1) Stormwater will generally not come into contact with feed, animals, manure, or bedding. Any contaminated runoff will not leave the Project site and (2) the feed piles will be covered with impermeable plastic on an asphalt feed pad to minimize rainwater contact with the feed. Stormwater from the feed pad and solid manure storage areas will flow to Facility 106 (Feed Storage Pad) and be contained in a Liquid Manure Storage Area (LMSA) preventing it from entering local waterways.
296	Commenter states, "What we know about wetlands is that they are a complex network of capillaries and underground water pathways that goes significantly beyond what we can see above ground."	The comment is out of scope for the EAW as it does not substantially inform the decision on the need for an EIS per the evaluation criteria in Minn. R. 4410.1700 subp. 7.
297	Commenter states, "Water quality for the whole state is currently being reviewed and new guidelines potentially coming forward. It would be wise to wait or at least look at the proposed new guidelines BEFORE granting a permit of this magnitude."	The comment is out of scope for the EAW as it does not substantially inform the decision on the need for an EIS per the evaluation criteria in Minn. R. 4410.1700 subp. 7.
298	Commenter states, "The Diocese of New Ulm is a fifteen county area. The Minnesota River runs diagonally through the area. How will the Riverview proposal affect the watershed feeding the Minnesota River?"	The comment is out of scope for the EAW as it does not substantially inform the decision on the need for an EIS per the evaluation criteria in Minn. R. 4410.1700 subp. 7.
299	Commenter states, "The Minnesota Pollution Control Agency estimates that 56 percent of surface waters do not meet basic water quality standards."	The comment is out of scope for the EAW as it does not substantially inform the decision on the need for an EIS per the evaluation criteria in Minn. R. 4410.1700 subp. 7.
300	Commenters ask who will pay the increasing costs of road repairs?	The comment is out of scope for the EAW as it does not substantially inform the decision on the need for an EIS per the evaluation criteria in Minn. R. 4410.1700 subp. 7.
301	Commenter requests, "Please do right by the civic infrastructure like roads."	The comment is out of scope for the EAW as it does not substantially inform the decision on the need for an EIS per the evaluation criteria in Minn. R. 4410.1700 subp. 7.

Comment Group	Comment	Response
302	Commenter states, "Traffic and road maintenance and the impact on transportation adjacent water ways with increased emissions from trucking."	Minnesota Department of Transportation data indicates that Annual Average Daily Traffic (AADT) near the Project on Stevens County Road 8 is 520 vehicles. The Project would increase current traffic counts by an estimated total of 45 vehicles per day. Therefore, the traffic on Stevens County Road 8 would increase by up to 8.7%, and the potential for traffic congestion is considered low. No improvements to County Road 8 are considered necessary to accommodate this increase in traffic. Vehicle emissions from construction equipment (1,915 tons/year) and additional Ag equipment (1,626 tons/year) have been accounted for within the EAW in attachment 21.
303	Commenter states, "Will local farmers haul more grain to the dairy, so ethanol plants will have to buy corn from farther away, increasing the need to repair roads in the region?"	The comment is out of scope for the EAW as it does not substantially inform the decision on the need for an EIS per the evaluation criteria in Minn. R. 4410.1700 subp. 7.
304	Commenters state the Project will increase traffic.	Minnesota Department of Transportation data indicates that Annual Average Daily Traffic (AADT) near the Project on Stevens County Road 8 is 520 vehicles. The Project would increase current traffic counts by an estimated total of 45 vehicles per day. Therefore, the traffic on Stevens County Road 8 would increase by up to 8.7%, and the potential for traffic congestion is considered low. No improvements to County Road 8 are considered necessary to accommodate this increase in traffic.
305	Commenter states, "It appears that very little of the existing infrastructure will be used to support this proposed project."	There will be no modifications to existing equipment or industrial processes. There will be no significant demolition, removal, or remodeling of the adjacent Existing Facility. There are no existing structures within the Project site. The construction of the Project will take place on undeveloped land and will include a barn, holding pen, parlor, feed storage pad, manure storage, loading areas, and water supply.
306	Commenters are concerned with damage to roads due to manure hauling.	Manure applications will be performed using drag hoses, which minimize road traffic from manure application equipment. The Proposer will develop and utilize an underground manure transfer line. The underground manure line system transports manure from the dairy to a field, typically in the middle of the field. This results in less impact on local infrastructure and a minimized risk of manure spills from overland transport.
307	Commenter states, "The above only touches on the water impacts, there is also road/traffic impacts that need to truly be evaluated."	Minnesota Department of Transportation data indicates that Annual Average Daily Traffic (AADT) near the Project on Stevens County Road 8 is 520 vehicles. The Project would increase current traffic counts by an estimated total of 45 vehicles per day. Therefore, the traffic on Stevens County Road 8 would increase by up to 8.7%, and the potential for traffic congestion is considered low. No improvements to County Road 8 are considered necessary to accommodate this increase in traffic.
308	Commenters stated that truck traffic increased the damage to the roads.	The Project will generate approximately 58 semi loads of milk per week to a cheese processing plant. Suppliers will deliver an average of 21 loads of feed to the Project each week. The Project will operate

Comment Group	Comment	Response
		seven days a week. Most heavy trucks will exit the Project site via 520th Avenue and turn north onto Stevens County Road 8. The Proposer will complete road improvements on 520th Avenue between County Road 8 and the Project location to accommodate increased heavy-traffic use and any damage caused by this. Please also see response to comment group 306.
309	Commenter states, "Traffic and road maintenance and the impact on transportation adjacent water ways with increased salt/sand.."	The comment is out of scope for the EAW as it does not substantially inform the decision on the need for an EIS per the evaluation criteria in Minn. R. 4410.1700 subp. 7.
310	Commenters state that the animal feedlots generate 5 tons of manure per for every man, woman, and child in the U.S.	The comment is out of scope for the EAW as it does not substantially inform the decision on the need for an EIS per the evaluation criteria in Minn. R. 4410.1700 subp. 7.
311	Commenters note the EAW says it takes 13,200 acres of cropland per year for land application of the manure	Local producers have identified and offered 16,669 acres of currently tilled cropland for manure application. With the expansion Project, West River Dairy expects to utilize approximately 13,200 acres per year. Manure can be used to replace or supplement commercial fertilizer. The Proposer will begin manure application following corn silage harvest starting around September 1 every year.
312	Commenter claims a 20,000-cow dairy will require 30 square miles of land to absorb their manure.	The Proposer established an ERA which includes sufficient manure acres for the Project and the Existing Facility and has over 3,000 additional acres extra to account for possible unknowns with manure production and application. These designated manure acres are not only established in this EAW, but they will also be reported in the Nutrient Management Plan that is submitted to the MPCA. The individual NPDES permit and associated Nutrient Management Plan.
313	Commenter states, "The EAW fails to adequately evaluate whether the surrounding cropland can consistently and safely absorb the Expansion Project's manure supply."	As required by the MPCA, the Proposer will sample soil from manure application fields every 4 years to monitor phosphorus (P) levels, using the Olsen or Bray P1 analysis. The Proposer will also use the Manure Management Plan (MMP) resources to prevent long-term soil P build-up. The steps in the MMP are to: determine crop P uptake, determine manure P level, determine the amount of P applied from commercial fertilizer, and compare the amount of P applied and removed. The Proposer can adjust the amount of manure applied or commercial fertilizer applied or adjust the crop rotation to prevent long term phosphorus build-up. The Project is required to comply with Minn. R. ch. 7020 and applicable Feedlot Permit conditions governing nutrient (manure) application, which address manure in combination with other nitrogen sources, including commercial fertilizer, residual manure from prior years, irrigation water, and nitrogen from legumes. The Project's nutrient management plan helps establish agronomic application rates by ensuring that estimated plant-available nitrogen does not exceed crop nitrogen demand for non-legume crops or nitrogen removal for legume crops. This provides a crop-based framework for matching manure application rates to intended crops and reducing excess nutrient application.

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		To further support appropriate nutrient management and limit nitrate leaching potential, the permit requires implementation of nitrogen best management practices based on timing and field conditions. These include applying manure to actively growing crops where appropriate, using cover crops, applying nitrogen stabilizers such as nitrapyrin, delaying application until soil temperatures are at or below 50 degrees for two consecutive days, incorporating crop rotations that include perennial crops for two years within a five-year period, and using reduced-rate split nitrogen applications. In addition, land application activities are subject to discharge prevention and monitoring requirements. Except where the federal agricultural stormwater exemption applies, the NPDES permit does not allow discharge from land application. When manure is applied during non-winter conditions, it must be injected or immediately incorporated if a greater than 50 percent probability of at least 0.5 inches of rainfall is forecast within 24 hours after application (unless under emergency conditions). Fields receiving manure must also be visually inspected at downgradient field edges and other potential discharge points, including tile intakes, ditches, and sensitive features, with inspections conducted daily during application, at completion, and following qualifying rainfall events within 14 days. Any observed discharge must be addressed and reported under permit requirements.
314	Commenter states, "these feedlots are not the only users of these resources. Area farms not associated with West River also apply either manure or fertilizer to virtually every field that is farmed in the area."	The comment is out of scope for the EAW as it does not substantially inform the decision on the need for an EIS per the evaluation criteria in Minn. R. 4410.1700 subp. 7.
315	Commenter states, "These feedlots are not the only users of these resources. Area farms not associated with West River also apply either manure or fertilizer to virtually every field that is farmed in the area."	The comment is out of scope for the EAW as it does not substantially inform the decision on the need for an EIS per the evaluation criteria in Minn. R. 4410.1700 subp. 7.
316	Commenter states, "Although a good argument is made for decreased use of chemical fertilizers by spreading manure, it seems that the impact of increased ammonia into the air and ground have been overlooked."	The modeling results suggest that the proposed West River Dairy expansion will not create ammonia concentrations at its property lines that exceed the acute ammonia iHRV. AERMOD calculated a maximum hourly property-line ammonia concentration of 1,861 µg/m3. When a background concentration of 148 µg/m3 is added to the AERMOD-calculated concentration, the maximum property-line ammonia concentration is 2,009 µg/m3, which is below the acute ammonia iHRV of 3,200 µg/m3. Thus, no exceedance of the acute ammonia iHRV was modeled at the property lines for the expanded dairy. The AERMOD results indicate that the expanded dairy will not create ammonia concentrations at the neighboring residences that exceed the chronic ammonia iHRV. The calculated maximum one-year time average ammonia concentration for the neighbors is 9.39 µg/m3. When a

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		background ammonia concentration of 5.72 µg/m3 is added to the AERMOD concentration, the maximum annual ammonia concentration for a neighboring residence is 15.11 µg/m3, which is below the chronic ammonia iHRV of 80 µg/m3. Thus, the AERMOD modeling results for the proposed West River Dairy expansion suggest compliance with the hydrogen sulfide air quality standard, no exceedances of the subchronic hydrogen sulfide iHRV, no exceedances of the acute ammonia iHRV, and no exceedances of chronic ammonia iHRV. See EAW item 17.A.2. Land application of manure provides farmers with a nearby source of organic fertilizer that would otherwise require chemical or synthetic fertilizers, such as ammonia. Having this nearby source of fertilizer in the form of manure from the Project reduces GHG emissions associated with synthetic fertilizer production. The manure generated by the Project will replace approximately 1,545 tons per year of anhydrous ammonia. The regional overall GHG emission factor for ammonia production by the Haber-Bosch process is about 5.85-ton CO_2/ton NH_3. Thus, the use of manure generated by the Project as fertilizer will reduce GHG emissions by an estimated 9,038 tons of CO_2/year, because the corresponding mass of anhydrous ammonia is no longer produced.
317	Commenter states, "Huge animal confinement systems in the USA use and misuse antibiotics on a huge scale, three to six times more than European farmers."	The comment is out of scope for the EAW as it does not substantially inform the decision on the need for an EIS per the evaluation criteria in Minn. R. 4410.1700 subp. 7.
318	Commenter states, "Although a good argument is made for decreased use of chemical fertilizers by spreading manure, it seems that the impact of increased release of anti-pathogenic chemicals (antibiotics, hormones, etc.) into the air and ground have been overlooked."	According to the University of Wisconsin Extension (Fall 2011) Publication, Assessing the Potential Effects of Hormones in Livestock Manure, hormones were found to be rapidy degraded in stormwater runoff, which suggests minimal impact on aquatic organisms, and efforts that prevent manure from entering waterways will likely prevent hormones from entering surface waters. “
319	Commenter states, "Anti-Degradation and Downstream Impacts: As the Minnesota River system is already impaired in many reaches, additional upstream nutrient loading may contribute to downstream degradation. *MPCA should evaluate this project under anti-degradation standards, ensuring it does not contribute to further impairment."	Antidegradation is in Minn. R. Ch. 7050 and applied to point source discharges and new discharge locations in surface waters. There are no point source discharges with the Project.

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320	Commenter would like to know the proven life expectancy of manure storage basin like those proposed at West River Dairy?	NPDES feedlot permits don't define a numerical life expectancy for manure basins, but they do require that basins be designed, maintained, and operated to remain compliant and functional until they are no longer suitable for use, at which point they must be closed and replaced. The Liquid Manure Storage Area liners are permitted and regulated under the individual NPDES feedlot permit associated with this facility. A monthly examination of the monitoring port or drain tile outlet for water flow and signs of discoloration or odor in any water flowing in the drain tile. A weekly visual inspection of the LMSA and any devices channeling manure-contaminated runoff to the LMSA to assess conformance to the approved plans and Permit. Note that LMSA operations and maintenance is required. Also, there will be no agitation needed due to separated solids increasing the longevity of liner integrity.
321	Commenters state, "Alleged best management practices of large confinement systems fail, not just in Minnesota but around the USA."	The comment is out of scope for the EAW as it does not substantially inform the decision on the need for an EIS per the evaluation criteria in Minn. R. 4410.1700 subp. 7.
322	Commenters state, "Given that the manure from the cows will be used as fertilizer on fields that will supply alfalfa for the cows, what are the long-term consequences of this closed-circuit consumption? ."	The comment is out of scope for the EAW as it does not substantially inform the decision on the need for an EIS per the evaluation criteria in Minn. R. 4410.1700 subp. 7.
323	Commenters state, "The nutrient load from manure on the lands surrounding the facility will likely be disproportionate, with closer locations receiving more inputs than locations farther away, as a function of transport cost and equipment abilities."	The Project is required to follow Minn. R. ch. 7020 and Feedlot Permit requirements relating to application of nutrients (manure) generated from the Project in combination with other nutrient sources. Potential sources of N include: commercial fertilizer, manure applied during the current crop year, manure applied during the previous crop year, irrigation water, and legumes grown during previous years. The Project's nutrient management plan describes how manure in combination with other nutrient sources will be applied at agronomic rates. N rates must be limited so that the estimated plant-available nitrogen (N) from all N sources does not exceed the expected crop N needs for non-legume crops or the expected N removal for legume crops. To further minimize the potential for nitrate leaching into the groundwater, the Feedlot Permit requires the Project implement N BMPs based on the timing of manure application and field location. Potential BMPs requirements include: application to actively growing crops, planting cover crops, use of a nitrapyrin-based nitrogen stabilizing product, delaying application until soil temperature as reached 50 degrees or less for two consecutive days, crop rotations that include growing perennial crops 2 years during any 5-year period and reduced rate split N applications.

Comment Group	Comment	Response
		Minn. R. ch. 7020 and Feedlot Permit requirements relating to application of nutrients (manure) generated from the Project in combination with other nutrient sources. Potential sources of N include: commercial fertilizer, manure. When manure from the project is transferred the manure recipient must comply with the manure management plan completed by the owner of the animal feedlot where the manure or process wastewater was produced and complete the manure management plan.
324	Commenters states, "AS alarming as water use is, even worse is a request to apply over 200 million gallons of manure on coarse textured ground."	The Project's application materials included Nutrient Management Plan (NMP). The plan identifies sensitive areas, including coarse textured soils, within or adjacent to land where manure application is planned. The Project's NMP identified 5,240 acres for land application of manure. Of the 5,240 acres approximately one (1) is identified as course textured soil. The NMP also indicates that manure from the Project will be transferred to other landowners. Prior to transferring manure, the permit requires the Permittee to provide manure recipients with a sensitive features map for each field where the transferred manure will be applied. The sensitive features map shall be developed using MPCA's online NMT service or MPCA's Interactive Nutrient Management Planning Map.
325	Commenters believe West River Dairy should compost their manure but notes that doesn't fit within their expansion model.	The comment is out of scope for the EAW as it does not substantially inform the decision on the need for an EIS per the evaluation criteria in Minn. R. 4410.1700 subp. 7.
326	Commenters believe that this is too much manure concentrated in one area.	Manure will be applied at agronomic rates, supplying only the nitrogen (N) needed by the crop to be grown. The Proposer will use the MPCA's Nutrient Management tool to calculate the amount of nitrogen that can be safely applied to each of their application fields. This tool considers manure N levels, the type of crop to be grown, and previous manure application (residual N levels) to indicate how many gallons per acre may be applied. The Proposer will also follow the state or county setbacks from ditches, lakes, tile intakes, and wells, to prevent nutrient runoff into those features. Several practices are required by the Feedlot Permit to prevent nutrient runoff that include application at agronomic rates to not exceed expected crop nitrogen needs, testing for soil phosphorus, application timing, planting cover crops, and setbacks from waterways. The Proposer will comply with manure application requirements set forth by the Feedlot Permit that are intended to protect waters of the state. Liquid Manure Storage Areas (LMSA) and Dry Manure Storage are the locations where manure is stored on the feedlot facility site. The individual NPDES feedlot Permit and manure management plan incorporates manure storage, transfer, and land application requirements that exceed those in the NPDES General Feedlot Permit, including 5 feet of compacted clay liner of LMSAs, synthetic covers and installation of a perimeter drain-tile system will

Comment Group	Comment	Response
		be at an elevation below the liner of each of the three LMSAs to control seasonal sub-surface saturation, and operation and monitoring and reporting requirements pertaining to freeboard of the LMSA. Manure from cattle in the free-stall barn will be collected twice daily using a self-propelled vacuum wagon. Solid manure will be stored on a concrete pad. Solid and liquid manure transferred to area farmers for use as fertilizer will be applied in accordance with Feedlot Permit requirements. The Proposer will install stormwater basins and modify the contour of the site to direct stormwater to stormwater basins.
327	Commenters state, "I was surprised to learn that it is raising the feed that often causes more of a nitrogen problem. Corn, a major feed component of dairy cows, is a monoculture crop. When nitrogen is applied, its easily overapplied."	The Project is required to follow Minn. R. Ch. 7020 and Feedlot Permit requirements relating to application of nutrients (manure) generated from the Project in combination with other nutrient sources. Potential sources of N include commercial fertilizer, manure applied during the current crop year, manure applied during the previous crop year, irrigation water, and legumes grown during previous years. The Project's nutrient management plan describes how manure in combination with other nutrient sources will be applied at agronomic rates. N rates must be limited so that the estimated plant-available nitrogen (N) from all N sources does not exceed the expected crop N needs for non-legume crops or the expected N removal for legume crops. To further minimize the potential for nitrate leaching into the groundwater, the Feedlot Permit requires the Project implement N BMPs based on the timing of manure application and field location. Potential BMPs requirements include application to actively growing crops, planting cover crops, use of a nitrapyrin-based nitrogen stabilizing product, delaying application until soil temperature as reached 50 degrees or less for two consecutive days, crop rotations that include growing perennial crops 2 years during any 5-year period and reduced rate split N applications.
328	Commenters state, "the EAW does not provide a field-by-field nutrient balance, distance-weighted transport analysis, or average and maximum manure movement distances. "	Manure will be applied at agronomic rates, supplying only the nitrogen (N) needed by the crop to be grown. The Proposer will use the MPCA's Nutrient Management tool to calculate the amount of nitrogen that can be safely applied to each of their application fields. The Proposer will also follow the state or county setbacks from ditches, lakes, tile intakes, and wells, to prevent nutrient runoff into those features. Field application information can be found in the Manure Management Plan (attachment 23).
329	Commenters ask, "Can they disperse it [manure] beyond the county? "	Manure will be applied according to the individual NPDES feedlot permit and manure management plan for the facility. This includes application of manure on available 13,200 acres (Project and existing facility). All permitted manure application sites are within Stevens County.
330	Commenters state, "Crop land used for manure spreading may need containment to avoid runoff reaching surface waters. "	Manure will be applied according to the individual NPDES feedlot permit and manure management plan for the facility. This includes application of manure on available 13,200 acres (Project and existing facility) All permitted manure application sites are within Stevens County.

Comment Group	Comment	Response
331	Commenters state that the EAW does not adequately address the cumulative impacts of manure application from all of the feedlots in the watershed.	Cumulative potential effects are summarized in section 21 of the draft EAW and are generally related to overlapping manure application and excess water usage within the same Environmentally Relevant Area (ERA) by other similar projects. The Proposer established an ERA which includes sufficient manure acres for the Project and the Existing Facility and has over 3,000 additional acres extra to account for possible unknowns with manure production and application. These designated manure acres are not only established in this EAW, but they will also be reported in the Nutrient Management Plan that is submitted to the MPCA. The individual NPDES permit and associated Nutrient Management Plan.
332	Commenters ask, "Who will supervise all that data?"	The MPCA requires Feedlot Permit holders sample manure yearly. This sample must be representative and follow the University of Minnesota Extension Service recommendations and be analyzed at a Minnesota Department of Agriculture certified lab. The Proposer will take representative samples each year and send them to a local laboratory and make these results available to all manure recipients.
333	Commenters state, "Those of you reading this and making the decision to allow the equivalent feces of about 250,000 people just upriver of where we live along the southern Pomme de terre river do NOT live there, nor do your children and grandchildren. "	The comment is out of scope for the EAW as it does not substantially inform the decision on the need for an EIS per the evaluation criteria in Minn. R. 4410.1700 subp. 7.
334	Commenters state, "Riverview's expansion would more than double its liquid manure storage capacity in Morris, from 102 million gallons to 250 million gallons."	Expanding liquid manure storage capacity is a necessary and appropriate response to the growing head count.
335	Commenters ask what will happen when adverse conditions require emergency situations caused by weather events.	Manure storage capacity has been designed with a 14-month capacity. This is greater than the minimum required storage capacity of nine months to prevent the potential for an emergency winter application situation. This additional contingency storage allows operational flexibility to apply in the spring and summer months and avoid winter application if fall weather conditions are not conducive to applying all manure before winter. However, if an emergency winter application was necessary, the Proposer would not apply manure to any fields with slopes greater than 6%. Fields with this condition make up a small portion of the total acres dedicated to the Project. The Proposer has a contract with Environmental Scientific as a contingency plan. Environmental Scientific will promptly notify the Minnesota State Duty Officer and work with the appropriate agencies to mitigate any contamination, hazardous materials, or waste.

Comment Group	Comment	Response
336	Commenter is concerned about the noxious gases produced in the storage pits.	The comment is out of scope for the EAW as it does not substantially inform the decision on the need for an EIS per the evaluation criteria in Minn. R. 4410.1700 subp. 7.
337	Commenters state, "There is also concern about how the guidelines for manure spreading are enforced when it is being done by outside partners on fields that are not controlled by the permit seeker."	Minn. R. Ch. 7020 and Feedlot Permit requirements include requirements relating to manure application in general and the transfer of manure. Minn. R. Ch 7020 requires that manure is applied in a manner that does not result in discharge to waters of the state during the application process or cause pollution of waters of the state due to manure contaminated runoff. When manure from the Project is transferred the manure recipient must comply with the Project's nutrient management plan (NMP). While Permittees do not control the ultimate actions of manure recipients, Permittees are required to include in their NMP protective measures a recipient must follow to ensure manure is applied in a proper manner. In this context Permittees do have responsibility for manure they transfer. The MPCA is the regulatory authority for the Project and manure applications relating to the project. The Minnesota Department of Agriculture provides oversight and requires training and licensing for Commercial Animal Waste applicators.
338	Commenters state, "Excessive concentrated gastly waste managment can not creep into Minnesota."	The comment is out of scope for the EAW as it does not substantially inform the decision on the need for an EIS per the evaluation criteria in Minn. R. 4410.1700 subp. 7.
339	Commenters state, "Manure Storage Risk and Extreme Weather: While the proposal includes lined manure storage basins, extreme precipitation events are increasing in frequency and intensity. Overflow or application during saturated conditions could result in significant nutrient releases. * I request evaluation of climate-adjusted storage capacity and land application timing safeguards."	The Liquid Manure Storage Area (LSMA) liners are permitted and regulated under the individual NPDES Feedlot Permit associated with this facility. A monthly examination of the monitoring port or drain tile outlet for water flow and signs of discoloration or odor in any water flowing in the drain tile. A weekly visual inspection of the LMSA and any devices channeling manure-contaminated runoff to the LMSA to assess conformance to the approved plans and this Permit. The permittee will also operate the LMSA to maintain freeboard and install visual markers to inspect freeboard of the LMSA. The LMSA will have three feet of freeboard, greater than one-to-two-foot standard, along with covers, both will prevent overflows. The available acres that could receive manure may or may not be available in any given year based on many factors, including, but not limited to, the desire by both parties involved to apply manure, crop rotation, and weather. There are time and weather-dependent BMPs and permit conditions that must be adhered to. These include, among other things, cover crops, nitrogen inhibitors, and adequate soil temperatures.
340	Commenters state, "The manure is applied largely in the fall when it has the greatest potential to leach nitrates into surrounding wells and waterways before it can be utilized by crops 6 months later in the summer."	The Proposer will begin manure application following corn silage harvest starting around September 1 every year. The Commercial Animal Waste Technician (CAWT) will land apply manure 24 hours a day, 6 days a week for approximately 30 days each year. Due to factors such as rain events or waiting on fields to become available for application, the CAWT may need to spread out the manure application over several weeks. No manure will be applied on Sundays. Manure will be applied at agronomic rates, supplying only the nitrogen (N) needed by the crop to be grown. The Proposer will

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		use the MPCA's Nutrient Management tool to calculate the amount of nitrogen that can be safely applied to each of their application fields. This tool considers manure N levels, the type of crop to be grown, and previous manure application (residual N levels) to indicate how many gallons per acre may be applied. The Proposer will also follow the state or county setbacks from ditches, lakes, tile intakes, and wells, to prevent nutrient runoff into those features.
341	Commenters state, "If 3,000 acres of prospective manure application fields have known drainage issues that will not be identified and remedied until after some future rain events this should be a red flag."	The nutrient management plan for the Project identifies sensitive features within or near land application areas where manure application is planned. Additionally, prior to transferring manure to a manure recipient, the feedlot Permit requires the permittee to provide manure recipients with a sensitive features map for each field where the transferred manure will be applied. The sensitive features map shall be developed using MPCA's online NMT service or MPCA's Interactive Nutrient Management Planning Map. Additionally, Minn. R. Ch. 7020 and the permit require that manure is not applied in a manner that exceeds the hydraulic loading capacity of the land application site based on soil conditions.
342	Commenters state, "The Feedlot Rules Plainly Require Feedlot Applicants To Describe Methods And Practices For Minimizing GHG Emissions An applicant for a feedlot or manure storage area capable of holding 1,000 animal units or more must submit an Air Emission Plan. That Plan must include "methods and practices that will be used to minimize air emissions resulting from animal feedlot or manure storage area operations including manure storage area start-up practices, loading, and manure removal.""	Currently, there are no federal or Minnesota thresholds of Greenhouse Gas significance for determining the impacts of Greenhouse Gas emissions from an individual project on global climate change. The air emission plan is recorded in the facilities permit application and copy of record that satisfies the requirements of Minn. Rule 7020.0505 subp. 4.B (1). Item 18.B.1 of the EAW includes several methods for minimizing or mitigating GHG emissions.
343	Commenters state, "Riverview has done everything in the past to apply the manure in a safe and responsible manner. If there was a issue, it was taken care of. Manure is not so much a waste product but a commodity, it is beneficial to the fields it is applied to and the farmers using it."	Thank you for your comment.

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344	Commenters state, "The EAW does not consider how leaks from the hoses it uses to pump waste to these fields could impact water quality, nor are there monitoring requirements to ensure any such leaks are discovered and stopped in a timely manner."	The Proposer will keep written documentation for the operation, maintenance and inspection of the Manure Storage Basin Area and related components as required by the Feedlot Permit. Corrective measures taken will be documented. Parcels receiving manure will be monitored and inspected by the operator of manure application to maintain proper operation of all distribution equipment. In the event of an unplanned discharge, the Proposer will take necessary corrective action promptly. Corrective actions will be documented and made available for inspection by the MPCA if requested. All records will be kept by the Proposer for five years. Any discharge will be reported to the MPCA as required by the Feedlot Permit. To apply manure at the correct agronomic rates, the CAWT will use pressure gauges and flow meters on each applicator. A monitor in the tractor cab displays the rate of manure application (flow), the pressure of the hose (pressure), and the revolutions per minute (RPM) of each engine pumping manure. If any malfunction were to occur such as a hose break, the monitor in the tractor cab immediately detects change in flow, pressure, and RPM. The CAWT can shut down the entire system, closing shutdown valves at the main pump and subsequent booster pumps. Additionally, each pump has an automatic shutoff mechanism should hose pressure exceed or fall below predetermined operating levels.
345	Commenters ask, "How can it be possible to spread these millions of gallons of manure in a timely fashion?"	The Proposer will install three basin containment systems to store liquid manure, covering 35.2 acres. The Liquid Manure Storage Area (LMSA) will have a capacity that will exceed the nine-month minimum requirements by providing 14 months of liquid manure capacity. The Proposer expects to store liquid manure for approximately 21 months each year until it is land applied. The Proposer executes manure application by a dragline hose system. Per the Manure Management Plan, the amount manure is defined under Manure Source Summary, and the fields receiving manure are shown in the Field Map Summary. Specific details including application rate, application method, and planned manure application timing are also included in the Manure Management Plan.
346	Commenters ask how and where all the manure will be disposed?	Liquid and solid manure will be collected, stored, processed, and land applied as fertilizer on cropland according to the associated NPDES permit and Nutrient Management Plan. Local producers have identified and offered 16,669 acres of currently tilled cropland for manure application. The Proposer expects to utilize approximately 13,200 acres per year. The manure application sites are within: Stevens County (Baker, Darnen, Horton, Synnes, and Scott Townships) and Swift County (Hegbert and Fairfield Townships) as shown in EAW Attachment 5 and Attachment 8. The manure application sites are currently cultivated for crop production, and landowners may have used the fields for manure application in the past. The Proposer will develop and utilize an underground manure transfer line. The underground manure line system transports manure from the dairy to a field, typically in the middle of the field. The Proposer then executes manure application by a dragline hose system. The

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		Proposer pumps manure from the Project through a series of hoses overland to reach application fields. This system provides flexibility in the number of available routes to reach manure application fields. It also greatly reduces the impact of manure application equipment on local road infrastructure. The Commercial Animal Waste Technician (CAWT) may land apply manure in the fall, spring, or summer if there is an existing crop on the applicable site. The CAWT will inject the manure directly into the soil when cover crop is not present. The CAWT must follow County ordinances and setbacks for manure applications at each manure application site. The CAWT must also adhere to applicable manure application setbacks as outlined in Item 12.B.5 of the EAW. The Feedlot Permit requires operations and maintenance of manure transport equipment to prevent leaks and breaks and requires immediate notification and response should equipment failure occur.
347	Commenter states, "Although a good argument is made for decreased use of chemical fertilizers by spreading manure, it seems that the impact of increased hydrogen sulfide into the air and ground have been overlooked."	Hydrogen sulfide (H_2S) and ammonia are odorous gases. These types of emissions are common on dairy farms. The Proposer contracted with Barr Engineering to conduct air dispersion modeling to predict how the Project's air emissions of hydrogen sulfide, ammonia, and odors would impact air quality at the Project's property lines and at the nearest residences. The modeling found that the Project will not create exceedances of the Minnesota Ambient Air Quality Standard or Sub-chronic Inhalation Health Risk Value (iHRV) for Hydrogen Sulfide. The highest concentration found at the property lines of the nearby residences was 12.44 ppb and which is below MN air quality ambient standard of 30 ppb; 17 ppb background is primarily representative of H_2S emissions that result from land application of manure along with other sources such as wetlands. The modeling confirmed that the Project would have no negative impacts on air quality and would not impact nearby residences. Please also see response to comment group 274.
348	Commenter states, "When they manure pumping crews are mainly made up of Hispanics and South Africans who's primary language isn't English it's hard to follow rules and directions."	The comment is out of scope for the EAW as it does not substantially inform the decision on the need for an EIS per the evaluation criteria in Minn. R. 4410.1700 subp. 7.
349	Commenters make the general statement that CAFOs are historically known to be bad for the environment.	The comment is out of scope for the EAW as it does not substantially inform the decision on the need for an EIS per the evaluation criteria in Minn. R. 4410.1700 subp. 7.
350	Commenter asks, "The other side of this debate is manure storage. This may sound good but it all has to be disposed of and that much manure will have to impact the	The comment is out of scope for the EAW as it does not substantially inform the decision on the need for an EIS per the evaluation criteria in Minn. R. 4410.1700 subp. 7.

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	water supply in the future. What will be the options then?"	
351	Commenter states, "I don't think we should be bearing the costs of this mega CAFO. Their manure plan is not adequate. I live near Minnesota River and can see the impacts of current nutrient load and hydrology."	The comment is out of scope for the EAW as it does not substantially inform the decision on the need for an EIS per the evaluation criteria in Minn. R. 4410.1700 subp. 7. Additionally, MPCA reviewed the Project's NMP and found it meets feedlot rule and permit requirements.
352	Commenters are concerned about increasing pollution from manure, including chemicals in the manure.	Please see responses to comment groups 102, 252, and 274.
353	Commenters state that all manure pits and lagoons leak.	The Liquid Manure Storage Area liners are permitted and regulated under the individual NPDES feedlot permit associated with this facility. A monthly examination of the monitoring port or drain tile outlet for water flow and signs of discoloration or odor in any water flowing in the drain tile. A weekly visual inspection of the LMSA and any devices channeling manure-contaminated runoff to the LMSA to assess conformance to the approved plans and Permit. Should a spill of hazardous material occur the Proposer has a contract with Environmental Scientific as a contingency plan.
354	Commenters are concerned that when you take the theoretical seepage rate of the basin liners and multiply the impact compared to a 280 head dairy.	The Proposer will construct proposed earthen lined manure storage areas with 5 ft compacted clay liners. The LMSA design requirements in rule and the Feedlot Permit, along with enhanced liner thickness will reduce theoretical seepage and provide greater groundwater protection.
355	Commenters want to know what type of monitoring there is for leaks in the liner?	The Liquid Manure Storage Area liners are permitted and regulated under the individual NPDES feedlot permit associated with this facility. A monthly examination of the monitoring port or drain tile outlet for water flow and signs of discoloration or odor in any water flowing in the drain tile. A weekly visual inspection of the LMSA and any devices channeling manure-contaminated runoff to the LMSA to assess conformance to the approved plans and this Permit.
356	Commenters ask for an in-depth long-term analysis of the nutrient/nitrate loading from manure applications and their impact on the soils and waters (ground water and surface waters) of the surrounding area.	The comment is out of scope for the EAW as it does not substantially inform the decision on the need for an EIS per the evaluation criteria in Minn. R. 4410.1700 subp. 7.
357	Commenter states, "Current manure handling should be re-considered in all your decisions, statewide."	The comment is out of scope for the EAW as it does not substantially inform the decision on the need for an EIS per the evaluation criteria in Minn. R. 4410.1700 subp. 7.

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358	Commenter states, "I believe it is important to protect the environment by ensuring proper manure management."	The comment is out of scope for the EAW as it does not substantially inform the decision on the need for an EIS per the evaluation criteria in Minn. R. 4410.1700 subp. 7.
359	Commenter states, "Problems with these massive dairy operations center around manure."	The comment is out of scope for the EAW as it does not substantially inform the decision on the need for an EIS per the evaluation criteria in Minn. R. 4410.1700 subp. 7.
360	Commenter states, "I also heard that they claim all the manure will be stored on site... If they consider stored on site to mean in fields such as the one next to our property, then I know that means they will locate a giant pile of manure right in the path of someone's place."	The comment is out of scope for the EAW as it does not substantially inform the decision on the need for an EIS per the evaluation criteria in Minn. R. 4410.1700 subp. 7.
361	Commenter states, "This project will need 250 million gallons of liquid manure storage waste."	The comment is out of scope for the EAW as it does not substantially inform the decision on the need for an EIS per the evaluation criteria in Minn. R. 4410.1700 subp. 7.
362	Commenter states, "Agronomic application rates are not designed to prevent excess nutrients or other farm chemicals from reaching groundwater, instead they are designed to maximize production with the least amount of application."	Anyone who land applies manure in Minnesota must comply with the requirements of Minnesota Rules, chapter 7020, which are designed to protect surface water and groundwater. Feedlots operating under a National Pollutant Discharge Elimination System (NPDES) or State Disposal System (SDS) permit are subject to additional manure management requirements. Under Minn. R. Ch. 7020, manure application rates are limited to the amount of plant-available nitrogen needed by the crop, generally following University of Minnesota Extension recommendations. Permittees must use the MPCA's Minnesota Nutrient Management Tool to develop and maintain a Manure Management Plan (MMP), which determines allowable application rates based on manure nutrient content, crop needs, and residual nitrogen from previous applications. The MMP incorporates permit requirements governing manure application rates, nitrogen and phosphorus management, application timing, inspections, and setbacks. These measures are intended to minimize the risk of surface water and groundwater contamination from land application of manure. The permittee and all manure recipients must comply with the MMP and all applicable

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		permit requirements. The Nutrient Management Tool satisfies applicable manure management planning requirements under Minn. R. 7001.0150 and Minn. R. 7020.2225.
363	Commenter states, "Although a good argument is made for decreased use of chemical fertilizers by spreading manure, it seems that the impact of increased methane into the air and ground have been overlooked."	Attachment 21 includes CO_2e emissions breakout. Enteric fermentation emissions account for 1,697 tons/year. Methane emissions associated with manure storage are 700 tons/year.
364	Commenter states, "I am fully aware that additional delay could have some economic impact upon Riverview. So would an environmental disaster. From the presentation at the public meeting, I am aware that the proposed application includes certain provisions designed to mitigate negative environmental impacts of the feedlot. I am not knowledgeable as to whether the mitigation efforts are state of the art, but I am assuming they probably are."	The comment is out of scope for the EAW as it does not substantially inform the decision on the need for an EIS per the evaluation criteria in Minn. R. 4410.1700 subp. 7.
365	Commenter states, "Future generations will be rolling in shit. Thanks a lot, MPCA! You knew what you were doing."	The comment is out of scope for the EAW as it does not substantially inform the decision on the need for an EIS per the evaluation criteria in Minn. R. 4410.1700 subp. 7.
366	Commenter states, "I heard that this liquid manure is tested once a year? Well, I don't think testing this liquid manure once a year is enough, because I imagine there could be some variations over the course of the year which could impact testing results."	The MPCA requires Feedlot Permit holders sample manure yearly. This sample must be representative and follow the University of Minnesota Extension Service recommendations and be analyzed at a Minnesota Department of Agriculture certified lab. The Proposer will take representative samples each year and send them to a local laboratory and make these results available to all manure recipients. Following laboratory analysis of manure samples, the Proposer will determine the agronomic rate using the University of Minnesota's recommendations for manure application based on the previous crop harvested, the available nutrients, yield goals, and the crop grown. Manure applications occur a single time per year per application site. The Proposer anticipates sufficient time is available from September 1 until freeze to apply all the manure while also factoring in unexpected downtime due to weather conditions. Typically, the Proposer will only

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		apply manure in the spring if the weather conditions during the previous fall prevented complete emptying of the LMSAs.
367	Commenters ask if the manure can be land applied without increasing the risk of nitrate pollution	Best Management Practices (BMPs) will be adhered to with this Project to limit the potential for nitrate impacts on water resources including manure which will be applied at agronomic rates, supplying only the nitrogen (N) needed by the crop to be grown. The Proposer will use the MPCA's Nutrient Management tool to calculate the amount of nitrogen that can be safely applied to each of their application fields. The Feedlot Permit includes nitrogen BMPs to mitigate N loss to waters.
368	Commenter states, "The manure runoff would lead to increased nitrates and phosphorus."	Land application of liquid and solid manure will be regulated under the individual NPDES permit and associated Nutrient Management Plan which includes nitrogen BMPs to minimize nitrate leaching and runoff. As required by the MPCA, the Proposer will sample soil from manure application fields every 4 years to monitor phosphorus (P) levels, using the Olsen or Bray P1 analysis. The Proposer will also use the Manure Management Plan (MMP) resources to prevent long-term soil P build-up. The steps in the MMP are to: determine crop P uptake, determine manure P level, determine the amount of P applied from commercial fertilizer, and compare the amount of P applied and removed. Manure will be applied at agronomic rates, supplying only the nitrogen (N) needed by the crop to be grown. The Proposer will use the MPCA's Nutrient Management tool to calculate the amount of nitrogen that can be safely applied to each of their application fields. This tool considers manure N levels, the type of crop to be grown, and previous manure application (residual N levels) to indicate how many gallons per acre may be applied.
369	Commenters are concerned about the odor that will be created by Project.	The maximum hourly odor concentrations along the Facility's property lines were below the "moderate" odor threshold of 244 OU, except for one hourly exceedance along the near-south property line. The maximum odor concentration for the near south property line was 260 OU. The calculated hourly odor concentration at any property-line receptor was less than or equal to the "faint" odor threshold of 83 OU at least 99.67 percent of the time.
370	Commenter states, "Also, the manure application initially and for the first few days--greatly affects the air quality making breathing it unpleasant at best. This seems to be caused by the applicators which when turning at the ends of the fields, raise above the dirt and spread the liquid on top of the ground."	The Proposer executes manure application by a dragline hose system. The Proposer pumps manure from the Project through a series of hoses overland to reach application fields. This system provides flexibility in the number of available routes to reach manure application fields. The Commercial Animal Waste Technician (CAWT) will inject the manure directly into the soil when cover crops are not present.
371	Commenters make the assertion that all farmers over-apply manure.	The comment is out of scope for the EAW as it does not substantially inform the decision on the need for an EIS per the evaluation criteria in Minn. R. 4410.1700 subp. 7.

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372	Commenters make the assertion that all manure pits overflow, which will be made worse by the increase in severe weather events.	The comment is out of scope for the EAW as it does not substantially inform the decision on the need for an EIS per the evaluation criteria in Minn. R. 4410.1700 subp. 7.
373	Commenters state that the Proposer does not have a good record of liquid waste management.	The comment is out of scope for the EAW as it does not substantially inform the decision on the need for an EIS per the evaluation criteria in Minn. R. 4410.1700 subp. 7.
374	Commenter states, "Contamination by manure seepage to perimeter tile draining shallow groundwater from under manure pits delivered to storm water basin is unaccounted for."	The risk of contamination of groundwater quality due to the Liquid Manure Storage Areas (LMSAs) is low given the two engineered concrete structures and three clay-lined design for the Project. Because the earthen LMSAs are being constructed with 5 feet compacted clay liners, the theoretical seepage rate that will be achieved will be more protective than the 1/56 required in rule. Based on review of the boring logs as well as the results of the laboratory tests, the clay soils encountered in the borings are suitable for use as liner material. The results of the laboratory tests indicate these soils should satisfy the recommended seepage rate of less than 1/56 inch per day at maximum operating depth if placed at the recommended compaction and moisture specifications. The Proposer may encounter shallow groundwater during construction of the LMSAs. The Proposer will install a perimeter drain-tile system at an elevation that is lower than the liner within the LMSA to reduce external groundwater pressure on the walls and to control seasonal subsurface saturation near the LMSAs. The Proposer will install an inspection port near the LMSAs to enable monthly visual inspections. After construction, the Proposer will ensure the drain-tile system is functioning correctly for each LMSA and look for signs of discoloration or odor that may indicate an issue with the liner. These items are included in the in the Minnesota NPDES Individual Feedlot Permit.
375	Commenters are making policy statements concerning the regulation of the handling of animal waste.	The comment is out of scope for the EAW as it does not substantially inform the decision on the need for an EIS per the evaluation criteria in Minn. R. 4410.1700 subp. 7.
376	Commenter states, "Unless this dairy can provide sustainable waste product processing, it is an extremely bad idea for Minnesota environment."	The comment is out of scope for the EAW as it does not substantially inform the decision on the need for an EIS per the evaluation criteria in Minn. R. 4410.1700 subp. 7.
377	Commenter states, "This is a profit-driven proposal for concentration of cows that would make it unlikely that considerations about manure run-off would be part of the operation."	The comment is out of scope for the EAW as it does not substantially inform the decision on the need for an EIS per the evaluation criteria in Minn. R. 4410.1700 subp. 7.

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378	Commenter states, "We need to reverse the way that animals are managed on the landscape in order to reintegrate their waste safely into the ecosystem."	The comment is out of scope for the EAW as it does not substantially inform the decision on the need for an EIS per the evaluation criteria in Minn. R. 4410.1700 subp. 7.
379	Commenter states, "The Minnesota legislature granted the MPCA the authority and resources to develop nitrate standards to protect aquatic life uses for the state's surface waters and regulate non-fertilizer sources of nitrates (primarily manure) from large feedlots decades ago but the agency has not completed the necessary rulemaking to implement this authority."	The comment is out of scope for the EAW as it does not substantially inform the decision on the need for an EIS per the evaluation criteria in Minn. R. 4410.1700 subp. 7.
380	Commenter states, "There certainly is a problem with millions of gallons of manure application in such a small area – application that is limited by season."	There are 16,669 manure acres designated for the Project for land application. Manure application is a predictable seasonal activity, typically occurring in the fall of the year. All manure application sites identified by and offered by local producers for the Project are on land that is already in crop production and typically fertilized annually. Please also see response to comment group 68, 323, and 326.
381	Commenter states, "Simply eliminating these areas [with drainage issues] from future manure application after the drainage problem has been experienced will not prevent this pollution."	Manure application is generally prohibited within 300 feet of a drainage ditch unless specific runoff protection measures are used. Compliance may be achieved through a combination of protective berms, setbacks with manure injection or incorporation and phosphorus management, vegetated buffers with increased setbacks, or a 50-foot perennial vegetated buffer where no manure is applied. (Minn. R. 7020.2225)
382	Commenter states, "The Proposer has agreements with landowners for manure application covering over 16,500 acres. Depth to groundwater will vary throughout these acres. There are no rules prohibiting manure application onto high water table soils. The Proposer uses and exceeds BMPs for manure application and follows all state rules and local ordinances. (bolding added for emphasis) This declaration (in bold) by the project proposer demonstrates how	The Proposer has agreements with landowners for manure application covering 16,669 acres. Depth to groundwater will vary throughout these acres. There are no rules prohibiting manure application onto high water table soils. The Proposer uses and exceeds BMPs for manure application and follows all state rules and local ordinances. These State rules are incorporated as conditions in the feedlot permit to protect water quality through setbacks from wells and surface waters, restrictions on application during winter conditions or snow-covered ground, phosphorus management, manure incorporation or injection requirements, runoff prevention, manure management planning, erosion control and vegetated buffers, and additional protections for vulnerable geologic settings such as karst. Minn. R. Ch. 7020 and the permit require that manure is not applied in a manner that exceeds the hydraulic loading capacity of the land application site based on soil conditions.

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	feedlot operators can take advantage of the agency's overly lax feedlot rules to apply manure where shallow water tables are vulnerable."	
383	Commenters suggest that smaller farmers are better able to manage manure handling.	The comment is out of scope for the EAW as it does not substantially inform the decision on the need for an EIS per the evaluation criteria in Minn. R. 4410.1700 subp. 7.
384	Commenters states, "I live 4 miles as the crow flies, we have noticed our well water smelling due to the saturation of soils with manure."	The comment is out of scope for the EAW as it does not substantially inform the decision on the need for an EIS per the evaluation criteria in Minn. R. 4410.1700 subp. 7.
385	Commenters note that manure spills happen whether through operator error, structural failure, or natural disaster.	The comment is out of scope for the EAW as it does not substantially inform the decision on the need for an EIS per the evaluation criteria in Minn. R. 4410.1700 subp. 7.
386	Commenters are concerned the Project will threaten groundwater.	The Project Site and the Off-Site Well/APEC Well are within the Pomme de Terre River Watershed. There are no lakes, streams, wetlands, or intermittent streams at the Project site. There are no aquatic invasive species or impaired waters within one mile of the Project site. Surface water from the Project will flow south/east to County Tile 30, which runs across the south side of the Project site. County Tile 30 outlets into two unnamed creeks (WID 070200002-551 and 07020002-552),13 which then flows to the Pomme de Terre River (WID 07020002-501), and then eventually to the Minnesota River (WID 070200001-552). The Off-Site Well/APEC Well is near the Pomme de Terre River valley and is screened in a Quaternary Water Table Aquifer (QWTA). The Project site is designed to capture and reuse most or all of stormwater runoff, largely eliminating the untreated runoff that currently leaves the property. In addition, Best Management Practices (BMPs) will be adhered to with this Project to limit the potential for nitrate impacts on water resources including manure will be applied at agronomic rates, supplying only the nitrogen (N) needed by the crop to be grown. The Proposer will use the MPCA's Nutrient Management tool to calculate the amount of nitrogen that can be safely applied to each of their application fields. This tool considers manure N levels, the type of crop to be grown, and previous manure application (residual N levels) to indicate how many gallons per acre may be applied. The Proposer will also follow the state or county setbacks from ditches, lakes, tile intakes, and wells, to prevent nutrient runoff into those features and other waterbodies. The Project will replace cropland with impervious surface, grass/landscaping, and stormwater basins. The addition of stormwater basins will balance stormwater flow by collecting and filtering the water before release. Additionally, the impervious surface will include feed storage and solid manure

Comment Group	Comment	Response
		storage areas. The Project will direct runoff from the feed storage and solid manure storage areas to an LMSA for land application. Ultimately, the calculated runoff for the Project site will decrease to 106 MGY and the post-treatment runoff sediment and nutrient amounts will decrease to 0.05 tons/acre of sediment annually. Water that is not recaptured would be discharged to the county tile system after passing through a stormwater basin with natural filtration. The water discharge rate would follow agronomic rates and would not be higher than it would be without the dairy.
387	Commenter states, "This amount of animals will also produce a record amount of manure that will be disbursed locally, also endangering the "public" asset of clean water."	The Project Site and the Off-Site Well/APEC Well are within the Pomme de Terre River Watershed. There are no lakes, streams, wetlands, or intermittent streams at the Project site. There are no aquatic invasive species or impaired waters within one mile of the Project site. Surface water from the Project will flow south/east to County Tile 30, which runs across the south side of the Project site. County Tile 30 outlets into two unnamed creeks (WID 070200002-551 and 07020002-552),13 which then flows to the Pomme de Terre River (WID 07020002-501), and then eventually to the Minnesota River (WID 070200001-552). The Off-Site Well/APEC Well is approximately 500 feet west of the Pomme de Terre River. The Project site is designed to capture and reuse most or all of stormwater runoff, largely eliminating the untreated runoff that currently leaves the property. In addition, Best Management Practices (BMPs) will be adhered to with this Project to limit the potential for nitrate impacts on water resources including manure will be applied at agronomic rates, supplying only the nitrogen (N) needed by the crop to be grown. The Proposer will use the MPCA's Nutrient Management tool to calculate the amount of nitrogen that can be safely applied to each of their application fields. This tool considers manure N levels, the type of crop to be grown, and previous manure application (residual N levels) to indicate how many gallons per acre may be applied. The Proposer will also follow the state or county setbacks from ditches, lakes, tile intakes, and wells, to prevent nutrient runoff into those features and other waterbodies. The Project will replace cropland with impervious surface, grass/landscaping, and stormwater basins. The addition of stormwater basins will balance stormwater flow by collecting and filtering the water before release. Additionally, the impervious surface will include feed storage and solid manure storage areas. The Project will direct runoff from the feed storage and solid manure storage areas to an LMSA for land application. Ultimately, the calculated runoff for the Project site will decrease to 106 MGY and the post-treatment runoff sediment and nutrient amounts will decrease to 0.05 tons/acre of sediment annually (EAW attachment 24). Water that is not recaptured would be discharged to the county tile system after passing through a stormwater basin with natural filtration. The water discharge rate would follow agronomic rates and would not be higher than it would be without the dairy.
388	Commenters are concerned that the Project will threaten water quality.	The Project Site and the Off-Site Well/APEC Well are within the Pomme de Terre River Watershed. There are no lakes, streams, wetlands, or intermittent streams at the Project site. There are no aquatic invasive species or impaired waters within one mile of the Project site. Surface water from

Comment Group	Comment	Response
		the Project will flow south/east to County Tile 30, which runs across the south side of the Project site. County Tile 30 outlets into two unnamed creeks (WID 070200002-551 and 07020002-552),13 which then flows to the Pomme de Terre River (WID 07020002-501), and then eventually to the Minnesota River (WID 070200001-552). The Off-Site Well/APEC Well is approximately 500 feet west of the Pomme de Terre River. The Project site is designed to capture and reuse most or all of stormwater runoff, largely eliminating the untreated runoff that currently leaves the property. In addition, Best Management Practices (BMPs) will be adhered to with this Project to limit the potential for nitrate impacts on water resources including manure will be applied at agronomic rates, supplying only the nitrogen (N) needed by the crop to be grown. The Proposer will use the MPCA's Nutrient Management tool to calculate the amount of nitrogen that can be safely applied to each of their application fields. This tool considers manure N levels, the type of crop to be grown, and previous manure application (residual N levels) to indicate how many gallons per acre may be applied. The Proposer will also follow the state or county setbacks from ditches, lakes, tile intakes, and wells, to prevent nutrient runoff into those features and other waterbodies. The Project will replace cropland with impervious surface, grass/landscaping, and stormwater basins. The addition of stormwater basins will balance stormwater flow by collecting and filtering the water before release. Additionally, the impervious surface will include feed storage and solid manure storage areas. The Project will direct runoff from the feed storage and solid manure storage areas to an LMSA for land application. Ultimately, the calculated runoff for the Project site will decrease to 106 MGY and the post-treatment runoff sediment and nutrient amounts will decrease to 0.05 tons/acre of sediment annually (EAW attachment 24). Water that is not recaptured would be discharged to the county tile system after passing through a stormwater basin with natural filtration. The water discharge rate would follow agronomic rates and would not be higher than it would be without the dairy.
389	Commenter states, "MPCA fails to extend its authority over pollution caused by manure delivered to other farmers and landowners."	Minn. R. Ch. 7020 and Feedlot Permit requirements include requirements relating to manure application in general and the transfer of manure. Minn. R. Ch. 7020 requires that manure is applied in a manner that does not result in discharge to waters of the state during the application process or cause pollution of waters of the state due to manure contaminated runoff. When manure from the Project is transferred the manure recipient must comply with the Project's nutrient management plan (NMP). While Permittees do not control the ultimate actions of manure recipients, Permittees are required to include in their NMP protective measures a recipient must follow to ensure manure is applied in a proper manner. In this context Permittees do have responsibility for manure they transfer. The MPCA is the regulatory authority for the Project and manure applications relating to the project. The Minnesota Department of Agriculture provides oversight and requires training and licensing for Commercial Animal Waste applicators.

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390	Commenter states, "There certainly is a problem with millions of gallons of manure application in such a small area – application that is limited by truck travel."	Liquid and solid manure will be collected, stored, processed, and land applied as fertilizer on cropland according to the associated NPDES permit and Nutrient Management Plan. Local producers have identified and offered 16,669 acres of currently tilled cropland for manure application. The Proposer expects to utilize approximately 13,200 acres per year. The manure application sites are within: Stevens County (Baker, Darnen, Horton, Synnes, and Scott Townships) and Swift County (Hegbert and Fairfield Townships) as shown in EAW Attachment 5 and Attachment 8. The manure application sites are currently cultivated for crop production, and landowners may have used the fields for manure application in the past. The Proposer executes manure application by a dragline hose system. The Proposer pumps manure from the Project through a series of hoses overland to reach application fields. This system provides flexibility in the number of available routes to reach manure application fields. It also greatly reduces the impact of manure application equipment on local road infrastructure.
391	Commenters make note of the sheer volume of manure that will be produced at the site. The facility would generate about 202.7 million gallons of liquid manure and wastewater annually, plus 26,400 tons of solid manure.	The comment is out of scope for the EAW as it does not substantially inform the decision on the need for an EIS per the evaluation criteria in Minn. R. 4410.1700 subp. 7.
392	Commenters express concern that there is an increasing number of extreme weathers events in Minnesota.	Increased precipitation may cause the loss of some acres of cropland due to saturation of low spots within fields or localized flooding after rain events. New drainage or water impoundment systems may need to be developed by landowners to handle increased volumes of stormwater in fields. If these structures are built on any of the manure application fields, they would take land out of crop production to convert to water management structures. With a contingency of over 3,000 additional manure application acres beyond what is needed each year, there is abundant operational flexibility if some portions of the fields are no longer available due to weather condition impacts. The Proposer has designed the Project to have 14 months of manure storage, which provides a buffer in case some application fields are temporarily unavailable.
393	Commenter states, "There certainly is a problem with millions of gallons of manure application in such a small area – application that is limited by weather conditions."	Increased precipitation may cause the loss of some acres of cropland due to saturation of low spots within fields or localized flooding after rain events. New drainage or water impoundment systems may need to be developed by landowners to handle increased volumes of stormwater in fields. If these structures are built on any of the manure application fields, they would take land out of crop production to convert to water management structures. Manure application begins around September 1st, following corn silage harvest and applied 24 hours a day, 6 days per week for approximately 30 days each year. The Proposer anticipates sufficient time is available between

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		September 1st until freeze to apply all manure. In addition, the Proposer has several thousand extra acres of tillable land available to spread manure to help account for unsuitable field conditions. However, if weather conditions during the fall prevent complete emptying of the LMSAs and land application of solid manure, the Proposer will apply manure the following spring. With a contingency of over 3,000 additional manure application acres beyond what is needed each year, there is abundant operational flexibility if some portions of the fields are no longer available due to weather condition impacts. The Proposer has designed the Project to have 14 months of manure storage, which provides a buffer in case some application fields are temporarily unavailable.
394	Commenters expressed concerns about impacts on human respiratory health from the Project.	The comment is out of scope for the EAW as it does not substantially inform the decision on the need for an EIS per the evaluation criteria in Minn. R. 4410.1700 subp. 7.
395	Commenters expressed concerns about human health impacts as a potential result of the Project.	The comment is out of scope for the EAW as it does not substantially inform the decision on the need for an EIS per the evaluation criteria in Minn. R. 4410.1700 subp. 7.
396	Commenters expressed concerns about water quality leading to human health impacts from the Project.	The comment is out of scope for the EAW as it does not substantially inform the decision on the need for an EIS per the evaluation criteria in Minn. R. 4410.1700 subp. 7.
397	Commenters express concerns about impacts to the community from the Project.	The comment is out of scope for the EAW as it does not substantially inform the decision on the need for an EIS per the evaluation criteria in Minn. R. 4410.1700 subp. 7.
398	Commenters describe concerns about impacts to the economy from the Project.	The comment is out of scope for the EAW as it does not substantially inform the decision on the need for an EIS per the evaluation criteria in Minn. R. 4410.1700 subp. 7.
399	Commenters discussed concerns about the Project's impacts related to environmental justice.	The comment is out of scope for the EAW as it does not substantially inform the decision on the need for an EIS per the evaluation criteria in Minn. R. 4410.1700 subp. 7.
400	Commenters have concerns about impacts to nearby economy.	The comment is out of scope for the EAW as it does not substantially inform the decision on the need for an EIS per the evaluation criteria in Minn. R. 4410.1700 subp. 7.
401	Commenters have concerns about the size of the Project.	The comment is out of scope for the EAW as it does not substantially inform the decision on the need for an EIS per the evaluation criteria in Minn. R. 4410.1700 subp. 7.
402	Commenters are concerned about the massive amount of strain the Project would put on the electrical grid.	The comment is out of scope for the EAW as it does not substantially inform the decision on the need for an EIS per the evaluation criteria in Minn. R. 4410.1700 subp. 7.
403	Commenters note multiple concerns related to social issues and values.	The comment is out of scope for the EAW as it does not substantially inform the decision on the need for an EIS per the evaluation criteria in Minn. R. 4410.1700 subp. 7.

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404	Commenters want to know if there is data on Contaminants of Emerging Concern (CEC) for Shakopee Creek	The comment is out of scope for the EAW as it does not substantially inform the decision on the need for an EIS per the evaluation criteria in Minn. R. 4410.1700 subp. 7.
405	Commenter states that they toured Riverview's Waukon Dairy and noted that there was no ongoing monitoring of the aquifer or surrounding water quality.	The comment is out of scope for the EAW as it does not substantially inform the decision on the need for an EIS per the evaluation criteria in Minn. R. 4410.1700 subp. 7.
406	Commenter states "This is not the kind of industrial farming that benefits anyone other than the corporation that reaps profits at the expense of everyone who seeks a safe water supply."	The comment is out of scope for the EAW as it does not substantially inform the decision on the need for an EIS per the evaluation criteria in Minn. R. 4410.1700 subp. 7.
407	Commenter states "There are better ways that don't harm water."	The comment is out of scope for the EAW as it does not substantially inform the decision on the need for an EIS per the evaluation criteria in Minn. R. 4410.1700 subp. 7.
408	Commenter notes that there used to be cows in the Pomme de Terre River.	The comment is out of scope for the EAW as it does not substantially inform the decision on the need for an EIS per the evaluation criteria in Minn. R. 4410.1700 subp. 7.
409	Commenter states "To comply with MEPA, MPCA cannot simply proclaim that the Expansion Project will have no cumulative effects on water quality—it must take a hard look at the potential for significant environmental effects. Thus far, it has not done so."	MPCA takes a hard look at the potential for significant environmental effects as it develops the Findings of Fact, Conclusions of Law, and Order, which is based on the Environmental Assessment Worksheet as well as all comments received during the public comment period.
410	Commenter states "The EAW's cumulative effects analysis does not recognize the poor water quality already existing in this part of Minnesota and how the Expansion Project will exacerbate the problem."	In the EAW the MPCA identifies the known impairments that could be affected by the Project. After collecting all of the information through the Environmental Assessment Worksheet and comments submitted during the public comment period, and then while developing the Findings of Fact, Conclusions of Law, and Order, the MPCA must consider the following factors: whether the cumulative potential effect is significant; whether the contribution from the project is significant when viewed in connection with other contributions to the cumulative potential effect; the degree to which the project complies with approved mitigation measures specifically designed to address the cumulative potential effect; and the efforts of the proposer to minimize the contributions from the project. The Proposer is required to follow Minn R. 7020 through conditions found in the feedlot permit, including the individual NPDES permit and nutrient management plan. These permit

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		conditions and requirements are intended to protect water quality through governing the storage, transportation, disposal, and utilization of animal manure.
411	Commenter states, "Also, I have noticed that our water quality has gone down in past 15 years."	The comment is out of scope for the EAW as it does not substantially inform the decision on the need for an EIS per the evaluation criteria in Minn. R. 4410.1700 subp. 7.
412	Commenter states, "The scale of the West River Dairy expansion poses the following significant risks: - Environmental Persistence: Estrogens in dairy wastewater are notably persistent and often fail to biodegrade under the anaerobic conditions found in manure storage lagoons."	According to the University of Wisconsin Extension (Fall 2011) Publication, Assessing the Potential Effects of Hormones in Livestock Manure, hormones were found to be rapidly degraded in stormwater runoff, which suggests minimal impact on aquatic organisms, and efforts that prevent manure from entering waterways will likely prevent hormones from entering surface waters.
413	Commenter states, "Are we playing to emotion or are we going to look at facts, data and research? Data such as water that impacts the environment and those around it."	The EAW has considered direct and cumulative impacts to surface water and groundwater resources at the facility, on areas identified for manure application, and within the Environmentally Relevant Area (ERA) within a one-mile radius of the Project site. These impacts are regulated through the MN DNR's water appropriations permitting program and process and the MPCA's feedlot permit for compliance with Minnesota Rules 7020
414	Commenter states, "I have concerns that the expansion will be part of contributing to this flooding as well as being affected by it."	The Project is outside of the 1% Base Flood Elevation and not located within a delineated flood plain (100-year flood). Critical infrastructure at the Project site (animal holding, manure storage, feed pad) is at a relatively higher elevation, which provides additional protection in case of extreme precipitation events.
415	Commenter states, "Crop and livestock production contribute to 85 percent of the state's water pollution."	The comment is out of scope for the EAW as it does not substantially inform the decision on the need for an EIS per the evaluation criteria in Minn. R. 4410.1700 subp. 7.
416	Commenter states, "This omission understates the true environmental harm and risks, allowing further degradation of already vulnerable water resources."	The omission in the comment is referring to is "The EAW ignores the cumulative and compounding increases in nitrate and phosphorus pollution, that an Expansion Project would contribute" a previous comment by the commenter that was responded to in comment group 256. The Commissioner of the MPCA will make the determination on the need for an EIS after carefully reviewing all the information in the EAW, written public comments, and the Response to Comments. Upon reviewing all of the available information, the Commissioner determines if the Project has the potential for significant environmental effects following the criteria specified in Minn. R. 4410.1700 subp. 7. The Commissioner issues Findings of Fact, Conclusions of Law, and Order to support either a positive declaration on the need for an EIS, or a negative declaration on the need for an EIS.

Comment Group	Comment	Response
417	Commenter states the Project is in the "Stevens County's Soil and Water Protection District."	The comment is out of scope for the EAW as it does not substantially inform the decision on the need for an EIS per the evaluation criteria in Minn. R. 4410.1700 subp. 7.
418	Commenter states, "My wife grew up on the farm we now live on, I'm very familiar with the water on this farm. Of the 40+ years of using the water here; it's only been in the past five to six years I've seen the water go from strictly a rusty iron and sand problem to a heavy manganese problem."	Manganese is a naturally occurring element and is commonly observed in Minnesota groundwater even at concentrations that exceed the Minnesota Department of Health (MDH) drinking water standard. Manganese can be mobilized due to a change in redox conditions in the groundwater. The Minnesota Department of Health (MDH) has information and resources for better understanding and addressing this contaminant in drinking water. https://www.health.state.mn.us/communities/environment/water/contaminants/manganese.html
419	Commenter states, "The extra methane would contribute to water pollution."	Methane is not a regulated water quality parameter under the Clean Water Act, the Minnesota Pollution Control Agency's surface water quality standards (Minn. R. Ch. 7050), or any federal or state CAFO regulatory framework. There is no numeric water quality criterion for dissolved methane in Minnesota waters, no drinking water standard for methane under the Safe Drinking Water Act, and no aquatic life criterion. Dissolved methane at concentrations encountered in normal surface waters does not cause toxic effects on aquatic life, does not affect drinking water suitability, and does not produce ecological impacts at any scale that has prompted regulatory standard-setting.
420	Commenter states, "The nitrates in our water due to ag waste runoff was well above advisable levels."	The comment is out of scope for the EAW as it does not substantially inform the decision on the need for an EIS per the evaluation criteria in Minn. R. 4410.1700 subp. 7.
421	Commenter states, "I believe it is important to protect the environment by preventing water contamination."	The NPDES/SDS feedlot permit (Attachment 22) addresses runoff, manure storage, agronomic-rate land application, and the manure management plan in compliance with state standards designed to protect the watershed. The EAW has considered direct and cumulative impacts to surface water and groundwater resources at the facility, on areas identified for manure application, and within the Environmentally Relevant Area (ERA) within a one-mile radius of the Project site. These impacts are regulated through the MN DNRs water appropriations permitting program and process and the MPCA's feedlot permit for compliance with Minnesota Rules 7020.
422	Commenter states, "The site is in an environmentally sensitive watershed,"	The NPDES/SDS feedlot permit (Attachment 22) addresses runoff, manure storage, agronomic-rate land application, and the manure management plan in compliance with state standards designed to protect the watershed.
423	Commenter states, "Please study the issue to determine if this many animals can live in close quarters without disrupting the water in the surrounding area."	The comment is out of scope for the EAW as it does not substantially inform the decision on the need for an EIS per the evaluation criteria in Minn. R. 4410.1700 subp. 7.

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424	Commenter states, "The more drainage tile that is put into farm field leads to more flooding as water moves faster than it historically did in the prairie pothole region of MN."	The Project is on cultivated agricultural cropland with improved drainage featuring a matrix of private pattern tile and County Tile 30. There is currently no retention or treatment of any surface water runoff within the Project area. The proposed Project will include the retention, filtering, treatment and/or reuse of surface water runoff that would otherwise be directed downstream by existing drainage. Therefore, surface hydrology changes expected from this Project would be reduced runoff post-construction.
425	Commenter states, "Thousands of feet of private drain tile connect to a nearby public county drain tile (underground pipe) that drains the acres in and around the dairy operation and flows east directly to the Pomme de Terre River. Drain tiles act as a direct conduit for toxic nutrients such as nitrates."	The Project is on cultivated agricultural cropland with improved drainage featuring a matrix of private pattern tile and County Tile 30. There is currently no retention or treatment of any surface water runoff within the Project area. The proposed Project will include the retention, filtering, treatment and/or reuse of surface water runoff that would otherwise be directed downstream by existing drainage. Therefore, surface hydrology changes expected from this Project would be reduced runoff post-construction.
426	Commenter states, "I also enjoyed the natural areas around Morris, such as the Big Stone National Wildlife Refuge and the Edwards Wetland Management Area, which, along with the city, depend on good water levels."	The comment is out of scope for the EAW as it does not substantially inform the decision on the need for an EIS per the evaluation criteria in Minn. R. 4410.1700 subp. 7.
427	Commenter states, "Farming is Everybody's Bread, Butter, and Water. What I do on my hills affects water quality and quantity for Everybody."	The comment is out of scope for the EAW as it does not substantially inform the decision on the need for an EIS per the evaluation criteria in Minn. R. 4410.1700 subp. 7.
428	Commenter states, "Water scarcity is a huge problem world-wide."	The comment is out of scope for the EAW as it does not substantially inform the decision on the need for an EIS per the evaluation criteria in Minn. R. 4410.1700 subp. 7.
429	Commenter states, "An EIS is necessary to explore alternative methods for land application of livestock wastes from this facility as part of the remedial actions called for in the TMDLs".	The comment is out of scope for the EAW as it does not substantially inform the decision on the need for an EIS per the evaluation criteria in Minn. R. 4410.1700 subp. 7.
430	Comments encouraging MPCA to approve the Project/Feedlot Permit.	The EAW is not an approval or denial document. The EAW is intended to be a screening document for the Potential for Significant Environmental Impacts. Projects where the RGU determines that there is

Comment Group	Comment	Response
		the Potential for Significant Environmental Impacts per Minn. R. 4410.1700 Subp. 7 Items A-D. must order an EIS.
431	Comments express support for the Project.	The comment is out of scope for the EAW as it does not substantially inform the decision on the need for an EIS per the evaluation criteria in Minn. R. 4410.1700 subp. 7.
432	Comments opposed to the Project.	The comment is out of scope for the EAW as it does not substantially inform the decision on the need for an EIS per the evaluation criteria in Minn. R. 4410.1700 subp. 7.
433	Comments noting the unprecedent size of the Project.	The comment is out of scope for the EAW as it does not substantially inform the decision on the need for an EIS per the evaluation criteria in Minn. R. 4410.1700 subp. 7.
434	Commenters express concerns about the size of the Project.	The comment is out of scope for the EAW as it does not substantially inform the decision on the need for an EIS per the evaluation criteria in Minn. R. 4410.1700 subp. 7.
435	Commenters expressed general concerns about the Project.	The comment is out of scope for the EAW as it does not substantially inform the decision on the need for an EIS per the evaluation criteria in Minn. R. 4410.1700 subp. 7.
436	Comments relate to the hydraulic connectivity of the off-site well to the Pomme de Terre River.	"From Comment Letter 1067 submitted by Nathan Kestner, Minnesota Department of Natural Resources. MN DNR's March 17 comment letter [Letter 482] had stated that the EAW did not consider impacts from the potential groundwater appropriation on the Pomme de Terre River. That comment was inaccurate as written - the EAW does describe potential interactions between groundwater appropriation and the Pomme de Terre River in Sections 12.B.3 and 12.B.4, including discussion of pumping restrictions intended to reduce impacts. MN DNR's March 17 comment was intended to clarify that: -Available aquifer test data (NRG, 2007) indicate that pumping from well 740629 is hydraulically connected to the Pomme de Terre River, and that a portion of pumped water is derived from induced infiltration or reduced baseflow to the river. -As a result, groundwater appropriation at this location has the potential to impact river flow, particularly during lower flow conditions, depending on pumping rates and duration. MN DNR is currently completing an updated evaluation of flow conditions in the Pomme de Terre River. This analysis will inform any permit conditions associated with application 2025-1502. Consistent with Minnesota Statutes and prior DNR guidance (MN DNR, 2016), any issued permit would include conditions designed to prevent negative impacts to the river, particularly during low-flow periods."
437	Comment states, "The EAW indicates in section 12.B.3.d that the wells for the existing facility and the off-site well are located in separate aquifers. The shallow	Comment will be forwarded to the Proposer. Although the on-site wells and the off-site well are screened in different aquifers, DNR's analysis shows that the shallow and deep aquifers in this area are hydraulically connected and function as a single groundwater system with limited water availability. Consequently, the proposed wells do not provide a diversified groundwater source.

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	and deep aquifers in this area are part of one connected system, and water availability from these aquifers is limited. The proposed water sources do not constitute a diversified groundwater source approach. Due to the aquifer connections, cumulative existing and proposed water appropriation will be considered during water appropriation permitting."	Because of these hydraulic connections, cumulative existing and proposed water appropriations will be evaluated during the DNR's water appropriation permitting process for this Project.
438	Comment states, "The current West River Dairy operation relies on two groundwater appropriation permits associated with the operation: • Permit 2004-1023: 95 MGY for livestock watering from four wells located near the current dairy operation. This permit includes groundwater-level monitoring conditions. • Permit 2009-0492: 21.3 MGY for livestock watering and 64.4 MGY for agricultural irrigation from one well located in the proposed expansion project area. This permit may need to be amended to reflect changes in land use.""	Comment will be forwarded to the Proposer.

Appendix B-2: Comment group and comment numbers

Comment Group	Comment Numbers (Comment Letter # - Comment # within Comment Letter)
1	6-9, 7-2, 8-3, 8-4, 9-8, 12-5, 15-2, 16-1, 16-3, 17-2, 17-15, 21-3, 23-1, 28-3, 31-1, 31-6, 35-3, 35-9, 37-11, 39-1, 39-10, 42-4, 43-3, 45-4, 46-1, 50-1, 51-6, 52-4, 53-1, 55-8, 57-9, 78-6, 78-20, 79-1, 81-1, 86-1, 87-1, 88-3, 88-6, 88-9, 88-11, 88-13, 89-1, 89-2, 89-9, 90-1, 90-8, 92-6, 95-1, 96-1, 96-8, 97-1, 97-4, 97-5, 101-1, 101-3, 105-2, 109-1, 109-8, 110-1, 110-8, 115-1, 115-8, 116-1, 119-1, 119-3, 126-1, 126-8, 127-1, 127-4, 127-11, 129-1, 137-4, 141-6, 145-2, 146-1, 146-5, 147-1, 149-1, 150-1, 150-8, 151-1, 151-8, 152-1, 152-2, 152-3, 153-1, 153-8, 154-1, 154-8, 159-1, 159-8, 159-9, 167-1, 170-1, 172-1, 172-2, 175-1, 175-8, 176-26, 176-27, 176-28, 177-7, 178-1, 181-6, 182-7, 184-1, 185-2, 186-1, 186-8, 194-1, 194-8, 195-1, 195-8, 196-1, 196-8, 200-1, 200-8, 202-1, 202-8, 203-1, 203-8, 204-1, 206-1, 207-1, 207-8, 209-1, 209-8, 210-1, 212-1, 212-8, 214-1, 214-8, 215-1, 216-1, 216-8, 217-1, 217-8, 218-1, 218-8, 219-1, 220-1, 221-1, 221-8, 222-1, 222-8, 223-2, 224-1, 224-8, 226-1, 226-8, 227-1, 227-8, 228-1, 229-1, 230-1, 230-8, 231-1, 231-8, 232-1, 232-8, 236-1, 238-6, 240-1, 240-8, 241-1, 241-8, 242-1, 242-8, 243-1, 243-8, 244-2, 245-1, 246-1, 246-8, 247-1, 247-8, 248-1, 249-1, 249-8, 250-1, 250-3, 250-4, 253-1, 255-1, 256-1, 256-8, 257-1, 258-2, 259-1, 259-8, 260-1, 260-8, 262-5, 264-1, 264-8, 266-1, 266-8, 267-1, 267-8, 268-1, 269-1, 269-8, 270-1, 270-8, 271-1, 272-1, 272-8, 274-1, 274-8, 275-1, 275-8, 276-1, 276-8, 277-1, 277-8, 279-1, 279-8, 280-1, 281-1, 281-8, 283-9, 284-1, 284-8, 286-1, 286-8, 287-1, 287-8, 288-6, 288-13, 289-1, 289-8, 292-1, 293-10, 295-6, 298-11, 300-1, 300-8, 301-7, 304-1, 304-8, 305-1, 306-1, 306-8, 308-1, 308-8, 309-1, 309-8, 310-7, 314-1, 314-8, 318-8, 319-1, 319-8, 320-4, 321-1, 324-1, 324-8, 325-1, 326-1, 326-8, 327-1, 327-8, 329-1, 329-8, 330-4, 331-4, 332-1, 332-8, 333-1, 333-8, 334-1, 334-8, 335-1, 337-1, 337-8, 339-1, 339-8, 340-3, 340-10, 341-1, 341-8, 342-1, 343-1, 343-8, 344-1, 346-2, 347-4, 347-10, 353-1, 353-8, 355-1, 355-8, 356-1, 358-5, 360-2, 361-1, 361-8, 363-1, 365-2, 368-4, 369-9, 370-1, 372-1, 372-9, 373-5, 373-15, 373-21, 374-7, 375-1, 375-8, 377-1, 377-8, 379-1, 379-7, 381-1, 381-8, 383-1, 384-1, 384-8, 389-1, 389-8, 391-1, 391-9, 392-17, 393-6, 395-2, 396-1, 396-8, 397-1, 397-8, 399-1, 400-1, 400-8, 400-9, 401-2, 401-10, 405-1, 405-8, 406-1, 407-2, 407-11, 408-1, 409-7, 409-16, 411-1, 411-8, 412-1, 412-8, 413-1, 413-8, 414-1, 414-8, 415-1, 415-8, 416-1, 416-8, 417-1, 417-8, 418-1, 419-1, 419-8, 421-1, 421-8, 422-7, 425-1, 425-8, 426-1, 426-6, 427-1, 427-8, 428-2, 429-1, 429-8, 431-1, 431-8, 432-1, 434-1, 434-8, 435-1, 435-8, 436-1, 436-8, 437-1, 437-8, 438-1, 438-8, 439-1, 440-1, 445-1, 447-1, 448-2, 448-9, 452-3, 453-1, 453-8, 456-1, 456-4, 458-1, 458-9, 459-2, 459-9, 460-6, 460-18, 462-1, 463-1, 466-1, 466-8, 467-19, 468-9, 476-1, 476-5, 483-6, 492-1, 500-1, 502-1, 507-15, 507-2b, 509-1, 515-2, 517-3, 525-4, 526-1, 532-1, 532-8, 542-4, 553-1, 553-8, 585-1, 594-5, 649-1, 649-8, 662-5, 671-3, 680-1, 680-9, 691-1, 691-8, 692-1, 728-1, 728-12, 730-1, 732-1, 735-1, 743-1a, 743-24b, 745-1, 745-19, 752-2, 752-4, 758-1, 758-9, 759-1, 761-1, 766-1, 767-6, 777-1, 777-18, 780-4, 790-2, 810-1, 816-1, 822-1, 825-8, 837-19, 863-3, 867-1, 870-2, 870-3, 875-6, 894-5, 896-1, 899-3, 905-6, 906-1, 907-1, 909-2, 910-6, 911-13, 913-3, 913-11, 927-2, 927-3, 930-2, 931-7, 939-7, 947-1, 947-11, 1041-1, 1052-1, 1055-1, 1058-1, 1059-1, 1060-1, 1068-7, 1079-2, 1079-10, 1081-1, 1083-1, 1099-2, 1099-3, 1113-1, 1115-8, 1118-14, 1121-5, 1123-2, 1124-11, 1124-17, 1125-2, 1128-1, 1131-20, 1135-2, 1136-6, 1137-1, 1150-1, 1191-1, 1198-1, 1214-8, 1238-2, 1238-4, 1238-14, 1238-18, 1254-2, 1259-1, 1259-13, 1275-1, 1275-2, 1275-9, 1275-16, 1275-41, 1276-1, 1276-17, 1277-2, 1278-1, 1278-29, 1278-42, 1278-43, 1278-44, 1289-6, 1289-13, 1289-25, 1289-105, 1289-108, 1289-126, 1289-142, 1292-2, 1293-1, 1293-5, 1293-6, 1293-7, 1293-8, 1293-14, 1298-75, 1302-7, 1302-50, 1302-52, 1304-11, 1311-1, 1311-2, 1311-5, 1311-23, 1311-31, 1311-46, 1311-50, 1311-51, 1311-70, 1315-1, 1326-1, 1334-1, 1337-1, 1338-8, 1338-17, 1342-3, 1343-1, 1343-15, 1344-1, 1355-1, 1364-17, 1368-1, 1372-1, 1372-17

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2	16-2, 51-3a, 57-1a, 85-1a, 86-4a, 97-3, 146-3, 178-3, 178-6, 302-7b, 318-3a, 474-1, 507-3a, 728-8b, 818-1a, 891-3, 894-2a, 925-5, 928-3, 1041-4, 1125-3, 1198-20, 1260-24, 1275-4, 1275-32, 1278-4, 1289-19, 1289-128, 1289-159, 1294-5, 1311-65, 1311-68, 1338-10, 1361-8, 1369-11
3	51-3b, 57-1b, 75-5, 78-15, 86-4b, 176-10, 318-3b, 507-3b, 728-8a, 758-4, 894-2b, 1041-5, 1125-4, 1137-2, 1276-12, 1278-8, 1278-14, 1278-15, 1289-115, 1289-120, 1294-4, 1311-10, 1372-12
4	112-4, 302-7a, 891-1, 925-4, 928-4, 1275-3, 1278-3, 1278-33, 1338-12
5	363-4, 368-14, 1198-14, 1275-11, 1275-42, 1289-41, 1289-89, 1289-102, 1311-19, 1338-16
6	818-1b, 891-2, 911-17, 1137-3, 1278-2, 1278-9, 1338-9
7	97-3, 493-3, 495-3, 911-16, 1275-38, 1311-42, 1338-11
8	51-3c, 57-1c, 97-3, 318-4, 321-2, 507-3c, 894-2c, 1041-6, 1125-5
9	97-3a, 97-3b, 1289-129, 1311-17
10	728-8c, 1338-13
11	79-4, 86-4c, 172-3, 250-5, 370-4, 810-15, 928-6, 1260-25, 1311-27, 1311-34, 1369-12
12	51-3d, 57-1d, 302-8, 318-5, 321-3, 507-3d, 818-1d, 894-2d, 911-14, 928-5, 1041-7, 1125-6
13	78-1, 743-1c, 818-1c, 911-15, 911-19
14	17-11, 36-6, 321-11, 507-11, 743-23, 743-1b, 743-24c, 766-3, 894-11a, 911-20, 928-7, 1125-11, 1198-4, 1198-11, 1275-17, 1302-29, 1311-77
15	40-2, 69-1, 82-1, 83-1, 85-3, 85-1b, 86-2, 89-3, 141-1, 146-2, 171-1, 181-1, 182-1, 295-5, 301-6, 367-4, 370-3, 385-1, 401-3, 449-1, 452-1, 507-2a, 625-2, 636-8, 743-24a, 792-1, 794-8, 821-1, 825-1, 850-2, 850-8, 855-2, 858-2, 892-5, 893-1, 893-5, 898-5, 900-1, 911-18, 915-2, 928-1, 928-2, 939-1, 944-5, 1118-7, 1260-15, 1260-26, 1264-3, 1278-7, 1294-1, 1298-4, 1298-11, 1311-71, 1312-12, 1316-1, 1340-8, 1369-2, 1369-13, 1370-3
16	18-6, 19-4, 20-5, 44-6, 50-6, 99-5, 179-3, 298-8, 401-1, 423-5, 504-2, 1079-3, 1124-12, 1311-69, 1321-2
17	78-14, 739-1
18	178-10, 288-4, 819-1, 1081-4, 1258-1, 1294-3, 1298-71, 1311-14
19	34-8, 35-1, 35-2, 61-1, 160-1, 160-3, 170-2, 313-1, 352-9, 483-7, 488-7, 497-2, 506-6, 636-6, 679-1, 698-2, 698-3, 698-4, 731-1, 842-3, 916-1, 1080-7, 1104-1, 1113-3, 1298-51, 1328-12, 1329-6
20	386-2, 402-2, 547-2, 549-3, 551-2, 552-2, 556-3, 559-2, 564-2, 565-2, 566-2, 569-3, 578-3, 582-3, 583-3, 587-2, 588-3, 590-2, 591-3, 592-2, 593-2, 595-2, 596-2, 598-2, 599-2, 603-2, 603-3, 604-2, 606-3, 615-3, 619-2, 624-3, 627-2, 628-3, 629-2, 630-2, 635-2, 641-2, 642-2, 648-2, 654-2, 660-2, 667-3, 672-2, 673-2, 678-2, 682-2, 686-3, 693-2, 698-5, 699-2, 700-2, 708-2, 710-3, 711-2, 712-2, 717-3, 718-3, 720-2, 727-2, 738-2, 741-3, 744-2, 748-2, 750-1, 762-2, 772-2, 778-2, 783-2, 788-2, 791-2, 793-2, 797-2, 798-1, 804-2, 823-2, 824-2, 827-1, 836-2, 841-2, 842-2, 849-2, 851-2, 852-2, 853-3, 860-2, 880-2, 883-1, 888-2, 902-2, 920-2, 923-2, 938-2, 942-1, 945-2, 948-2, 952-1, 956-1, 957-2, 958-2, 959-2, 960-2, 962-2, 963-2, 964-2, 965-2, 966-2, 967-2, 968-2, 969-2, 970-2, 971-2, 972-2, 973-2, 975-2, 976-2, 977-2, 978-2, 979-2, 981-2, 983-2, 986-2, 989-2, 990-2, 991-2, 992-2, 993-2, 996-2, 998-2, 1001-2, 1002-2, 1003-2, 1004-2, 1007-2, 1008-2, 1009-2, 1010-2, 1011-2, 1012-2, 1013-2, 1015-2, 1020-2, 1021-2, 1022-2,

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	1023-2, 1025-2, 1026-2, 1027-2, 1028-2, 1029-2, 1030-2, 1031-2, 1032-2, 1033-2, 1035-2, 1036-2, 1038-2, 1039-2, 1040-2, 1042-2, 1044-1, 1045-5, 1046-2, 1049-4, 1051-2, 1061-2, 1063-2, 1070-2, 1073-3, 1075-2, 1084-2, 1085-2, 1087-2, 1088-2, 1089-2, 1090-2, 1091-2, 1092-2, 1093-2, 1094-2, 1096-2, 1097-2, 1098-2, 1100-2, 1103-2, 1107-2, 1111-2, 1127-2, 1129-2, 1130-2, 1133-1, 1139-2, 1141-1, 1142-2, 1143-2, 1144-2, 1145-2, 1146-3, 1147-2, 1149-2, 1151-2, 1152-2, 1154-2, 1155-2, 1156-1, 1157-2, 1159-2, 1160-2, 1161-2, 1162-2, 1163-2, 1164-2, 1166-2, 1168-2, 1169-2, 1170-1, 1171-2, 1172-2, 1173-2, 1177-2, 1180-2, 1182-2, 1183-2, 1184-2, 1186-2, 1187-2, 1189-2, 1190-2, 1192-2, 1194-2, 1199-2, 1200-2, 1201-2, 1202-2, 1203-2, 1204-2, 1205-2, 1206-2, 1208-1, 1208-2, 1209-1, 1209-2, 1210-1, 1210-2, 1211-1, 1211-2, 1212-1, 1212-2, 1213-1, 1213-2, 1215-1, 1215-2, 1216-1, 1216-2, 1217-1, 1217-2, 1218-1, 1218-2, 1219-1, 1219-2, 1220-1, 1220-2, 1221-1, 1221-2, 1222-1, 1222-2, 1223-1, 1223-2, 1224-1, 1224-2, 1225-1, 1225-2, 1226-3, 1227-2, 1228-2, 1229-2, 1231-2, 1232-2, 1233-2, 1237-2, 1239-2, 1240-2, 1245-2, 1246-2, 1247-2, 1248-2, 1249-2, 1251-2, 1253-2, 1261-2, 1262-2, 1267-2, 1268-2, 1269-2, 1271-1, 1272-2, 1273-2, 1274-2, 1280-2, 1281-2, 1284-2, 1285-2, 1287-1, 1295-1, 1296-2, 1297-1, 1299-2, 1301-2, 1305-1, 1307-2, 1309-2, 1313-1, 1314-2, 1335-1, 1345-2, 1349-2, 1356-2, 1357-2, 1371-2, 1374-2, 1375-1
21	1289-18
22	1054-1, 1069-1, 1069-4, 1081-3, 1114-1, 1124-15, 1259-2, 1290-1, 1302-1
23	86-3, 113-9, 113-15, 743-22, 1275-40
24	1289-92, 1311-3, 1311-4, 1311-28, 1311-36
25	1289-62, 1289-63, 1289-64
26	78-8, 78-9, 78-19, 728-5, 728-7, 758-3, 761-12, 855-3, 855-4, 855-5, 875-4, 1289-154
27	113-1, 374-1
28	376-1, 781-9, 1128-2
29	17-10, 188-3, 291-4, 291-5, 347-8, 393-1, 526-3, 576-5, 623-1, 663-6, 44-1, 51-2, 59-4, 61-3, 67-6, 82-10, 87-6, 89-8, 94-2, 95-3, 112-1, 113-12, 154-3, 154-7, 172-5, 176-2, 188-1, 190-3, 204-4, 205-3, 239-1, 265-1, 268-6, 273-1, 278-1, 292-7, 297-9, 303-1, 316-3, 349-1, 352-7, 352-8, 354-2, 368-10, 432-8, 459-1, 467-14, 498-1, 498-3, 542-6, 585-10, 634-6, 663-2, 663-3, 663-4, 702-6, 731-2, 731-3, 732-5, 735-4, 758-7, 759-4, 766-2, 766-4, 769-3, 777-2, 822-16, 838-1, 838-3, 889-1, 894-10, 896-5, 903-1, 908-1, 908-8, 913-1, 913-2, 913-8, 949-13, 949-14, 949-16, 1064-12, 1102-5, 1109-3, 1114-2, 1116-1, 1125-1, 1125-10, 1125-15, 1254-3, 1300-1, 1306-5, 1328-11
30	1275-37, 1289-84, 1289-88, 1311-41
31	12-1, 500-3, 726-1, 730-2, 732-3, 837-2b, 1150-2, 1298-52, 1298-54, 1298-59, 1328-13
32	45-3, 145-4, 282-3, 291-7, 321-4, 325-3, 501-9, 722-15, 732-2, 837-2a, 838-4, 1298-10, 1298-53, 1298-67, 1298-70, 1298-72
33	6-10, 13-5, 33-1, 223-3, 254-4, 254-6, 261-1, 263-1, 290-1, 290-4, 294-1, 316-7, 336-3, 336-4, 350-3, 362-1, 380-8, 403-1, 403-5, 486-4, 487-2, 490-17, 494-9, 497-9, 501-1, 506-1, 607-12, 637-3, 653-10, 661-8, 671-4, 687-6, 702-7, 705-7, 709-1, 713-1, 756-8, 794-9, 796-6, 809-5, 812-1, 812-4, 867-8, 870-7, 873-1, 873-6, 874-5, 878-9, 903-3, 908-9, 1053-1, 1123-3, 1191-2, 1196-4, 1340-9, 1348-1, 1355-3
34	92-4, 92-5, 96-7, 109-7, 110-7, 115-7, 126-7, 127-10, 150-7, 151-7, 153-7, 159-7, 174-6, 175-7, 182-6, 184-2, 186-7, 194-7, 195-7, 196-7, 200-2, 202-7, 203-7, 207-7, 209-7, 212-7, 214-7, 216-7, 217-7, 218-7, 221-7, 222-7, 224-7, 226-7, 227-7, 230-7, 231-7, 232-7, 238-5, 240-7, 241-7, 242-7, 243-7, 246-7, 247-7, 249-7, 256-7, 259-7, 260-7, 264-7, 266-7, 267-7, 269-7, 270-7, 272-7, 274-7, 275-7, 276-7, 277-7, 279-7, 281-7, 284-7, 286-7, 287-7,

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	288-12, 289-7, 293-9, 300-7, 304-7, 306-7, 308-7, 309-7, 314-7, 319-7, 320-3, 324-7, 326-7, 327-7, 329-7, 332-7, 333-7, 334-7, 337-7, 339-7, 340-9, 341-7, 343-7, 353-7, 355-7, 361-7, 372-8, 375-7, 377-7, 381-7, 384-7, 389-7, 393-3, 396-7, 397-7, 400-7, 405-7, 411-7, 412-7, 413-7, 414-7, 415-7, 416-7, 417-7, 419-7, 421-7, 425-7, 426-5, 427-7, 429-7, 431-7, 432-7, 434-7, 435-7, 436-7, 437-7, 438-7, 448-8, 453-7, 458-8, 459-8, 466-7, 476-4, 553-7, 649-7, 691-7, 870-5
35	49-1
36	81-2
37	35-6, 35-7
38	360-3, 1311-52
39	1311-44, 1311-45, 1311-47, 1311-48
40	1373-28
41	1118-1, 1131-19
42	76-3, 930-12, 1266-4a, 1266-5a
43	761-13
44	1043-2
45	1373-23
46	542-5
47	67-1, 67-2, 67-03, 67-4, 67-5, 1266-4b, 1266-5b
48	113-11, 404-6
49	910-7
50	346-1
51	349-2
52	352-4
53	401-7
54	401-8
55	790-14
56	401-6, 485-3, 726-3, 867-7, 1150-3
57	1361-11
58	1337-2

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59	60-4
60	939-6
61	1328-4
62	490-21
63	1373-2, 1373-3, 1373-16, 1373-18, 1373-21, 1373-30
64	1373-22
65	1298-60, 1298-61, 1298-62
66	1298-63
67	1298-64
68	113-14
69	113-16
70	307-1
71	1373-7, 1373-8, 1373-9
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Greg Reuter **Letter 1**

I am grateful to have Riverview as part of our community. I support this project because they are an outstanding company that cares for people, animals, and the environment. The manure produced will replace commercial fertilizer—reducing the need for imported products—while helping grow future crops and improve soil health. In addition, it will give area farmers the opportunity to sell their crops for local use rather than shipping them long distances. This project is a great opportunity for our community and will not have a negative impact on the environment.

Paul Wulf **Letter 2**

My name is Paul Wulf, I am submitting this in favor of West River expansion. I have been a Stevens County resident for 46 years. I have farmed for the last 20 years. Having Riverview as a neighbor has been a good experience for me. I live and farm in the middle of the 3 sites that they have in Stevens Co. They go out of there way to make sure the neighbors are happy. From watering roads for dust control during harvest to adding some extra gravel when they are done harvesting when it is muddy I feel they go above the call of duty. They even pay for Chloride on the gravel road(for dust Control) past my house every summer because of the increased traffic. They have also provided another option for marketing my crop, and the manure program that they have is a big benefit to my farm for productivity but also soil health. I am also a drainage contractor that works with Riverview. I know that water quality is important to them as we have done many projects with them to help stop erosion and have eliminated many open intakes with French Drains to improve water quality running off of their farms. Livestock is an important part of our rural community and we welcome the West River expansion.

Respectfully

Paul Wulf

Travis Moser **Letter 3**

I've lived in Stevens County for more than 30 years and farmed here for 18 years. In that time, I've seen how much Riverview contributes to our community. They partner with local farmers to raise silage, alfalfa and other crops needed to feed their cattle, providing a lot of opportunities locally for our crops. They also provide manure for our crops that we have seen improve our overall cropping system. They follow best practices when applying manure. Their sites are clean and contained.

This expansion would bring new jobs to the area, which means more families and more students for our rural communities and schools. Riverview's presence supports our county in more ways than just economically, and I believe this project will continue to have that positive impact. Riverview has always gone above and beyond in being a great neighbor in our community. For these reasons, I fully support MPCA to approve the expansion permit for West River Dairy.

Thank you,

Travis Moser

Marc Stevens **Letter 4**

My name is Marc Stevens, and I farm in Chippewa County. I grow sugar beets, corn, soybeans, and alfalfa, and I have worked with Riverview for several years.

I receive manure from the dairy as part of my nutrient management plan. Before any application, my fields are soil tested and manure is applied at agronomic rates following state guidelines. From my experience, this is a structured and responsible process.

Manure has improved my soil health, increased organic matter, and reduced my need for commercial fertilizer. The dairy greatly reduces shipping of inputs and commodities we produce. The long term partnership supports improved environmental aspects and the long-term sustainability of the farm.

I understand this expansion is being reviewed through the state's environmental process. Based on my firsthand experience working within those rules, I am confident the project can continue to operate responsibly.

I support approval of the West River Dairy expansion.

Respectfully,

Marc Stevens

Mitch Koehl **Letter 5**

I have lived in Stevens County 46 years. I have farmed here for over 20 years. I currently live less than 1 mile from one of Riverview's existing dairy sites. Riverview has been very respectful of their neighbors. The gravel road I live on is better today than when the dairy was first built due to Riverview adding gravel to repair any damage that may have been caused by harvest operations. They have also provided us opportunities that would have never been available to us without their presence in our county. These opportunities include added value to the sale of our crops, manure which has added value to our land, and job opportunities for us and our kids assisting with harvest operations. I support the West River Expansion project as it will add value to additional acres in this region and provide opportunity to future generations.

Thank You,

Mitch Koehl

Daniel Zimmerli **Letter 6**

The environmental and social implications Riverview's plan to construct a feedlot of this magnitude alone are appalling. Riverview and CAFO feedlots like it externalize costs, pollute our environment, destroy family farms and deliver no benefit to consumers.

Feedlots like Riverview's externalize costs by putting such significant strain on the environment and the pollution they cause from such a huge concentration of animal manure on a small geographic location. Even with the best of plans the manure inevitably ends up in the water either through structure failure, natural disaster or both. Nitrate pollution in the water is a leading contender for increased cancer rates in the population.

Further, feedlots like Riverview destroy family farms. Through their sheer size they outbid small family farmers for inputs and resources. They claim they'll deliver lower prices for consumers and that may be true in the short term but over a long enough time, and after they've put small farmers out of business, they will increase their prices.

At a minimum an Environmental Impact Statement should be completed and made public. However, this project SHOULD NOT be permitted because of the extreme threat of pollution, the costs the pollution

will incur to the communities around it and down stream of it, and the dire threat CAFOs like this pose to small family farmers.

Robert Schultz **Letter 7**

A development of this magnitude with the capability to pollute our already fragile water system in this state must at least require an Environmental Impact Statement (EIS).

Pete McDonnell **Letter 8**

I support what Land Stewardship Project says about this unprecedented CAFO operation: Minnesota's largest dairy producer has applied to build the first livestock operation in the state to hold over 20,000 animal units. If built, the concentrated animal feeding operation (CAFO) will hold 18,855 dairy cattle, bringing the total animal units to 26,397 in one facility.

This proposed operation is the first of its size in Minnesota. It would be nearly double the size of the next largest livestock operation in our state in terms of animal units. This makes it a fundamentally new and particularly powerful threat to Minnesota farmers and rural communities.

The Minnesota Pollution Control Agency (MPCA), which is the agency that issues Minnesota's feedlot permits, must recognize the fundamentally new nature of this threat and give this permit greater scrutiny than it ever has to previous proposals. This proposal by Riverview, LLP must be required to undergo a full Environmental Impact Statement (EIS).

Please make sure due diligence is done for the people of MN, and conduct a thorough EIS on this huge dairy operation!

Sincerely,

Pete McDonnell

Melissa Driscoll **Letter 9**

Hello MPCA Staff and Commissioners,

I farmed for 15 years near Kenyon, MN. In my experience even a small confinement dairy can pollute the air within 2 miles of the facility, and the water many miles downstream. It is extremely important as we look at the future of our beautiful state to protect the water and air quality that we have, and improve both. Confinement dairy's are not good for rivers, streams, human health or animal health, or our agricultural economy. In order to learn more about exactly how our natural resources will be affected we must have an EIS completed as described in MN Rules 4410.2300. Sincerely,

Melissa Driscoll

Aaron Christopher **Letter 10**

This proposed operation is an unprecedented escalation in scale for Minnesota—nearly double the size of the state's next largest facility in animal units. This isn't just another farm; it is a fundamentally new and dire threat to the survival of Minnesota's independent farmers and rural communities.

The sheer volume of waste—over 200 million gallons of wastewater and 26,000 tons of solid manure annually—makes a comprehensive environmental impact assessment non-negotiable. We are looking at a massive ecological footprint in the Pomme de Terre watershed, an area already classified as sensitive. With the Pomme de Terre River and a nearby creek already officially listed as impaired by the MPCA,

allowing an expansion of this magnitude is a reckless gamble that will inevitably worsen an already critical situation.

Diane Wood **Letter 11**

This is insanity in action.

Robert Christie **Letter 12**

A proposal requesting removal of 300 million gallons of water from any aquifer that is already a water source for many families should voluntarily agree to do an EIS. AS alarming as water use is, even worse is a request to apply over 200 million gallons of manure on coarse textured ground. Here in SE MN. an area of high livestock numbers we have an alarming number of wells that have developed high nitrate levels. Now is the time to get it right and ask the right questions. Please make every effort to protect our greatest resource WATER. Require an EIS!

Katie Subra **Letter 13**

I oppose the building of yet another CAFO in Minnesota - namely Riverview, LLPs proposed facility for 18,855 dairy cattle in one facility. Not only does an operation of this scale decimate the ability for small farmers to continue to be viable, but it also threatens the ability to ensure environmental securities and labor securities for years to come. Please prevent this license.

Anna Loney **Letter 14**

When "get big or get out" becomes "grow to gargantuan proportions and take up all the resources" it reminds me of Grandma's saying - "I like a pig, but damn a hog."

Stop hogging!

Sincerely,

Anna Loney

Nancy Ellison **Letter 15**

I am concerned about the impact of such a huge concentration of cattle on the people living in the area and hope you will require an environmental impact statement and study it carefully.

Alison Leathers **Letter 16**

I am writing to ask for a full EIS to be done on Riverview, LLP(for the proposed 11,000-cow dairy feedlot in Section 1 of Synnes Township in Stevens County). An EIS will allow the proposal's negative impacts on water quality and quantity, local roads, and existing independent family dairy farms to be fully analyzed before the project is allowed to seek a permit. This proposal is the largest the state has ever seen so a full EIS should be required and conducted. Thank you for considering my request.

Diane Johnson **Letter 17**

Riverview, based out of Morris, Minn., is one of the largest dairy producers in the country. With barns and facilities spread across western Minnesota, Riverview, LLP already milks over 125,000 dairy cows in Minnesota alone. They also have a presence in North Dakota, South Dakota, and Arizona. Now, they

have begun the permitting process to build the largest CAFO in Minnesota, which could create a model of industrial dairying that our state has never seen.

An EIS will allow the proposal's negative impacts on water quality and quantity, local roads, and existing independent family dairy farms to be fully analyzed before the project is allowed to seek a permit.

According to the documents filed by Riverview, the proposed operation would require:

- To supply water for the operation, pumping from an off-site well will be limited to 226 million gallons per year. For reference, the City of Morris, which is home to over 5,000 people, is permitted to pump up to 300 million gallons of water a year.

- Liquid manure storage encompassing 250 million gallons of waste.

- 13,200 acres of farmland for manure application.

Riverview has a recent history of manure spills in western Minnesota. In Arizona, the company recently agreed to deliver $11 million to residents affected by the dairy's overpumping. The proposed Stevens County site sits within five miles of eight different protected waterfowl and wildlife production areas and is part of the Pomme de Terre River watershed, just 25 miles from its confluence with the Minnesota River. A facility of this scale located in such a vulnerable area calls for a thorough environmental review

Just as importantly, an EIS of the West River Dairy Expansion proposal would address socio-economic impacts. Minnesota is already losing dozens of dairy farms annually due to inconsistent and often below cost-of-production milk prices. Massive dairy operations, like the one Riverview is proposing to build, have glutted the market and tightened Big Milk's stranglehold on the industry, allowing them to push small and medium-sized family farms out of business and off the land. This operation would only exacerbate the situation and accelerate the loss of dairy farms in our state, decimating Main Street economies in the process.

PLEASE do an EIS!!! This kind of project will do irreversible harm to our agricultural community for generations to come.

Joshua Howe **Letter 18**

This proposed operation is the first of its size in Minnesota. It would be nearly double the size of the next largest operation in our state in terms of animal units. This makes it a fundamentally new and particularly powerful threat to Minnesota farmers and rural communities.

Minnesota is already losing dozens of dairy farms annually due to inconsistent and often below cost-of production milk prices. Massive dairy operations, like the one Riverview is proposing to build, have glutted the market and tightened Big Milk's stranglehold on the industry, allowing them to push small and medium sized family farms out of business and off the land. This operation would only exacerbate the situation and accelerate the loss of dairy farms in our state, decimating Main Street economies in the process.

No feedlot has ever undergone an Environmental Impact Statement (EIS) in Minnesota. Each time the MPCA has determined that an operation should undergo one, the operator that requested the permit has withdrawn their application. And all of those operations that were determined to need an EIS were significantly smaller than Riverview's proposed operation will be.

If built, the Riverview operation would be allowed to pump up to 226 million gallons of water per year from an off-site well. For reference, the City of Morris, which is home to over 5,000 people, is permitted

to pump up to 300 million gallons of water a year. Once constructed, the facility would produce 202,744,000 gallons of liquid manure and wastewater a year and 26,400 tons of solid manure a year.

The Minnesota Department of Natural Resources has not yet completed a mapping of Stevens County's groundwater resources and aquifers for their County Geologic Atlas Series. In fact, they have not even begun the hydrological survey of the county. It is irresponsible to other water users and residents of the area to move forward with this permit without a full understanding of the potential impacts.

The Pomme de Terre watershed, where this expansion is proposed, is already considered a sensitive watershed. The MPCA already lists the two closest waterways to the facility, the Pomme de Terre River and an unnamed creek, as impaired, and this proposal would only exacerbate the impairment.

Janet Lenius **Letter 19**

Minnesota is already losing dozens of dairy farms annually due to inconsistent and often below cost-of production milk prices. Massive dairy operations, like the one Riverview is proposing to build, have glutted the market and tightened Big Milk's stranglehold on the industry, allowing them to push small and medium sized family farms out of business and off the land. This operation would only exacerbate the situation and accelerate the loss of dairy farms in our state, decimating Main Street economies in the process.

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The Pomme de Terre watershed, where this expansion is proposed, is already considered a sensitive watershed. The MPCA already lists the two closest waterways to the facility, the Pomme de Terre River and an unnamed creek, as impaired, and this proposal would only exacerbate the impairment.

Thank you for your time and consideration.

Sincerely,

Janet Lenius

Paul Moss **Letter 20**

Please consider the following comments:

This proposed operation is the first of its size in Minnesota. It would be nearly double the size of the next largest operation in our state in terms of animal units. This makes it a fundamentally new and particularly powerful threat to Minnesota farmers and rural communities.

Minnesota is already losing dozens of dairy farms annually due to inconsistent and often below cost-of production milk prices. Massive dairy operations, like the one Riverview is proposing to build, have glutted the market and tightened Big Milk's stranglehold on the industry, allowing them to push small and medium sized family farms out of business and off the land. This operation would only exacerbate the situation and accelerate the loss of dairy farms in our state, decimating Main Street economies in the process.

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The Pomme de Terre watershed, where this expansion is proposed, is already considered a sensitive watershed. The MPCA already lists the two closest waterways to the facility, the Pomme de Terre River and an unnamed creek, as impaired, and this proposal would only exacerbate the impairment.

Thank you for your consideration.

Jack Judkins **Letter 21**

Large CAFOs do not have a good environmental record and are not more efficient than smaller operations. Should at the very least require an EIS. Groundnwater as well as run off pollution are real possibilities.

Mark Klinski **Letter 22**

Being from SE MN , where smaller dairy farms ,less than 200 cows, are usual, we need some common sense in regulations to control Massive CAFOs, flooding the milk market & running other farmers out of Business, Truckers also, & regional Processors all declining, In my opinion there is No Way the Manure can be managed from this size of operation, without detrimental effects to Roads, Neighborhoods & Land ,& Environment

We need to exercise Caution On these concerns, WE do not Need this, Just because a Conglomerate wants to Take Over more Markets, Thank You, Mark

Kathleen Wold **Letter 23**

Please require an environmental impact assessment of this massive project.

Elizabeth Brandt **Letter 24**

Just say no! This is wrong on so many levels. Small dairy farms need to be part of the MN fabric. Allowing this turns people into employees. We need INDEPENTED FARMERS in MN.

Nancy Zaworski **Letter 25**

Please do not allow such a monstrous operation. It will be destructive to our rural communities.

Thank you

Robert Walser **Letter 26**

As a small-scale farmer (about 30 tillable acres) I am extremely concerned about the environmental risks of CAFOs. The concentration of wastes exceeds capacity for use as soil amendments resulting, historically, in lagoons, spills and environmental degradation. Further, the bio hazard of so many animals in confined spaces increases the risk of disease and, in particular, the negative impact of antibiotic resistance due to the so-called prophylactic use of antibiotics in CAFOs. This project demands deep questioning and scrutiny.

Nick Olson **Letter 27**

It has come to my attention that Riverview Dairy is looking to expand their operation to a level that we have not seen before in Minnesota. As a small scale farmer in central Minnesota who is connected to a lot of other farmers in the region, we are all struggling to get by financially. Dairy farms continue to close up shop in all of our counties and the answer is not to have one large dairy farm operating in our region. This is a recipe for disaster on so many levels from our local farm economies to the environmental impact on such a large operation. I have a friend who used to run a dairy farm near Riverview and they could not get the milk truck to pick up at their farm because they were too small. This is not the farm economy we want in rural Minnesota. Driving farmers out of business due to scale and capital is the exact opposite of what is going to keep our rural communities thriving. Let's think of creative solutions to protect our water and land while keeping farmers on the land in our communities.

Audrey Arner **Letter 28**

Wow, that's just too many cows in one spot! Because of my concern for the potential for contamination of the gifts of creation, especially including the waters around the proposed Riverview site, an EIS should be absolutely required for this enormous expansion. Please do right by the precious remaining wetlands that are within proximity to this site as well as the civic infrastructure like roads. Come on now.

Faye Duvall **Letter 29**

This large scale is against wise and environment best practices use of our land and water.

Evan Skaurud **Letter 30**

My name is Evan Skaurud, I grow corn, sugar beets, soybeans, dry beans and alfalfa, and I have worked with RiverView Dairy for several years.

I receive manure from the dairy as part of my nutrient management plan. Before any application, my fields are soil tested and manure is applied at agronomic rates following state guidelines. From my experience, this is a structured and responsible process.

Manure has improved my soil health, increased organic matter, and reduced my need for commercial fertilizer. The dairy also provides a reliable local market for crops like silage and alfalfa.

I understand this expansion is being reviewed through the state's environmental process. Based on my firsthand experience working within those rules, I am confident the project can continue to operate responsibly.

I support approval of the West River Dairy expansion.

Respectfully,

Evan Skaurud

James Tjepkma **Letter 31**

I formerly lived among farmers in Southern Minnesota and have done various kinds of educational and service work with farmers both for pay and as a volunteer. Much of what I did focused on sustainable agriculture. I have also participated in actions lead by an environmental group that included apposing a project that required an Environmental Impact Statement. Based on my understanding of EISs and of sustainable agriculture and agriculture in general I am strong in support requiring an EIS for the West River Dairy Expansion Project.

If this project goes forward there is no doubt it would have great potential for many kinds of environmental damage and damage to communities near by as well as wider damage to the state's dairy industries. I don't see how this would not be true for an operation that would be very much larger than any current existing operation. I don't think I need to list all of the ways such a large operation would have the potential for being very damaging in many ways. An EIS is very definitely needed to looked at these potential damages, present this information to the public, and hold hearing where the public can be informed and can make comments.

Michael Kennedy **Letter 32**

This operation would use excessive amounts of ground water (a public asset) for any single business. We need to conserve not flagrantly over use this resource. This amount of animals will also produce a record amount of manure that will be disbursed locally, also endangering the "public" asset of clean water. This expansion is a foolish proposal and should be denied in the public interests of health and environmental damage.

David Anderson **Letter 33**

Please deny Riverview's application for expansion of their dairy farm. We already have enough nitrates in the ground water and runoff into streams and rivers are also a problem.

Pam Hartwell **Letter 34**

One of the many reasons dairy farmers are struggling throughout the state is that they have to compete with the benefits given, efficiencies and corner cutting of large scale operations. Large scale operations may make sense on purely economic level, but the concentration of animals does not make sense by any other measurement of success. Small farmers across the state are better able to manage herd health, manure handling, and pasture. Large operations with large amounts of animals and their manure NEED to have plans in place APPROVED by environmental scientists that are MANDATED to protect water and land! And neighbors have a right to now what the impact of these extraction facilities, because they are no longer farms at this level! The thought that adding 11,000 cows in one place does not trigger an Environmental review is insane to me.

Myron Sylling **Letter 35**

I am concerned to see this has not been addressed in government yet. A project of this size and scope should have a mandatory EIS performed. EAW's should be for smaller projects. This project affects so many acres that an EIS is a must to thoroughly look into ALL potential risks to the people and environment. The volume of products brought into and shipped out of this facility will create many potential issues. The amount of manure created in this concentrated area should be a major concern for potential water quality issues. Currently the MPCA rules and the BMP's for synthetic fertilizer do not align. Neither do the BMP's for fertilizer/manure application. Water quality for the whole state is currently being reviewed and new guidelines potentially coming forward. It would be wise to wait or at least look at the proposed new guidelines BEFORE granting a permit of this magnitude. Safety of people and the environment should be a top consideration and the best way to ensure that is to perform an EIS.

Mike Menzel **Letter 36**

As a Minnesotan I value our unique natural resources such as clean abundant water. Allowing a super mega dairy and cattle farm near Morris, MN would endanger our water resources, risk contamination of our wetlands and rivers, and force smaller to mid size farms to close due to competition from this behemoth Riverside project. Therefore I urge a rigorous EIS on the environmental and economic impacts to this community.

Mike Menzel, MD

Daniel Belgum **Letter 37**

Minnesota Pollution Control Agency

To Whom it may Concern:

I am deeply concerned about a proposal by Riverview LLP (Dairy) to expand it's operation here in my county: Stevens. This is a huge increase in animal units and will be producing a massive amount of methane, CO2, climate warming gases; massive amounts of waste; and massive amounts of water usage. It also will significantly impact roads, and ground water supplies. I believe, and understand, that this would be the largest dairy facility in the state, and that this size of facility is unprecedented in the state of Minnesota.

This size of dairy will negatively impact small and mid-sized dairy producers, downtown (Main Street) businesses, and poses a significant risk to the multiple watersheds it is near -- including the Pomme de Terre River nearby which is just 20-25 miles from the Minnesota River.

I strongly urge that MPCA do a detailed and deep EIS on this request to add on to this dairy. The public deserves to know more.

Thank you.

Sincerely,

Daniel Belgum

Mary Polta **Letter 38**

Please Let farming be human scale and animals treated humanely. Stop this.

Robin Moore **Letter 39**

This project MUST undergo an environmental review, first and foremost. I can not overstate the impact that CAFO's have on rural residents. Aesthetics and quality of life aside (who really cares about that anyway, right? House values, ability to hang laundry out, ability to take walks outside, all trivial), the impact that a facility like this has on ground and surface water is terrifying. In rural areas, we all know that the acres that they report available for manure distribution are a perfect-case scenario, and the larger the operation, with so much volume and the time it takes to get that volume of manure distributed, the more likely that the ground will be : 1. too wet to get onto which leads to concentration in dry (higher, sandier) acres and any concentration affects surface water 2. Frozen, which leads to run off and contamination of surface water. We have all seen this happen. 3. That not all of the acres will actually be available, that some of the acres will be too far, that concentration will happen.

That's just obvious contamination of surface water. Who pays for that? I haven't seen a tax or any real penalties or any responsibility on Riverview's part to pay for cleaning water.

What about ground water and aquifers - apparently this permit asks for 226 million gallons per year. That's over 2/3rds of what Morris MN is permitted - and how many people does that serve? How many people does Riverview serve? How is this massive CAFO going to affect anyone sharing that aquifer - with concentration of manure, which will undoubtedly happen, especially with larger and larger operations, there will be groundwater contamination. Is Riverview going to pay for RO systems for every rural household on the aquifer? What about volume? How many houses/businesses/towns are going to find their wells dry? Do you know? Probably not, the DNR barely knows this. Will Riverview pay for a thorough study?

This just isn't fair, there is nothing ok about Riverview, but there's even less ok about forgoing an the requirement for an environmental impact statement. No feedlot of whom this has been required has ever continued, because there is nothing environmentally sound about massive feedlots. Those operations were all a lot smaller than Riverview's proposal, how can it be permissible to forgo an Environmental Impact Statement? This sets frightening precedents for corporations (no, Riverview is not a family operation, it is a massive, for profit business that seeks to extract resources with no consideration for the environment or people who live near their operations) to turn our rural areas into "sacrifice zones", sacrificing water, resident flora and fauna, habitat, and live-ability in a huge radius around these areas.

How about economic impact - on dairies, on house values, on rural infrastructure - are you making Riverview fund a 3rd party economic impact assessment? How many small farms is this going to asphyxiate? How many independent farmers is this going to be the final straw for?

I feel like my rural community is becoming an industrial zone, and that's not how agriculture will survive, it's what it looks like before it dies, choking on it's own excess. There should be extra barriers, extra costs, extra diligence, extra taxes, extra requirements for any one business that seeks to impact an entire watershed. Not one single regulation less.

John Gabbert **Letter 40**

As a citizen of Winona County, where we have long fought a large dairy expansion situated on sensitive karst geology, I can really sympathize with the people near Morris where this Riverview expansion will dwarf all other confined animal feeding operations (CAFOs) in the state. It is imperative that the MPCA and its regulators require a full Environmental Impact Statement (EIS for a project of this enormous scope. The MPCA must hold this organization to the letter of the law, and work to protect the people and the environment in the region. Thank you very much.

Michael W Yost **Letter 41**

I am writing to support the approval of the permit allowing Riverview LLP to expand their West River Dairy in Section 1 of Synnes Township in Stevens County. I am a farmer and landowner near several existing Riverview sites and have twenty six years of experience with Riverview and their dairy sites in west central Minnesota. I support the permit for the West River Dairy for several reasons.

1. We live less than two miles from one of Riverview's existing sites and have experienced few if any nuisance issues. No flies, minimal odor, and only slight increase in traffic.

2. Their existing sites are impeccably neat, and runoff is contained.

3. Manure application is done by injection, soil tests are used to determine the quantity applied and manure is a renewable product that replaces thousands of tons of commercial fertilizer.

4. The West River Dairy will require hundreds of acres of alfalfa. An alternative crop for the area's corn and soybean farmers. It is a perennial crop that prevents soil erosion, promotes soil health, sequesters carbon, and provides excellent bee habitat.

5. I have toured multiple dairies from the southwestern United Sates to New England. None are as well operated as a Riverview dairy.

6. The West River Dairy would have a positive effect on our communities, environmentally, economically, and socially.

I strongly support the proposed West River Dairy permit.

Sincerely,

Michael W. Yost

Laura Matanah, Compassionate Action for Animals **Letter 42**

Minnesota's largest dairy producer, Riverview, LLP, has applied to build the first livestock facility in Minnesota to hold over 20,000 animal units. If built, the facility will hold 18,855 dairy cattle, bringing the total animal units to 26,397 in one facility. This proposed expansion would be nearly DOUBLE the size of the next largest livestock operation in our state in terms of animal units. This makes it a fundamentally new and particularly powerful threat to Minnesota farmers and rural communities. It will also be far worse for the cows who have to live there. This proposal by Riverview must be required to undergo a full Environmental Impact Statement (EIS).

Kay Drache **Letter 43**

This proposed expansion would be nearly double the size of the next largest livestock operation in our state in terms of animal units. This makes it a fundamentally new and particularly powerful threat to Minnesota farmers and rural communities.

You must recognize the fundamentally new nature of this threat and give this permit greater scrutiny than it ever has to previous proposals. This proposal by Riverview must be required to undergo a full Environmental Impact Statement (EIS).

Amy Grace **Letter 44**

This Industrial-Scale Projects Need Industrial-Scale Review.

This proposed operation is the first of its size in Minnesota. It would be nearly double the size of the next largest operation in our state in terms of animal units. This makes it a fundamentally new and particularly powerful threat to Minnesota farmers and rural communities.

Minnesota is already losing dozens of dairy farms annually due to inconsistent and often below cost-of-production milk prices. Massive dairy operations, like the one Riverview is proposing to build, have glutted the market and tightened Big Milk's stranglehold on the industry, allowing them to push small and medium-sized family farms out of business and off the land. This operation would only exacerbate the situation and accelerate the loss of dairy farms in our state, decimating Main Street economies in the process.

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The Minnesota Department of Natural Resources has not yet completed a mapping of Stevens County's groundwater resources and aquifers for their County Geologic Atlas Series. In fact, they have not even begun the hydrological survey of the county. It is irresponsible to other water users and residents of the area to move forward with this permit without a full understanding of the potential impacts.

The Pomme de Terre watershed, where this expansion is proposed, is already considered a sensitive watershed. The MPCA already lists the two closest waterways to the facility, the Pomme de Terre River and an unnamed creek, as impaired, and this proposal would only exacerbate the impairment.

Rob Super **Letter 45**

I am very concerned about near-term and long-term impacts of this project. Specifically, I share all the concerns being expressed by the Land Stewardship Project. I now live in Saint Paul but I grew up in a small community in northwestern Minnesota and I understand the negative impacts projects of this size impose on local environments.

I am especially concerned about the precedent that would be set by not requiring an environmental impact statement for this project. I see the EIS as a necessity for this project and others like it.

Benedict Wagner **Letter 46**

An operation this size definitely needs and EIS. It will use almost as much water as the city of Morris. Especially concerning are the nearby water sheds.

Mary Zink **Letter 47**

We are very alarmed by the idea that Minnesota would harbor a massive dairy CAFO. The ecological impacts are many and serious; but the socio-economic impacts are also great. Minnesota is already losing dozens of dairy farms annually due to inconsistent and often below cost-of-production milk prices. Massive dairy operations will glut the market and allow them to push small and medium-sized

family farms out of business and off the land. Minnesota is already losing family farms and allowing this CAFO operation will only accelerate the loss of dairy farms in our state, decimating Main Street economies in the process.

Please support the environment, family farms and Main Streets throughout our state and say NO! to CAFO operations

Thank you for your consideration

Mary Zink **Letter 48**

We are very alarmed by the idea that Minnesota would harbor a massive dairy CAFO. The ecological impacts are many and serious; but the socio-economic impacts are also great. Minnesota is already losing dozens of dairy farms annually due to inconsistent and often below cost-of-production milk prices. Massive dairy operations will glut the market and allow them to push small and medium-sized family farms out of business and off the land. Minnesota is already losing family farms and allowing this CAFO operation will only accelerate the loss of dairy farms in our state, decimating Main Street economies in the process.

Please support the environment, family farms and Main Streets throughout our state and say NO! to CAFO operations

Thank you for your consideration

John LaFave **Letter 49**

Please review this permit with extreme caution, it seems these big dairies only wreck our environment. There has never been any good that comes from having that many animals in one small location. If there was a sewage spill it would create havoc on the local people. Thanks for considering my thoughts.

John

Rebekah Schulz **Letter 50**

Dear MPCA,

I am writing with concern about the Riverview Expansion Act. I request that the proposal by Riverview must be required to undergo a full Environmental Impact Statement (EIS).

This proposed operation is the first of its size in Minnesota. It would be nearly double the size of the next largest operation in our state in terms of animal units. This makes it a fundamentally new and particularly powerful threat to Minnesota farmers and rural communities.

Minnesota is already losing dozens of dairy farms annually due to inconsistent and often below cost-of-production milk prices. Massive dairy operations, like the one Riverview is proposing to build, have glutted the market and tightened Big Milk's stranglehold on the industry, allowing them to push small and medium-sized family farms out of business and off the land. This operation would only exacerbate the situation and accelerate the loss of dairy farms in our state, decimating Main Street economies in the process.

No feedlot has ever undergone an Environmental Impact Statement (EIS) in Minnesota. Each time the MPCA has determined that an operation should undergo one, the operator that requested the permit has withdrawn their application. And all of those operations that were determined to need an EIS were significantly smaller than Riverview's proposed operation will be.

If built, the Riverview operation would be allowed to pump up to 226 million gallons of water per year from an off-site well. For reference, the City of Morris, which is home to over 5,000 people, is permitted to pump up to 300 million gallons of water a year. Once constructed, the facility would produce 202,744,000 gallons of liquid manure and wastewater a year and 26,400 tons of solid manure a year.

The Minnesota Department of Natural Resources has not yet completed a mapping of Stevens County's groundwater resources and aquifers for their County Geologic Atlas Series. In fact, they have not even begun the hydrological survey of the county. It is irresponsible to other water users and residents of the area to move forward with this permit without a full understanding of the potential impacts.

The Pomme de Terre watershed, where this expansion is proposed, is already considered a sensitive watershed. The MPCA already lists the two closest waterways to the facility, the Pomme de Terre River and an unnamed creek, as impaired, and this proposal would only exacerbate the impairment.

Thank you for your consideration and attending to this matter.

Peace,

Kim Hiltner **Letter 51**

I am writing to express my concerns with Riverview, LLP's proposal to build the first livestock operation in Minnesota to hold over 20,000 animal units. The MPCA must recognize the fundamentally new nature of this threat and give this permit greater scrutiny than it ever has to previous proposals. This proposal must be required to undergo a full Environmental Impact Statement (EIS) on its impacts on water quality and quantity, local roads, and existing independent family dairy farms to be fully analyzed before the project is allowed to seek a permit. Minnesota is is already losing dozens of dairy farms annually due to inconsistent and often below cost-of-production milk prices. Agricultural consolidation is pushing small and medium-sized family farms out of business and off the land. We must require an EIS before this proceeds.

Connie Schad **Letter 52**

To whom it may concern:

As a concerned citizen of Minnesota, I urge the MPCA to respect our ground water, our air quality and the smaller farmers who are trying to feed us.

Please perform an EIS!

Thank you!

Connie Schad

Dayna Burtness **Letter 53**

According to Minn. R. 4410.1700, subp. 1, the MPCA must order an EIS for projects that have the potential for significant environmental effects.

In deciding whether a project has the potential for significant environmental effects, the MPCA must compare the impacts that may be reasonably expected to occur from the Project with the criteria set forth in Minn. R. 4410.1700, subp. 7.

These criteria are:

A. Type, extent, and reversibility of environmental effects.

B. Cumulative potential effects. The RGU shall consider the following factors: whether the cumulative potential effect is significant; whether the contribution from the Project is significant when viewed in connection with other contributions to the cumulative potential effect; the degree to which the Project complies with approved mitigation measures specifically designed to address the cumulative potential effect; and the efforts of the proposer to minimize the contributions from the project.

C. The extent to which the environmental effects are subject to mitigation by ongoing public regulatory authority. The RGU may rely only on mitigation measures that are specific and that can be reasonably expected to effectively mitigate the identified environmental impacts of the project.

Due to the unprecedented size of this expansion and the potential for significant environmental effects, an EIS is warranted and required by law.

Taylor Gramm **Letter 54**

Dear MPCA,

I have lived in Hancock, MN area for 40 years, and worked in the Ag world for 25 years. The Riverview system has been a huge benefit to our community by bringing in talented individuals, innovation to area farming and area businesses, and overall is very positive to our communities.

It is impressive to see their awareness in environmental situations, and we have witnessed their careful approach to many processes including manure application, diligence in road protection during harvest, and they are quick to respond when the need arises. I appreciate their efforts in neighbor relations also.

Riverview is a true leader in the ag world on safety, cleanliness, and best practices. I believe the West River expansion would be of great value to our area by adding value to farm ground and many more opportunities for area people to stay local.

Thanks, Taylor Gramm

Laura Inman **Letter 55**

I am very concerned about the harmful effects of industrial dairying by Riverview, LLP. A concentrated animal feeding operation of over 20,000 animal units is a major strain on the environment and water resources. With Riverview's history of manure spills and overpumping, the location being in a vulnerable area, and effects on local dairy producers, I'm asking the MPCA to require a full EIS.

Thank you

Mason Koehl **Letter 56**

I am in support for this dairy expansion because of the past history of how well they have taken care of the manure application, how they are great to work with as a neighbor. They care of the community and the well being of the environment. Great company to work with and always kind.

Ellen Rozek **Letter 57**

The Minnesota Pollution Control Agency (MPCA) must require the proposal by Riverview, LLC to undergo a full Environmental Impact Statement in order to analyze the potential negative impacts on water quality and quantity, local roads, and existing independent family dairy farms. Riverview's recent history of manure spills in Western Minnesota (including a manure leak from a biogas digester system in March of last year), as well as the recent settlement the company had to pay out to Arizona residents who had been affected by the dairy over pumping water, both raise concerns that Riverview's planned CAFO will

adhere to the state and local regulations that protect people and water systems. And given that the proposed site for this new CAFO sits within five miles of eight different protected waterfowl and wildlife production areas and is part of the Pomme de Terre River watershed, just 25 miles from its confluence with the Minnesota River, any pollution is likely to have far reaching consequences.

I spent thirteen years living in Iowa prior to moving to Minnesota. Most of Iowa's animal agriculture operations are CAFOs, and regulation is minimal. As a result, most of Iowa's rivers and streams are aggressively polluted, many as a result of uncontained manure run-off. I do not want to see the same thing happen here.

Furthermore, Minnesota is already losing dozens of dairy farms annually due to inconsistent and often below cost-of-production milk prices. Massive dairy operations, like the one Riverview is proposing to build, have glutted the market and tightened Big Milk's stranglehold on the industry, allowing them to push small and medium-sized family farms out of business and off the land. This operation would only exacerbate the situation and accelerate the loss of dairy farms in our state, decimating Main Street economies in the process.

Before signing off on Riverview, LLC's proposal, the MPCA must require a full Environmental Impact Statement to be conducted. This way, the potential scope of hazards or problems can be evaluated and documented before any final decisions are made.

Clark Koehl **Letter 58**

Riverview has had a positive impact in our community in many ways. They offer countless job opportunities, purchase our crops, provide manure for our fields, and bring a positive, safe feel to the community. They go out of their way to build strong relationships within the community, and have always been very respectful. They have a very strict manure application process to ensure that the manure is always contained and does not affect the environment. They are always quick to respond to cleaning up the roads during harvest, and leave the roads better than they found them. This expansion will bring future opportunity that will benefit the generations to come. I am confident that Riverview will continue to be a positive impact to our community and will continue to operate responsibly with this expansion. As a young farmer I fully support the expansion of the West River Dairy.

Thank You,

Clark Koehl

Sadie Pendaz Foster **Letter 59**

As a Minnesotan and a social scientist who studies the social impacts of climate change and inequality, the recent history of CAFO expansion doesn't bode well for economic and social development, much less for the environment and our waterways. Systemic review of environmental impacts is an absolute must and should be a minimum threshold undertaking. We've seen the nitrates build-up and impact on our pristine water supply from farm runoff in our state already, and studies from Iowa and Minnesota confirm that an inverse relationship exists between economic vitality and confined animal feeding operations within localized communities. Thank you, Dr Sadie Pendaz-Foster

Evelyn Benson **Letter 60**

Riverview Dairy poses a great natural threat to the environment around it. They could completely uproot the entire ecosystem and cause small, honorable, family-owned farms around them to go bankrupt. They ethically should be reviewed for their proposed actions.

Heather Benson **Letter 61**

When I look through the mandatory EIS categories found in Minnesota Administrative Rules 4410-4400, I find it almost laughable that I even need to write this comment to ask the MPCA to require this EIS. How could it possibly be that a facility housing 26,000+ animal units producing over 250,000 gallons of waste PER DAY, drawing over half a MILLION gallons of water from my local aquifer and covering a physical plant footprint of over 1 MILLION square feet not be required to submit a mandatory EIS?

When I look through that list of mandatory EIS triggers, I see many things that would worry me far less than an industrial dairy facility:

Subp. 11. Industrial, commercial, and institutional facilities.

A. For construction of a new or expansion of an existing warehousing or light industrial facility equal to or in excess of the following thresholds, expressed as gross floor space,

(1) unincorporated area, 375,000 square feet;

(2) third or fourth class city, 750,000 square feet;

(3) second class city, 1,000,000 square feet;

Subp. 14. Residential development. A. 100 or more unattached or 150 or more attached units in an unsewered unincorporated area or 400 unattached units or 600 attached units in a sewered unincorporated area;

Subp. 15. Airport runway projects. For construction of a paved and lighted airport runway of 5,000 feet of length or greater

Subp. 22. Sports or entertainment facilities. For construction of a new outdoor sports or entertainment facility designed for or expected to accommodate a peak attendance of 20,000 or more persons or a new indoor sports or entertainment facility designed for or expected to accommodate a peak attendance of 30,000 or more persons, or the expansion of an existing facility by these amounts.

How could it possibly be that a sports stadium hosting 20,000 people (only 4,000 AUM FYI) only periodically need more environmental review than an industrial dairy holding 26,000 AUM 24/365? How can that be?

I am pro-farmer. I want Minnesota farmers to have the best chance to succeed in every way. But we need to recognize there is an important and fundamental difference between a local family farm that runs 223 cows (the average Minnesota dairy herd size) and 18,000. If a business wants to operate at an industrial scale, as Riverview does, then they need to be prepared to undergo industrial review. It is that simple. If you want to play with the big boys, then you need to play by big boy rules. This doesn't even mean anyone is trying to "stop" their business—it is simply Minnesota holding an industrial facility to the same laws and standards that other industrial businesses (and sports stadiums, ahem) must abide by.

Marissa Munsterman **Letter 62**

I support the proposed expansion of this dairy. It's often the small things a business does that show how much they care about their community. Offering free cones on National Ice Cream Day is a simple gesture, but it shows the kind of relationship they want to have with the people around them.

Through my work with the lead farm partnered with Waukon Dairy and Riverview LLP, I have seen firsthand how well the operation is run. The employees treat each other with kindness and respect, and

it's clear that everyone takes pride in their work. I have also never seen such a large facility maintained so well.

Expanding the dairy would only strengthen its positive impact by supporting the local economy and continuing to create opportunities for area farmers and landowners to grow crops for the dairy. From what I've seen, this is an operation that values its employees, neighbors, and community.

Adam Koehl **Letter 63**

I am a farmer that lives in close proximity to Riverview Dairy sites. They have been excellent stewards of the environment and take the utmost care to ensure that this continues. Manure is injected directly into the ground so that crops can quickly utilize the nutrients and no manure runs off. The manure replaces the need for commercial synthetic fertilizers. An expansion would mean more alfalfa is grown in the area which is an excellent rotational crop that improves soil health and surface water quality. This expansion is 3 miles from where I live and I am writing in strong support of this project. It will improve our environment and our community.

Thank you,

Adam Koehl

Megan Horsager **Letter 64**

I have worked closely with Riverview in Chippewa County for several years both by growing forage crops and helping on a harvest crew during silage harvest. Riverview has quickly become one of the most trusted names in our community and have continually showed that they are committed to being good stewards of our resources. Soils are tested before manure application, local wells are monitored for water quality, and their people are contually working with both the local community and state officials to follow the rules and be good neighbors.

The economic possibilities it has brought to our farm have allowed another generation of farmers to flourish, all while going above and beyond the highest levels of environmental stewardship. I fully support their business as a whole including the expansion at West River and I am confident they will comply with all regulations required.

Lucas Koehl **Letter 65**

I am writing in support of the MPCA approving Riverview's Permit application to expand West River Dairy in Synnes Township. I have lived in Stevens County for 42 years, and currently live close by 2 of Riverview's dairy sites. Riverview's sites are among the cleanest, if not the cleanest and well maintained in the industry. Riverview operates their business in a manner that is conscious of those around them, realizing the value of being a good neighbor in the community. Riverview hauls harvested feed past my house and pays for chloride to be applied to the road. If this isn't sufficient, they are quick to water the road as well, respecting local residences, and creating a safer roadway with less dust.

Speaking as a former employee, Riverview has created many employment opportunities locally. My family operates a business supporting the dairies operations of harvesting feed and field applying manure. Manure application operations are done complying with MPCA's strict standards. Manure produced from Riverview's dairies is a very valuable resource for local farmers, being able to cycle naturally produced nutrients back where they came from in order to grow the next years crop.

The dairy expansion will create demand for more feed, including many more acres of alfalfa. Alfalfa adds diversity to crop rotations, reducing crop disease and insect pressure, promoting soil health and increasing profitability for other crops.

This expansion project will provide gainful employment and business opportunities currently and in the future for the families that live in our community.

For these reasons, I strongly support the West River Dairy Expansion.

Respectfully,

Lucas Koehl

John Peck **Letter 66**

I wish to strongly oppose this expansion plan for Ridgeview Dairy. We do not need to encourage more expansion of factory farms in our state - we need more small dairy farms, not larger corporate operations. There are only 2 dairy farms left in my township - there were over a dozen 30 years ago. This loss of small dairy farms is destroying our local economies and is also jeopardizing our state's environmental quality. I've personally seen the adverse impact of manure spills in our watersheds with thousands of dead fish in our nearby river. I do not trust the capacity (or interest) of a Ridgeview Dairy when it comes to protecting our state's environment or even caring about supporting our state's economy. I will also be submitting a seperate comment to MN Attorney General, Keith Ellison, about this situation since Dairyview's expansion is also likely violating federal anti-trust regulations. Dairyview is the LARGEST dairy farm operation in the U.S. – with multiple factory farms in many states milking 100,000 cows - so it is hard to imagine how this huge milk cartel will not lead to price gouging for Midwest consumers.

Mark Gutierrez **Letter 67**

Industrial operations of this size should be required to get a permit and education on mitigating pollution via soil health practices, such as utilizing cover crops to prevent runoff and leaching of nitrates into our water supplies. In addition, these permits should come with a requirement to implement no-till and cover crops across all acres within 3 years. These practices achieve green house gas reductions, draw down CO2, and reduce nitrates and phosphorus from entering our water supply. They maybe a family farm but they are industrial at that size and should be regulated at an industrial level.

Emily Kelly **Letter 68**

Commenting on the West River Dairy expansion; land use and impacts. Having massively unprecedented amount of bovines in one area will definitely impact the site land and surrounding areas in exponential ways. Ground water usage must be considered as well as where and how the millions of gallons of water will be going. This giant proposal is like a small city and is the local water sources as well as waste water processing equip to handle that much?? Rainwater run-off from roofs is another source of displaced water. With numerous huge buildings to house animals on that scale there will be ecosystem impacts from rainwater run-off. Proper manure handling and disposal is paramount especially when the state has never had a feedlot/facility of this size. Given the questionable track record of West River Dairy in other states, the environmental & social impacts of the air pollution, water contamination, and increased soil application must be considered.

Uli Koester **Letter 69**

I am deeply concerned about Riverview LLP's plans to build a large new dairy operation in western Minnesota. This operation could hold up to 20,000 animal units. A dairy this size demands a full EIS by your agency. Please consider the pollution concerns of such a large operation, and how they will effect Minnesotans. Of special concern are the use of ground water, poor air quality stemming from the manure lagoons, and the dangers of these lagoons in a watershed of the Minnesota River.

Grant Visser **Letter 70**

I beleive this expansion would be a benefit in many ways. I have personal experience with a different Riverview site and they have been nothing but good for the community. They support local farmers and even neighbors that don't farm. In my opinion an expansion would only benefit more people, they will buy more feed from more farmers, produce more manure for fertilizer, bring more employees in who can support local businesses. From my personal experience they are very careful and strategic about smell and appearance of all Riverview properties. I know if they expanded an existing dairy the same guideline would be set and they would keep the new part just as neat and odorless as the existing one. They have there manure management and all water management very precise and very well thought out. I know they can easily handle expanding an existing site and all waste management would be just as organized. If this expansion was proposed in our area I would be 100% pushing for it so I don't see how it could be a bad thing in your area.

Kaleb Koehl **Letter 71**

My name is Kaleb Koehl, and I have lived in Stevens County for more than 26 years. During that time, I have seen firsthand the positive impact that Riverview LLP has had on our local community.

Riverview works closely with local farmers to produce the silage and other crops needed to feed their herds, helping keep agricultural production and economic activity within our region. They operate well-managed and clean facilities and have consistently demonstrated that they take their operational and environmental responsibilities seriously.

This proposed expansion would also provide meaningful benefits to our rural communities by supporting local jobs and helping attract and retain families in our small towns and schools.

In addition to Riverview's commitment to the local community, their proposed plan reflects a strong focus on environmental stewardship. Their approach to water quantity management, land stewardship, and manure handling practices demonstrates a clear commitment to responsible resource management. Through these practices, Riverview is prioritizing long-term land stewardship to ensure cropland remains productive for future generations.

For these reasons, I respectfully support the expansion permit for West River Dairy and ask the Minnesota Pollution Control Agency to approve the expansion permit.

Thank you

Kaleb Koehl

Byron Wulf **Letter 72**

My name is Byron Wulf, and I live and farm in Stevens County. I have been working with Riverview Dairy for over 20 years, selling corn and silage to them and buying manure in return. It has been a major benefit to my farm, as my products are used locally and my fertility inputs are sourced locally. This has greatly reduced the miles on my truck and the transportation of commercial fertilizers that would

otherwise be needed. This is a great win for everyone, our economy, both local and nationally, our roads, and our environment. Plus a greater supply of dairy products! The expansion of West River dairy would create more opportunities for me and others to grow this relationship across additional acres. Riverview has been very good to work with, and I appreciate how they show a respect for their neighbors and our government agencies at all levels.

As a neighbor, I am in favor of the West River expansion, and it is my hope that the MPCA can see the benefits as well.

Thomas Borgen **Letter 73**

I have been on site at multiple Riverview dairies and can't believe how clean and functional these sites are. I believe they are a value to the community and to the economy to the surrounding areas. Milk and cheese are part of the daily routine of many people and we need to keep the commodity healthy and strong for our own economy.

Perry Skaurud **Letter 74**

I am a farmer who works with Riverview Dairy in our area. They have been an incredible positive influence into our township, county, our churches, our schools. They do exactly as they say they will do. With this we have a very trusting relationship, (something that's hard to find these days). I believe our state agenceys have also found this all to be accurate statements. Riverview follows the rules to the letter of the law, and if they have a mistake or accident. It will be corrected or fixed, whatever is needed for a solution. They are very sensitive for neighbors, the environment and their relationships in the communities they have facilities. Their facilities are a standard above all I'm aware of in Minnesota. Incredibly clean, odor controlled, their employees are great to work with. When they were first considering a facility in our region and those few concerned citizens who had some oppositions, have had a complete change of mind after touring the facility and being a neighbor now for several years and seen how Riverview does business and treats the region, have no concerns and are very supportive. With the above statements in consideration, I fully support Riverview's permit for its West River Dairy expansion.

Sincerely, Perry Skaurud

Angela Anderson **Letter 075**

This proposed operation is the first of this size in Minnesota. It would be nearly double the size of the next largest operation in our state in terms of animal units. This makes it a fundamentally new and particularly powerful threat to Minnesota farmers and rural communities and our natural environment. The existing West River Dairy operation in Stevens County wants to dramatically expand its footprint.

The Minnesota Department of Natural Resources has not yet completed a mapping of Stevens County's groundwater resources and aquifers for their County Geologic Atlas Series. In fact, they have not even begun the hydrological survey of the county. The Pomme de Terre River watershed where the expansion is located is a tributary to the Minnesota River, is already considered impaired. Because of the lack of detailed information about the groundwater situation in Stevens County and the unprecedented size of this operation in Minnesota I believe an EIS will be needed before allowing this expansion. I hope the findings of the EAW will show the way.

Kimberly Bemis **Letter 76**

I am extremely concerned about the run off from the lot entering local water ways. We will need mitigation strategies detailed, emergency plans in case of natural disasters, and continued testing of down stream waterways should this gain approval. The land is not meant to hold nearly 20,000 cattle in such a small area.

I'm also concerned about how they plan to staff their facilities. As I understand, labor has been difficult to obtain and the rumors indicate Riverview uses undocumented workers to fill their ranks. A detailed examination of their payroll should also be taken before allowing such an expansion project as well, though I'm sure that falls to a different department.

Jim Murn **Letter 77**

I am in support of approving the Riverview LLP's proposal to expand their West River Dairy operation. As an agronomist for a farm that has worked with the Waukon Dairy in Gary, MN since its inception, I can't say enough good things about Riverview and the people that work for them.

I am confident their proposed expansion is as well thought out and environmentally sound as any of their existing facilities. You won't find a better dairy operation that cares for its cows, its employees, the environment AND its neighbors (farming or not).

In today's world, the synergy that is generated when local crop farms get together to raise feed for one of these dairy's is the best thing in the long run for all participants: The dairy gets the feed they need at a fair price, we pay for and utilize their manure for the crops we raise, we get a price for our crops that is at a premium to bringing it to town. PLUS our region gets additional residents that would otherwise not be here. And it keeps building from there. Simple economics. Just at more efficient scale to fit today's world than the original dairy and crop farms of years ago.

Adding capacity to an existing dairy in the Riverview system can only increase the potential for farms in the area to participate in the synergy and success that is the result of this animal-crop production relationship.

Sincerely,

Jim Murn

Sydney Bauer **Letter 78**

As a resident of Stevens County I am deeply concerned about the environmental impacts that a project of this scale could have on my community, my state, and the downstream waterways. I think a full, thorough Environmental Impact Statement is necessary for a project of this novel size.

The GHG testing done in this EAW should account for the total number of cows in the facility, not just for the intended additions. An analysis of simply the increased number of cows DOES NOT equate to the total impact of the facility on water, land, and rural economy. If this facility needs 13,200 acres of farmland for manure application, this should be further looked into. The impacts of this facility will not just be within the confines of its property. I would like to see an EIS that takes into account how the 13,200 acres of farmland and their surrounding areas will be impacted.

The location of this facility is within the Pomme de Terre watershed, just 25 miles north of its confluence with the Minnesota River. The EAW does not provide enough detail into how this will affect our downstream neighbors from here to the Gulf. This EAW does not provide enough detail into how it will affect our water resources in Western MN.

As someone with dairy farming family members, I am also interested in this project requiring higher scrutiny for how it will impact small and medium sized dairy farms. Will this project impact the milk market in unsustainable ways? Will this project support local economies across the state in keeping their family farms afloat? What is the pattern of small and medium family farmers in Stevens County and the surrounding area?

I am also concerned about a facility of this size being granted permitting access without a full EIS because of Riverview's history of manure spills and water overpumping. This project will need 250 million gallons of liquid manure storage waste. I believe there should be scrutiny here to assess the impacts of this facility on communities, especially if these facilities have had already spilled their waste in our rural communities (Kandiyohi County). This EAW does not look at the impacts these spills have had on our communities. Riverview also just made an agreement with Arizona communities to pay $11 million dollars as a result of their overpumping the aquifer. This EAW does not look at the impact this facility will have on water resources with enough detail.

A full EIS is required to better understand the impact of this novel and impactful project. As a resident of Stevens County and someone who cares about considering the future of our local economy and natural resources, this project should require a full Environmental Impact Statement.

Miriam Gieske **Letter 79**

As a resident of Stevens County MN, where the proposed Riverview Dairy expansion would be located, I am concerned about its environmental impact and would like the MPCA to require a full Environmental Impact Statement before the project can go forward. This project would more than double the size of Riverview's dairy operation in Stevens County, with the final size being almost twice as large as the next largest livestock operation in our state in terms of animal units. A project of this unprecedented scope demands particular care in reviewing its impacts, which a full Environmental Impact Statement would provide. In addition, I believe it is important for the EIS to take into account the total projected size of Riverview's Stevens County dairy operations, including existing animal units, not just the size of the expansion. Total size matters because the larger the total size, the larger the potential impact if something goes wrong. For example, Riverview's Feb. 2025 manure spill in Kandiyohi County likely spilled approximately the same amount of manure in 5 days that an average sized MN dairy farm would produce in 6 months, based on early reports.

Nate Hultgren **Letter 80**

We write this letter in support of the West River Dairy expansion. Our family farms next to another Riverview dairy (Meadow Star near Pennock, MN) and can sincerely say that our experiences with Riverview have been positive for our family farm.

Applying manure each fall instead of commercial fertilizer has been a documentable soil health improvement. Instead of buying fertilizer from across the globe and incurring all of that shipping cost and environmental impact, we are getting our nutrients from one mile away. We also raise forages--silage and alfalfa. The alfalfa in our rotation has also helped improve soil health and the perennial vegetation fights soil erosion. Raising the silage and selling our dry corn to the dairy, here again, takes truck off the highways where we might have incurred 10-15 miles hauling product to elevators.

Riverview's sites are clean and well-maintained. Their employees, some of whom live on-site and are our neighbors, are respectful, clean and quiet. The dairy makes sure to take care of the roads around the site, and collaborates with us as neighboring farmers to make sure the site is living up to high expectations.

Riverview supports our local communities and has filled an economic development void in an otherwise declining commercial area. Our family has been able to participate in helping with forage production, manure application, and community events.

We stand in full support of the West River Dairy expansion as we know from experience that Riverview will conduct this expansion with no compromises of safety, environmental protection, and attention to detail. The community will benefit from this expansion.

Sincerely,

Nate & Jaime Hultgren

Cameron Berthiaume **Letter 81**

I am concerned about the impact of this project and believe it needs a full environmental impact statement. I would also like to request a public meeting regarding this project if possible. As a Morris resident, this project is close to home.

Looking through the documents and looking at the maps, I see that there are prairie conservation areas and at least one area important to birds (attachment 7c) - having ecologically significant areas nearby merits careful investigation of the potential impacts of such a large project. There are also lakes that support biodiverse populations (7d).Though page 53 of the EAW says that project areas were changed to avoid overlap, "...the DNR noted that the Minnesota Biological Survey (MBS) identified one or more sites of Biodiversity Significance adjacent to some of the proposed manure application areas (Attachment 7d)... in all cases, these ecologically significant areas are outside the tillable fields designated for manure application." Even if manure application guidelines are followed, I believe the impact of areas adjacent to these ecologically significant zones warrants more investigation. Just because an activity does not take place directly on the ecologically significant land does not mean it will not affect said land - adjacent is still nearby enough to be important. I also see that some of the manure application areas are near the Pomme de Terre River, in some cases right up against it.

I am also concerned about the amount of water used. Hundreds of millions of gallons per year is an incredible amount that's hard to conceptualize. I am glad that there will be pumping restrictions, but these restrictions seem to target shorter lengths of time (years or seasons). More consideration must be given to the long-term impacts of utilizing the area's aquifers. When all the water use around the facility is considered (more ag and nearby communities), the amount is staggering. Is there data that can verify the water used by this facility won't deplete the aquifers faster than they can recharge?

Also, talking climate change - I read the section of the EAW on greenhouse gas emissions. Efficient practices and carbon sinks help, but they can't do it all. More cows means more methane.

My final thought - I would like to see more in-depth data on the hydrology of the area, including the aquifers. A fuller picture and better understanding of the area's groundwater resources must be gained.

I appreciate the work that has been so far, but a closer look is necessary.

Lizzy Haywood **Letter 82**

The West River dairy expansion, proposed by Riverview LLP, is a project that must be preceeded by an EIS. The size of this project is something MN has not seen before and must be measured and evaluated through the accepted methods of an EIS.

I believe that careful evaluation of projects like this can ensure rural Minnesota's environment is protected, and that agriculture can thrive.

With a project of this size, the mpca should NOT set a new precedent of not evaluating effectively. For the healthy future of Minnesota's farm economy and water quality, require the EIS for the West Dairy Expansion.

Thank you,

Lizzy Haywood

Mary Ellen Frame **Letter 83**

The application of Riverview LLP is of such enormous proportions that a full Environmental Impact Statement must be filed with MPCA. Damage to the environment, local residents, and economy seems inevitable with such a monstrous, industrial entity in a vulnerable rural area--or anywhere else.

Gabriela Santiago **Letter 84**

Minnesota is already losing dozens of dairy farms annually due to inconsistent and often below cost-of-production milk prices. Massive dairy operations, like the one Riverview is proposing to build, have glutted the market and tightened Big Milk's stranglehold on the industry, allowing them to push small and medium-sized family farms out of business and off the land. This operation would only exacerbate the situation and accelerate the loss of dairy farms in our state, decimating Main Street economies in the process.

Naomi Skulan **Letter 85**

As a resident of Stevens County, I am incredibly concerned about the possible environmental impacts a dairy operation of this size would have. Without a full Environmental Impact Statement, we won't know the costs this massive operation would have on the local waterways and land until after the damage was already done. In particular, I am concerned about manure spills and protection of our waterways and waterfowl and wildlife production areas. A farming operation of this magnitude should have a full Environmental Impact Statement completed before being allowed in operation.

Danielle Green **Letter 86**

As a Stevens County resident, I'm concerned about the potential environmental impact of the proposed Riverview Dairy expansion and think the MPCA should require a full Environmental Impact Statement before the project moves forward.

This expansion would more than double Riverview's dairy operation in Stevens County and make it much larger than any other livestock operation in Minnesota in terms of animal units. A project of this size really deserves a thorough environmental review.

Any review should look at the total size of Riverview's Stevens County operations, not just the proposed expansion. The larger the operation, the greater the potential impact if something goes wrong. Recent events, like Riverview's tank failure at Meadow Star Dairy near Pennock, show why careful review matters when operations reach this scale.

There's also precedent for this. In 2014, the MPCA Citizens' Board required a full Environmental Impact Statement for a proposed 8,850 cow Riverview dairy in Stevens County because of concerns about water quality, water use, and cumulative impacts. A full EIS makes sense for projects of this scale.

Gwendolyn Fassett **Letter 87**

This Riverview-proposed expansion of West River Dairy MUST have an EIS before it goes any further. It would be the largest CAFO in the state, when we should be moving rapidly away from CAFOs toward more sustainable forms of agriculture. We can't afford the amount of water it would require, let alone the potential for pollution of the water and land around it! Please do a thorough study, not a performative one! Thank you!

Bonnie Haugen **Letter 88**

Bonnie Haugen comment on West River Dairy Expansion Farming is Everybody's Bread, Butter, and Water. What I do on my hills affects water quality and quantity for Everybody.

I am a retired dairy farmer. Our family milked 100 – 200 cows 1994 until 2024. Due mostly to unstable and low milk prices, we ceased shipping milk and transitioned to a beef farm. The pressure from the existing large Confined Animal Feeding Operations (CAFO) dairies is causing harm to our milk markets for many farmers. They can flood the market, tip the market to a monopoly, and create unfair financial pressure on the existing farms. That pressure makes the milk income price fluctuate and unsustainably low. Farm families quit milking or sell the farm business. Therefore, our towns receive less business, and the community struggles.

A Full Environmental Impact Statement (EIS) is needed.

I was a member of the Southeast Minnesota Nitrate Strategies Collaborative Work Group. I learned about water quality and quantity issues during our meetings July of 2024 through June of 2025. One of those issues which comes to mind when I think of this permit application is related to the feed for the 18,855 cows. Certainly, containing and spreading the liquid manure has many concerns for people's safety, the high risk of contaminating water, air, and ground. However, I was surprised to learn that it is raising the feed that often causes more of a nitrogen problem. Corn, a major feed component of dairy cows, is a monoculture crop. When nitrogen is applied, its easily overapplied.

Further, in these unprecedented weather events, a farmer may apply nitrogen pellets in good faith, but a rain of surprise timing and deluge can wash it away, polluting our water and giving the farmer cause to apply more fertilizer, risking more nitrogen going into our drinking water. Cover cropping, precision application, and following recommendations alleviate nitrate runoff and improves soil health. Yet, following regulations does not always protect our environment. Weather events can cause catastrophic overflows, cracks or leaks in structures and hoses happen.

A Full Environmental Impact Statement (EIS) is needed to better minimize the huge risks this huge business proposes. The environment and people in that region and watershed deserve a EIS be conducted with integrity.

Water tables, aquifers, streams, creeks, pathways do not abide by township, county or state borders. This proposed expansion is within five miles of eight different waterfowl and wildlife production areas. Allowing the pumping of 226 million gallons of water every year needs study. Can the aquifer handle that much additional drawdown and not cause issues of quantity or quality for the existing towns, rural wells, farmland, and rivers? Can the watershed survive? I think a full study needs to be completed before a decision can be made on permitting this size of an industrial agriculture business.

A Full Environmental Impact Statement (EIS) is needed.

Manure lagoons and miles of hoses also give me concerns for people and water safety. Lagoons of these sizes can be very risky. Man made structures fail eventually. But even if not often, when a hose or

lagoon of these sizes leaks, the pollution is not easily or quickly cleaned up. The risks of this size need extra special study before permitting.

A Full Environmental Impact Statement (EIS) is needed.

There are not other CAFO's of this huge size in our state. There are studies showing the social and economic effects of CAFO's on our communities. Should we assume that those same effects will be the same except the impact will be huge, as the CAFO is huge? We should not make uneducated and unresearched guesses before allowing a permit for this size CAFO.

A Full Environmental Impact Statement is needed.

Thank you for your needed attention to this critical nature of this threat to our environment and people.

Respectfully,

Bonnie Haugen

Maddie Brown **Letter 89**

I am a concerned citizen from Southeast Minnesota. I appreciate the opportunity for public comment on this EAW for the West River Dairy Expansion. Based on the EAW, I see a clear obligation for MPCA to issue an EIS on this project.

The MPCA has the statutory obligation to issue an EIS in this instance. Minn. R. 4410.1700, subp. 1 states that the MPCA must order an EIS for projects that have the "potential for significant environmental effects." The criteria for significant environmental effects includes the cumulative potential effects (as stated in Subp. 7 of the same statue). Similar dairies of the proposed size (a combined total of 26,397 AU), have shown clear cumulative impacts to surrounding communities including groundwater nitrate contamination, odor issues, reduced air quality (particulate matter/ammonia), increased greenhouse gases, and increased water consumption. As it stands, the EAW does not provide sufficient information (as referred to in Subp. 2a) to fully quantify these likely impacts. Therefore West River Diary Expansion clearly meets the criteria that mandates MPCA must issue an EIS.

Allowing the proposer to create the largest mega-dairy in Minnesota without the due diligence of an EIS would be an insult to family dairy farmers across the state who are struggling to survive while doing the right thing. In addition, by not issuing an EIS, the State risks allowing the proposer to pollute our waters at no cost to them, pushing the bill for cleanup onto future taxpayers. Dairies of the proposed size can pose an economic threat to family farms, a hazard to the health and wellbeing of rural communities, and can become a costly burden to taxpayers in the long run. Citizens deserve to understand the full risks of the project without the MPCA rubber stamping its approval.

I urge the MPCA to uphold their statutory obligation and issue an EIS on the proposed West River Dairy Expansion.

Diane Michelfelder **Letter 90**

It is vital that the Riverview Dairy be required to submit an environmental impact statement. It is nearly twice as big as any current operations in the state, and its environmental harm would be enormous. Here's what we know now.

Massive water use: Riverview would pump up to 226 million gallons/year from an off-site well—nearly as much as the entire City of Morris (permitted for 300 million gallons/year for 5,000+ residents).

Huge waste output: The facility would generate about 202.7 million gallons of liquid manure and wastewater annually, plus 26,400 tons of solid manure.

Unknown groundwater impacts: The DNR hasn't begun the hydrologic survey or completed the County Geologic Atlas for Stevens County, so aquifers and groundwater resources aren't mapped—making it risky to permit large withdrawals now.

Sensitive, already-impaired waters: The expansion sits in the Pomme de Terre watershed, designated sensitive; the nearest waters—the Pomme de Terre River and a nearby unnamed creek—are already listed as impaired. The project would likely worsen these impairments.

Advancing permits without a full understanding of groundwater and water-quality risks is irresponsible. It is critical that the MPCA require a full Environmental Impact Statement.

I think an excellent source of information about the risks of CAFOs on water quality can be found in a publication from the journal Environmental Health Perspectives. I respectfully would like to call it to your attention by uploading it here as a .pdf. It is also available on the National Library of Medicine website.

Yeshwant Kethineni **Letter 91**

Given Riverview's history of manure spills, water use and water overpumping, I would like there to be testing / research done on how this may affect water resources in the area

Emily West **Letter 92**

Feedlots destroy land, water, and nearby residents' quality of life. Advancing permits without a full understanding of groundwater and water-quality risks is irresponsible. It is critical that the MPCA require a full Environmental Impact Statement.

Nathan Koehl **Letter 93**

My name is Nathan Koehl and I have lived in the area surrounding existing sites for most of my life. We have never noticed any changes or negative impacts on our well water quality or quantity. We also have worked closely with sites in our area for manure application. The application is always carried out responsibly and with utmost care for neighbors and farmers in the area. Soil sampling and monitoring has been diligently followed so that soil and water health are maintained. Manure has helped support us in serving our soil better and has allowed us to raise healthier and more sustainable crops on our ground.

The crews that work with Riverview to harvest their crops are always very respectful and maintain road quality, manage dust properly, and make sure that neighbors and safety are top priorities. As a long-time neighbor to Riverview I encourage the MPCA to approve the expansion permit for West River Dairy.

Thank you.

Melissa Swenson **Letter 94**

This project is too large and potentially environmentally destructive to the area. Please make an informed decision by having a fair environmental study completed. Better to be safe than sorry.

Rebecca Tryon **Letter 95**

The Riverview Dairy project must be required to get an Environmental Impact Statement. The potential for a profound impact on local water resources is too substantial to ignore based on data from other large animal agriculture projects. Please require a more extensive review of the potential harms before implementing. The land of 10000 lakes should protect its greatest resource

David Smith **Letter 96**

The Riverview Dairy project must be required to get an Environmental Impact Statement. I am very concerned of the impact the Riverview Dairy will have on the environment. It is vital that the Riverview Dairy be required to submit an environmental impact statement. It is nearly twice as big as any current operations in the state, and its environmental harm would be enormous. Here's what we know now.

Massive water use: Riverview would pump up to 226 million gallons/year from an off-site well—nearly as much as the entire City of Morris (permitted for 300 million gallons/year for 5,000+ residents).

Huge waste output: The facility would generate about 202.7 million gallons of liquid manure and wastewater annually, plus 26,400 tons of solid manure.

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Sensitive, already-impaired waters: The expansion sits in the Pomme de Terre watershed, designated sensitive; the nearest waters—the Pomme de Terre River and a nearby unnamed creek—are already listed as impaired. The project would likely worsen these impairments.

Advancing permits without a full understanding of groundwater and water-quality risks is irresponsible. It is critical that the MPCA require a full Environmental Impact Statement.

Anna Kilian **Letter 97**

Hello I am a resident of Stevens County and I have concerns about the new expansion of the Riverview dairy lot. I am requesting a full Environmental Impact Statement (EIS) be made to help guide the planning of this expansion.

I have done a general review of the environmental assessment worksheet (EAW) and see the beginnings of plans to lower the impact on the environment. I am concerned that not all plans have been throughly fleshed out. Such as "Increase impervious surfaces by 121 acres" and "increase in manure storage". In the last year Stevens county and surrounding areas were heavily impacted by above average rainfall in short windows with 5+ inches in a 24 hour period. I think a full EIS will help ensure that the EAW plan will prevent further road floodings, sediment deposition in the river, wildlife impacts, and any potential leaks of manure or other hazardous materials into the pomme de terre river. This feedlot will have environmental impacts and I wish to see all plans to minimize these as much as possible with an EIS.

Thank you for your consideration and work to help make this dairy lot possible. I recognize the importance of having animals to feed the country, and as an avid cheese fan myself I am not against the expansion just want to see a full Environmental Impact Statement to help prevent irreversible damage to the prairie and wetlands around my home. We have few chances to keep our environment safe and look forward to this lot not being part of the problem.

Ian Hoxworth **Letter 98**

We don't need expansion of a plant that creates more environmental disasters.

Sarah Hollinger **Letter 99**

This proposed operation is the first of its size in Minnesota. It would be nearly double the size of the next largest operation in our state in terms of animal units. This makes it a fundamentally new and particularly powerful threat to Minnesota farmers and rural communities.

Minnesota is already losing dozens of dairy farms annually due to inconsistent and often below cost-of-production milk prices. Massive dairy operations, like the one Riverview is proposing to build, have glutted the market and tightened Big Milk's stranglehold on the industry, allowing them to push small and medium-sized family farms out of business and off the land. This operation would only exacerbate the situation and accelerate the loss of dairy farms in our state, decimating Main Street economies in the process.

No feedlot has ever undergone an Environmental Impact Statement (EIS) in Minnesota. Each time the MPCA has determined that an operation should undergo one, the operator that requested the permit has withdrawn their application. And all of those operations that were determined to need an EIS were significantly smaller than Riverview's proposed operation will be.

If built, the Riverview operation would be allowed to pump up to 226 million gallons of water per year from an off-site well. For reference, the City of Morris, which is home to over 5,000 people, is permitted to pump up to 300 million gallons of water a year. Once constructed, the facility would produce 202,744,000 gallons of liquid manure and wastewater a year and 26,400 tons of solid manure a year.

The Minnesota Department of Natural Resources has not yet completed a mapping of Stevens County's groundwater resources and aquifers for their County Geologic Atlas Series. In fact, they have not even begun the hydrological survey of the county. It is irresponsible to other water users and residents of the area to move forward with this permit without a full understanding of the potential impacts.

The Pomme de Terre watershed, where this expansion is proposed, is already considered a sensitive watershed. The MPCA already lists the two closest waterways to the facility, the Pomme de Terre River and an unnamed creek, as impaired, and this proposal would only exacerbate the impairment

Eric Zeltwanger **Letter 100**

I fully support Riverview in the expansion of West River dairy. They maintain their sites impeccably and are great neighbors. I consider myself lucky to be able to see modern ag at its finest close to my home. Thank you

Andrew Falk **Letter 101**

This must have an EIS. This is not farming but an industrial scale operation. Riverview is nothing more than a corporate entity. It has Human Resources departments, accounting departments, logistics departments, lobbying efforts, all the things that a large corporate business entity has; not a family farm.

Please do the right thing and require an EIS.

Benjamin Koehl **Letter 102**

My name is Benjamin Koehl, I am a resident of stevens county, I have grown up with riverview dairys around my home all my life. Riverview has been a huge asset to the stevens county area supporting the community with jobs for electricians, plumbers, construction workers farmers,truckers the list goes on, and also not to mention all the workers that are brought in to work spend money in the county which

help boost our local economy. As a farmer riverview takes care of the land they are very careful on how and when they put on manure they are easy to work with as well. The manure is a huge benefit to our soils boosting microbiology, organic matter and providing a cheap source of fertilizer for us as the farmer. As a farmer riverview gives us the farmer to have different crops like alfalfa in our rotation to diversify, and offers a positive basis for our corn for corn silage.

Whenever I see somthing done by riverview its always done 110% and better than the status quo. When i drive around the current west river dairy site the feed and manure runoff is properly contained to avoid runoff everythings "tour ready" whenever i drive around. In conclusion to the matter I am in full support of the west river dairy site as a local Stevens county citizen.

Beth Kieffer **Letter 103**

Where is all this water coming from? Where will all the manure be disposed of? Not a good move.

Cathy Solvie **Letter 104**

I think the Riverview is large enough and already uses way too much resources to let this expansion happen. You need to think of the pollution that could happen and this expansion will only put more money in the pockets of people who have more than enough already.

Brandon Semel **Letter 105**

This proposed dairy is enormous, and it will create waste and resource demands greater than entire towns. It would be irresponsible not to require an EIS be completed to ensure that the proper safeguards are in place prior to the approval of this expansion.

Terry Maloney **Letter 106**

This will affect everything and everyone in the area. It will suck the life out of the surrounding area where they get their water from and drain their manure to. Maybe not right away but when it does, it will be too late! They're big enough, there's no need to get bigger. They only want to fill their pockets. They have no regard for the community. LEAVE OUR COMMUNITY ALONE!! It's perfect the way it is right now and so is Riverview there's no need for it to get bigger! Who's this going to benefit...Riverview and only Riverview...Ugh.....

Sylke Boyd **Letter 107**

I am concerned about the impact of this facility on several factors: (1) the ground water supply, (2) pollution of the surface water shed, (3) increased traffic, (4) the welfare of the animals involved, (5) further degradation of the soil, biodiversity, landscape of the county. This project should undergo much scrutiny in terms of the true necessity to further degrade our natural resources. I am opposed to sacrifice them for the increase in wealth and influence of a corporation that has previously shown to act irresponsibley with public goods.

Agnes Dieter **Letter 108**

Rural Minnesota is constantly fighting to keep local business, agriculture, and resources protected and local. Allowing Riverview to monopolize the dairy industry is not conducive to the tenants that make rural Minnesota what it is. The pros — more jobs and expanded industry — do NOT outweigh the possible economic, environmental, and social cons. Depleting and/or damaging a county's resources to

further the monopolization agenda is not sustainable in rural Minnesota. Resources, such as water, are already at an environmental risk at large in this country due to other risk factors, that putting Steven's county on the map for danger to water only furthers the risks already in place. Riverview may want to think they deserve to be a monopoly, or titan of industry, or some other self-imposing title, but no amount of money or veiling should make a county turn a blind eye to the risks of our natural resources, land, and local community and economy.

Alia McIntosh **Letter 109**

It is vital that the Riverview Dairy be required to submit an environmental impact statement. It is nearly twice as big as any current operations in the state, and its environmental harm would be enormous. Here's what we know now:

Massive water use: Riverview would pump up to 226 million gallons/year from an off-site well—nearly as much as the entire City of Morris (permitted for 300 million gallons/year for 5,000+ residents).

Huge waste output: The facility would generate about 202.7 million gallons of liquid manure and wastewater annually, plus 26,400 tons of solid manure.

Unknown groundwater impacts: The DNR hasn't begun the hydrologic survey or completed the County Geologic Atlas for Stevens County, so aquifers and groundwater resources aren't mapped—making it risky to permit large withdrawals now.

Sensitive, already-impaired waters: The expansion sits in the Pomme de Terre watershed, designated sensitive; the nearest waters—the Pomme de Terre River and a nearby unnamed creek—are already listed as impaired. The project would likely worsen these impairments.

Advancing permits without a full understanding of groundwater and water-quality risks is irresponsible. It is critical that the MPCA require a full Environmental Impact Statement.

Kathy Dunn **Letter 110**

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Advancing permits without a full understanding of groundwater and water-quality risks is irresponsible. It is critical that the MPCA require a full Environmental Impact Statement.

Grant Ascheman **Letter 111**

My name is Grant Ascheman.

I am a resident of rural Swift County, Minnesota. I am 28 years old and have lived here my entire life. My family farm lies 1 1/2 miles from Stevens County the county where the West River Dairy expansion is being permitted. I strongly support the expansion and the approval of its permitting.

Riverview has been and continues to be an excellent company in both Stevens and Swift counties. They are a great employer in these counties that continue to see populations declining. Providing good jobs in our local community.

As a farmer they have provided our family the opportunity to sell silage corn to them providing an alternative and local end user market for our crop. I have personally helped with harvest at 2 of Riverview's dairies in Stevens County and another in Swift County. Riverview goes above and beyond in regards to being good neighbors. During their harvest season they take great safety precautions, maintain dust control on gravel roads, and avoid their harvest equipment meeting on the road whenever possible. All at their expense to be neighborly.

Our family farm has also had the opportunity to purchase manure from Riverview to apply as fertilizer on our land. They are diligent in testing the nutrients in the soil and manure prior to application to assess appropriate application rates. This process maintains environmental excellence while providing our land with the necessary nutrients needed to raise great crops in Western MN. We have seen great benefits to our soil health from these manure applications and they will continue to be a benefit to our land into the future.

Riverview's sites are extremely clean and well maintained. They have maintained this excellence for decades in Stevens County.

I believe Riverview will not compromise on safety, the environment, or being good neighbors in this expansion. For those reasons I stand fully in support of the permitting of this expansion and believe it will be a great benefit to our community.

Sincerely,

Grant Ascheman

Jennifer Keller **Letter 112**

As someone who values protected areas and watersheds and all natural resources in general this expansion should not be allowed until a thorough assessment is completed. Furthermore, Riverview has shown that they overuse resources as evidenced by their Arizona locations. In addition, there are days that it smells extremely pungent in Morris, so much so that I, who suffer from asthma, have issues going outside due to the overwhelming odor of manure. Expanding would only make that problem worse and hinder people from enjoying the outdoors. So I urge you to fully study the environmental impact, including air quality before allowing this expansion. I, for one, am vehemently against this.

Wesley Sisson **Letter 113**

I submit the following public comment regarding the proposed expansion of the West River Dairy operation. As a citizen concerned with environmental stewardship and the long-term sustainability of Minnesota's natural resources, I urge the MPCA to carefully scrutinize this proposal and consider the substantial risks associated with creating what would become the largest concentrated animal feeding operation (CAFO) in the state.

Large-scale CAFOs pose significant environmental challenges, particularly in regions where groundwater, surface water, and rural community health are closely interconnected. The proposed scale of the West River Dairy expansion raises several concerns that warrant heightened regulatory review and public transparency.

First, manure management at this scale presents a serious risk to water quality. With thousands of dairy cattle producing millions of gallons of manure annually, the potential for nutrient runoff, nitrate contamination, and phosphorus loading into nearby waterways increases dramatically. Minnesota has already experienced widespread nitrate contamination in groundwater and harmful algal blooms in lakes and rivers due to agricultural runoff. Expanding the state's largest CAFO could exacerbate these existing challenges, if manure storage, land application, and monitoring systems fail or are overwhelmed.

Second, groundwater protection must be a central consideration. Much of rural Minnesota relies on shallow aquifers for drinking water. Studies across the Midwest have demonstrated that large livestock operations can contribute to nitrate contamination of groundwater through manure seepage, over-application on fields, or extreme weather events. As climate change increases the frequency of heavy rainfall and flooding, manure lagoons and storage systems face greater risks of overflow or leakage.

Third, the cumulative environmental impact of such a large operation must be evaluated, not merely the direct facility footprint. The transportation of feed, manure spreading over wide land areas, increased truck traffic, and air emissions which include ammonia and methane can affect surrounding ecosystems and nearby residents. Air quality impacts, odors, and particulate matter are well-documented concerns associated with high-density livestock operations.

Fourth, the scale of this proposal raises broader questions about agricultural sustainability in Minnesota. While dairy farming is an important part of the state's rural economy, the consolidation of livestock into extremely large operations can create environmental risks that smaller-scale systems distribute more sustainably across the landscape. The MPCA has a responsibility to ensure that economic development does not come at the expense of Minnesota's water, soil, and public health.

For these reasons, I respectfully request that the MPCA:

1. Conduct a thorough and transparent environmental review of the proposed expansion.

2. Require rigorous groundwater monitoring and publicly accessible reporting.

3. Ensure that manure management plans account for extreme weather events and long-term soil nutrient loading.

4. Evaluate cumulative environmental impacts, including air emissions and watershed-level nutrient pollution.

5. Provide meaningful opportunities for public participation and community input before any final approval.

Minnesota's lakes, rivers, and groundwater are among the state's most valuable natural assets. Decisions regarding large-scale agricultural developments must reflect a precautionary approach that protects these resources for future generations.

Thank you for considering these comments.

Respectfully submitted,

Edwin Garcia **Leetter 114**

Given the fact that the company has been sued for over usage of water, and not caring for the well being of it neighbors, I am saying no to the expansion.

It's a only a matter of time they drain the resources from the area and move on to the next state.

Douglas Hauge **Letter 115**

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Sensitive, already-impaired waters: The expansion sits in the Pomme de Terre watershed, designated sensitive; the nearest waters—the Pomme de Terre River and a nearby unnamed creek—are already listed as impaired. The project would likely worsen these impairments.

Advancing permits without a full understanding of groundwater and water-quality risks is irresponsible. It is critical that the MPCA require a full Environmental Impact Statement.

Catherine Day **Letter 116**

I support a strong environmental impact review for this project. The scale of the proposed farm is too large and will have a negative effect on the river and the ecosystem of the area.

Kristi Trout **Letter 117**

I do not think this expansion should be allowed to go through. This area used to be known for small family owned dairyfarms, providing livelihoods for hundreds of families. These big companies have come into farming communities and taken over. Today, if one where to around drive around this area, they would be hard-pressed to find more than a couple of small family dairyfarms. We also need to protect our lakes and rivers, the environment as a whole, needs to be taken into consideration. We need clean rivers, as well as lakes. Producing that much manure and using that much water from the existing facility is enough, we don't need more added to the environment. Let's also take into consideration the livelihoods of small family owned dairyfarms.

Laura S **Letter 118**

No, I do not support this expansion. I understand it would bring work and economic growth to Morris, but destroying our watershed isn't the way to do it. Pomme de Terre has a special place close to my heart because I grew up less than a mile from it and often times fished, threw pebbles, and just enjoyed the water. Please don't ruin this river! It's my childhood and so many others, on a personal level.

Cecily Melde Erickson **Letter 119**

This must have an EIS. This is not farming but an industrial scale operation. Riverview is nothing more than a corporate entity. It has Human Resources departments, accounting departments, logistics departments, lobbying efforts, all the things that a large corporate business entity has; not a family farm.

Please do the right thing and require an EIS.

Gail Johnson **Letter 120**

No. Provide more opportunities to the young independent generation of farmers to take over and manage their family farms. Excessive water use and concentrated gastly waste managment can not creep into Minnesota. The pararie lakes, rivers, beautifully scenic crop fields, and vacation areas are too precious to the Minnesota econony.

Sammy Johnson **Letter 121**

I vote no. We don't want this. The land should go to the local farmers and their families that will take over the farming business for years to come.

Kristin McNeill **Letter 122**

We live a couple of miles from the West Riverview location and have lived here most of my life. What about our water? We've already seen a noticeable decline in water quality. When our well needs to be dug deeper - or even relocated - because they have pulled the level so far down, will they be footing that bill? Will there be any concern for the neighbors?

Cassandra Carskadon **Letter 123**

Already water is a precious resource. We already have corporations trying to take this precious resource for various enterprizes. There is no need for this expansion. Especially when you're not done doing all the research about ground water in the area.

Jeremey Katopol **Letter 124**

The proposed feedlot is high risk from both an environmental and economic standpoint. Please do not allow them to destroy our water further.

Jacqueline Hadrath **Letter 125**

No to the expansion. Save our small farmers and the land!

Fred Tio **Letter 126**

It is vital that the Riverview Dairy be required to submit an environmental impact statement. It is nearly twice as big as any current operations in the state, and its environmental harm would be enormous. Here's what we know now.

Massive water use: Riverview would pump up to 226 million gallons/year from an off-site well—nearly as much as the entire City of Morris (permitted for 300 million gallons/year for 5,000+ residents).

Huge waste output: The facility would generate about 202.7 million gallons of liquid manure and wastewater annually, plus 26,400 tons of solid manure.

Unknown groundwater impacts: The DNR hasn't begun the hydrologic survey or completed the County Geologic Atlas for Stevens County, so aquifers and groundwater resources aren't mapped—making it risky to permit large withdrawals now.

Sensitive, already-impaired waters: The expansion sits in the Pomme de Terre watershed, designated sensitive; the nearest waters—the Pomme de Terre River and a nearby unnamed creek—are already listed as impaired. The project would likely worsen these impairments.

Advancing permits without a full understanding of groundwater and water-quality risks is irresponsible. It is critical that the MPCA require a full Environmental Impact Statement.

Kay Slama **Letter 127**

Require a Riverview Dairy EIS!

I taught some courses at UM_Morris and worked at the Stevens Community Medical Center in Morris MN. At the latter job, I occasionally treated workers at Riverview Dairy. I also enjoyed the natural areas around Morris, such as the Big Stone National Wildlife Refuge and the Edwards Wetland Management Area, which, along with the city, depend on good water levels and good air quality.

It is vital that the Riverview Dairy be required to submit an environmental impact statement. It is nearly twice as big as any current operations in the state, and its environmental harm would be enormous. Here's what we know now.

• Massive water use: Riverview would pump up to 226 million gallons/year from an off-site well—nearly as much as the entire City of Morris (permitted for 300 million gallons/year for 5,000+ residents).

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Advancing permits without a full understanding of groundwater and water-quality risks is irresponsible. It is critical that the MPCA require a full Environmental Impact Statement.

Charlie Rea **Letter 128**

Please for the sake of the local people, animals, and land do NOT allow this to happen! The long term effects will be un-doable and will negatively impact so many. Please keep things as they currently are i beg of you

Kathryn Droske **Letter 129**

I have lived and worked in Morris and currently raise cattle in a nearby community. For the sake of the community, the waterways, and wildlife, the unprecedented expansion proposed by Riverview must be subject to a full environmental review.

Kelli Olson **Letter 130**

Living not far from this dairy(within 30 min) I have already seen first hand how this large operation has taken over so much farmland as small families cant even compete with what they pay for land and dont feel this would help change that. I think this would be a big mistake!

Joel Hoffmann **Letter 131**

No, there will be no small farms left if Riverview keeps expanding . Greed is destroying AG and ruining opportunities for young people to milk cows or join agriculture. Not to mention Riverview draining wells of water .There is no reason for anyone to milk 100,000 cows and more . And have all the workers be visa workers it's really sad what they are doing to Dairy and destroying small communities economy's . Bring back small farms and stop with corporate farms and greed. Pretty soon it will just be Riverview being the only dairy farm in MN

Eric Koehl **Letter 132**

I am in favor of the West River Dairy expansion. We live and work close to the Riverview and D45 dairy sites. The sites are kept super clean and have very little odor. The dairies we live next to provide and economic engine for other businesses and a healthy tax base. The dairies we live next to are good neighbors. We feel the West River, Riverview and D45 dairies are a synergy for our farm and community.

Thanks, Eric

Brenna Rollie **Letter 133**

Absolutely NO! CAFO is just a creative way to use language that doesn't say factory farm and industrial scale farming.

Robert Filipczak **Letter 134**

Please don't let this happen. We need smaller farms, not factory farms.

Jeff Engebretson **Letter 135**

Today's money grab industries should really feel how the communities and environment can and will be affected from decisions that are solely based on profits.

The impact that this will have to our water sources and environments are and can be detrimental to a wide range of areas. The Pomme de ter reaches into three other major water sources and if you think there won't be an impact done because of runoff and seapage you are mistaken.

This is a no-brainer and it should be stopped from happening. Not to mention the little farms that it will crush a long the way. Absolutely disgusting and when you think of rural Minnesota you definitely don't see this as being a community driven outcome.

Stop this from happening.

Julie Lloyd **Letter136**

There is way too much at stake here. There must be more information gathered before a decision of this magnitude is made without considering all the ramifications. We must protect our water and our family farms!! This huge operation will not only destroy the environment, but will also destroy many small farms. THIS IS NOT PROGRESS.

Sue Bruer **Letter 137**

I am very concerned about the impact of this facility for several reasons: 1) ground water supply, 2) pollution of water shed, pollution of soil and biodiversity, and 3) impact on small family farms in the area. A full EIS needs to done to understand the impact of this project. Also, past history with previous Riverview projects need to be taken into account. An undertaking this large is sure to create unseen problems. Please be diligent in all aspects of researching this project.

Thank you

Tracy Zickur **Letter 138**

Why award this to a company that has already shown gross misuse of and harm to resources that are beneficial to native species of plants, animals, and residents of the areas they occupy? The fact that they so closely border 5 different land areas already should be enough to warrant a veto of their expansion.

Christine Newcomer **Letter 139**

No

Diane Baum **Letter 140**

why is it we here in Morris were not IMMEDIATELY made aware of this??? Our watershed is already being contaminated by high levels of nitrogen from farming, to add more cows to this is deterimental to our well-being and way of life. Look to Arizona, what Riverview is doing there, they are using up all of the water there!

https://www.youtube.com/watch?v=MRCD_jFsMVo&t=22s

Sheryl Lyke **Letter 141**

It is vital that the Riverview Dairy be required to submit an environmental impact statement. It is nearly twice as big as any current operations in the state, and its environmental harm would be enormous. Here's what we know now.

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Advancing permits without a full understanding of groundwater and water-quality risks is irresponsible. It is critical that the MPCA require a full Environmental Impact Statement.

Edith Thiel **Letter 142**

Commenter requested this comment be removed from the record. See **Letter 489** by same commenter.

Greg Anderson **Letter 143**

Riverview should not be allowed to expand on this sight. IMO they are responsible for the degradation of the Gorder Lake water quality by way of nutrient runoff coming from the excessive manure application of the fields they cut for silage. This degradation has resulted in water that is green all year around, has no fresh water shrimp in it (Gorder and all of the surrounding waters use to be teaming with aquatic invertebrates) and is no longer of use to migrating waterfowl. Riverview has artificially driven up the land values making it very difficult for the local farmers to purchase land without repressive debt. Riverview refuses to enter written contracts for silage with local farmers so that they can back out of their commitment if bad weather damages the corn.

How much milk did Riverview donator offer to sell to local school districts during the milk shortage a few years ago?

Riverview imports all of their labor force from Mexico which leaves locals with no chance at a job.

Tyler Solvie **Letter 144**

I am a lifelong resident of Stevens County, and I am writing to express my full support for the West River Dairy expansion.

I am a local farmer and have had the opportunity to work with Riverview through silage production and other farm-related work. Riverview has consistently been a positive and reliable partner. Each dairy provides silage and forage opportunities that support local farming operations like mine, allowing me and other neighboring farms to remain productive, especially during the off-season. Riverview also creates opportunities for many other local businesses, helping strengthen the economy in the areas where they operate.

Riverview is required to follow strict manure application standards, and they take those responsibilities seriously. Manure application is carefully managed and based on crop needs and soil conditions, while following regulations designed to protect land, water, and the environment.

Riverview's sites are clean and well maintained, and their employees are respectful and easy to work with. Communication has always been strong, and they make sure operations are handled responsibly.

I fully support the West River Dairy expansion and believe Riverview will continue to be responsible stewards of the land and the communities where they operate. This expansion will provide ongoing benefits to local farmers and the surrounding community.

Thank you,

Tyler Solvie

Megan Helling **Letter 145**

Riverview, LLP has applied to house an estimated 26,397 dairy cattle at a single site, an alarming proposal that would represent an unprecedented scale for dairy production in Minnesota.

A full Environmental Impact Statement (EIS) must be required. An operation of this size presents complex and far-reaching risks to water quality, air quality and surrounding ecosystems in addition to serious animal welfare concerns that cannot be adequately evaluated through a more limited review.

The proposed expansion also raises concerns for Minnesota's small independent farmers by placing additional economic pressures to those who are already struggling to compete in an increasingly consolidated market.

Minnesota must ensure that decisions of this magnitude are made with public transparency, complete information and careful consideration for the long-term sustainability of our environment.

Steve Deslauriers **Letter 146**

As a resident of Stevens County MN, where the proposed Riverview Dairy expansion would be located, I am concerned about its environmental impact and would like the MPCA to require a full Environmental Impact Statement before the project can go forward.

This project would more than double the size of Riverview's dairy operation in Stevens County in terms of animal units, and almost twice as large as the next largest livestock operation in the state. A project of this unprecedented scope demands particular care in reviewing its impacts, which a full Environmental Impact Statement would provide.

In addition, I believe it is important for the EIS to take into account the total projected size of Riverview's Stevens County dairy operations, including existing animal units, not just the size of the expansion. Total size matters because the larger the total size, the larger the potential impact if something goes wrong. For example, Riverview's Feb. 2025 manure spill in Kandiyohi County likely spilled approximately the same amount of manure in 5 days that an average sized MN dairy farm would produce in 6 months, based on early reports.

To ignore the potential environmental impacts of this expansion would be completely reckless. A full Environmental Impact Statement should absolutely be obtained before proceeding.

Micah Norman-Pace **Letter 147**

It is vital that the Riverview Dairy be required to submit an environmental impact statement. It is nearly twice as big as any current operations in the state, and its environmental harm would be enormous. Operations of this scale are bad for animals, workers, and the environment in a myriad of ways.

Kersti Malmberg **Letter 148**

I think this expansion would be a catastrophic mistake. There is no need for a dairy operation that large, it would negatively affect the water first in the area surrounding the farm and spread out to the rest of the state and beyond. This drain on and contamination of natural resources is a colossal mistake in a very critic time for our environment. I'm staunchly opposed to this expansion.

Kimberly Milligan **Letter 149**

The Riverview Dairy project MUST be required to get an Environmental Impact Statement

Kimberly Milligan **Letter 150**

It is vital that the Riverview Dairy be required to submit an environmental impact statement. It is nearly twice as big as any current operations in the state, and its environmental harm would be enormous. Here's what we know now.

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Advancing permits without a full understanding of groundwater and water-quality risks is irresponsible. It is critical that the MPCA require a full Environmental Impact Statement.

Deanna Arce **Letter 151**

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Advancing permits without a full understanding of groundwater and water-quality risks is irresponsible. It is critical that the MPCA require a full Environmental Impact Statement.

Rachel Johnson **Letter 152**

I live in Stevens County MN, the same county as the proposed Riverview Dairy expansion, and I am requesting that the MPCA require a full Environmental Impact Statement before the project moves forward. The proposed expansion is significant and it seems only reasonable to expect a full Environmental Impact Statement. While I am happy that Riverview, an important part of our community in Stevens County, wants to invest in an expansion here, I do think it is necessary to require a full Environmental Impact Statement.

Rachael Rich **Letter 153**

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Advancing permits without a full understanding of groundwater and water-quality risks is irresponsible. It is critical that the MPCA require a full Environmental Impact Statement.

Tracey Anderson **Letter 154**

10 March 2026

To: Minnesota Pollution Control Agency

From: Tracey Anderson

RE: Proposed Riverview, LLP 11,000-cow dairy feedlot in Section 1 of Synnes Township in

Stevens County

I am writing to encourage the Minnesota Pollution Control Agency to require a full environmental impact statement for the proposed expansion of Riverview's dairy feedlot (mentioned above.) I realize the Riverview is a successful agribusiness and brings much to our community, but the magnitude of this expansion is such that it poses potential threats to the environmental quality (land, air, water) in Stevens County. I believe these threats should be full investigated and necessary actions to prevent and/or mitigate environmental impact should be identified before the project moves forward.

More specifically, I am concerned about the potential impact that a dairy feedlot that is significantly larger than the current operation will have on water quality. I am an aquatic ecologist who has studied aquatic life in both the Pomme de Terre River and in local prairie pothole ecosystems. I value the opportunities to enjoy the natural resources that support fish and wildlife in our area and recognize that many depend on uncontaminated groundwater for drinking water and other household uses. Our freshwater ecosystems and connected ground water have the potential to be directly impacted by such a large dairy operation; I am concerned about both water quality and water quantity.

I think that before moving ahead with such a large project that the potential impact on the local environment should be investigated more thoroughly. This expansion will result in the largest dairy feedlot in the state of Minnesota. Given the magnitude of this dairy operation it believe it is essential that the MPCA and Riverview undertake the full Environmental Impact Statement process before this project moves forward.

Andrea Swenson **Letter 155**

Having this many animals in one area cannot be healthy to our waterways. This is just a big huge company thinking they can push us all around. I can't imagine trying to drill a well anywhere near there and think you're gonna get good clean water. You cannot let this happen.

Jennifer Winn **Letter 156**

As a former resident of NW Iowa - this sounds like a horrible proposal and sets future precedent that nobody wants. See the rates of cancer in Iowa? It's connected to the ag pollution in the air and water.

Don't make the mistakes Iowa has in terms of putting the profits of Mega Agriculture Monopolies ahead of the well being of the citizens in this community.

As a former organizer for Food and Water Watch - I saw the significant amount of environmental damage and quality of life degradation in my own community in Sioux County - which houses more factory farms than any other place in the country.

The nitrates in our water due to ag waste runoff was well above advisable levels, the cancer rates in that area of Iowa are especially high, not to mention every other illness related to breathing CAFO polluted air and drinking livestock waste littered water.

I'm thankful to live in Madison where we have a Reverse Osmosis treatment plant for our drinking water - but if this project comes to pass - expect that MANY more Minnesotans and everyone downstream from the waterways surrounding this expansion will have their health jeopardized just for Big Ag profits.

I very loudly and clearly disagree with this expansion proposal. Do what is right for Minnesotans, not the ag monopolies that leave our communities struggling economically and environmentally.

Cory Ahrens **Letter 157**

My name is Cory Ahrens, and I am a custom manure applicator who works with Riverview. I am writing in support of the West River Dairy expansion.

As a young farmer, the opportunity to work with Riverview has allowed me to build and grow my own business in manure pumping and application. Opportunities like this are not easy to come by, and the work Riverview provides has been a key part of helping me get started and stay involved in agriculture.

In my experience working with their sites, Riverview holds themselves and the people they work with to a very high standard. Their sites are well managed, clean, and professionally run. They take their responsibilities seriously and expect the same from their partners and contractors.

Riverview has also been a strong partner for the local agricultural community. Their operations support local farmers, contractors, and businesses, and the expansion of West River Dairy will continue to create opportunities for people like me who are working to build a future in agriculture.

I appreciate the chance to share my perspective and strongly support the approval of Riverview's West River Dairy expansion.

Sincerely,

Cory Ahrens

David Jungst **Letter 158**

I have two main concerns about the West River Dairy Expansion:

1. Possible depletion through over-pumping of the local ground water aquifer. An in-depth analysis of the impact on the local aquifer(s) needs to be done before hand. The buried drift aquifers of this area tend to have very slow re-charge and therefore can be over drawn and depleted by large quantity withdrawals, leading to permanent destruction of the aquifer.

2. An in-depth long-term analysis of the nutrient loading from manure applications and their impact on the soils and waters (ground water and surface waters) of the surrounding area.

Thousands of feet of private drain tile connect to a nearby public county drain tile (underground pipe) that drains the acres in and around the dairy operation and flows east directly to the Pomme de Terre River. Drain tiles act as a direct conduit for toxic nutrients such as nitrates.

The soils in this area are already naturally high in phosphorus. Manure spreading adds large quantities of phosphorus to the soil, often far in excess of the needs of crops. Phosphorus binds to soil particles. When soils erode due to high winds and flooding (common on cropland in this area) the phosphorus can cause severe toxic algal blooms in nearby water bodies. Attached is an example of a recent blue-green algae bloom on near-by hypereutrophic Long Lake just east of Morris, MN.

Alex Marie **Letter 159**

It is vital that the Riverview Dairy be required to submit an environmental impact statement. It is nearly twice as big as any current operations in the state, and its environmental harm would be enormous. Here's what we know now.

Massive water use: Riverview would pump up to 226 million gallons/year from an off-site well—nearly as much as the entire City of Morris (permitted for 300 million gallons/year for 5,000+ residents).

Huge waste output: The facility would generate about 202.7 million gallons of liquid manure and wastewater annually, plus 26,400 tons of solid manure.

Unknown groundwater impacts: The DNR hasn't begun the hydrologic survey or completed the County Geologic Atlas for Stevens County, so aquifers and groundwater resources aren't mapped—making it risky to permit large withdrawals now.

Sensitive, already-impaired waters: The expansion sits in the Pomme de Terre watershed, designated sensitive; the nearest waters—the Pomme de Terre River and a nearby unnamed creek—are already listed as impaired. The project would likely worsen these impairments.

Advancing permits without a full understanding of groundwater and water-quality risks is irresponsible. It is critical that the MPCA require a full Environmental Impact Statement.

My godson went to the U at Morris and we and friends still visit regularly to watch sports teams. We cannot stress enough how important an environmental impact statement is to determine just how dangerous this business would be for the surrounding community. Thank you.

Darin Broton, Minnesota AgriGrowth **Letter 160**

After reviewing the EAW for Riverview's proposed expansion at West River Dairy, the state's environmental review of the project is comprehensive and complete. While data on water use for many other large water-user projects in Minnesota are not public or unclear, the state's EAW process for feedlots includes water use. In this case, the water needed for the West River Dairy expansion will be supplied from a previously vetted and permitted source. The well that West River Dairy proposes to use as its water source was originally permitted for 452 million gallons per year. West River Dairy now proposes reducing that total water appropriation by half, to 226 million gallons per year. Additionally, West River Dairy will construct water storage basins as a contingency and climate-resiliency measure.

Riverview has a proven track record of environmental stewardship, including continuous efforts to reduce water use and the construction of innovative water-recapture basins to reduce reliance on a single water source. In addition, Riverview has been a leader in manure management plans, ensuring that not only is manure appropriately managed onsite, but also when transferred to other farms. The West River Dairy expansion will provide an organic fertilizer source for thousands of acres in the area,

reducing reliance on synthetic fertilizers and helping reduce nutrient runoff potential from farmland, and improving soil health.

Lastly, some submitted public comments have suggested the need for an Environmental Impact Statement due to the expansion's potential economic impact on local dairy farms. The purpose of an Environmental Impact Statement is to assess potential significant environmental impacts of the proposed project, not create public policy on the appropriate size of dairies in Minnesota. The legislature is best suited to determine how best to support Minnesota's dairy farmers and the overall dairy industry. Weaponizing environmental review and permitting to address broader economic policy issues is inappropriate and undermines the state's environmental regulatory process.

As a reminder, the MPCA has numerous tools at its disposal to ensure Minnesota's waters are protected, including issuing an individual permit with additional conditions rather than a general feedlot permit. We encourage the MPCA to use science and data when using those tools.

Amy Storbakken **Letter 161**

I am concerned that Confined Animal Feedlot Operations produce unhealthy products, are cruel to animals, and impact air and water quality negatively. It seems likely that they would also create biohazards, fostering conditions that spread disease. They also could amount to illegal monopolies.

I encourage all these problems to be further investigated.

Kaye Marohl **Letter 162**

We don't need another huge farm in western Minnesota. Too much extra water usage and we need to protect our wildlife. Enough is enough. So NO!!!!

Lucas Olson **Letter 163**

I am not in favor of Riverview Dairy building this expansion.

Autumn Johnson **Letter 164**

I live in Morris and I do NOT support the expansion. Not only is this getting close to a monopoly, but it will also have detrimental impacts to the local environment ans economy.

Levi Koehl **Letter 165**

My name is Levi Koehl and I am a resident of Stevens County. I currently live between two of the existing Riverview dairies, one of them being West River of the proposed expansion. I grew up here as well and have lived in the community all of my life. I farm here with my family and we have the benefit of working with Riverview, including selling crops, receiving manure for fertilizer, and we also provide custom services for the dairies. They are always good to work with, they maintain very high standards for their sites and the other operations that go along with it. The business Riverview does in the community is an economic engine that provides a lot of employment directly and indirectly. As a former employee of Riverview I can also say that they treat their employees very well.

As far as the concerns around water, I can say that within the last 3 years I have worked to develop a couple of our own new wells (residential and irrigation) in the region exactly between these existing dairies, and we have found there to be plenty of water, and of good quality as well. My family and I drink it everyday. Being a life long resident here, I have also enjoyed living near the Pomme de Terre

River. I can tell you that often, my kids go fishing there and catch many different species of fish, just as I did 20-25 years ago.

As one drives across rural America, you see the decline of many of the small towns and the main streets that are the backbone of this great country. The communities that survive and thrive are the ones where people and their families stay and do business, innovate and move forward. Stevens County is such a community, and we enjoy a lively, vibrant main street because of it.

For these reasons and many more not mentioned, I support the expansion of West River Dairy.

Scott Heinrich **Letter 166**

No to the expansion and limit herd size in a specific area

Martha Wheeler **Letter 167**

There should be a full environmental review of the proposed Riverview Expansion. Expanding the operation to 26,397 animals is a likely disaster for the land, the farmers and the local community. Huge industries should not be allowed to spoil the land, the water, and the living of local community members. Creating this expansion within 5 miles of eight protected wetland and wildlife areas needs to be thoroughly examined. Quality of life is more important than the profits of huge corporations.

Devin Nohl **Letter 168**

My name is Devin Nohl and I am a young farmer 24 years old and have been born and raised in Stevens County, just a few miles from the proposed dairy expansion. As an actual resident of this immediate area and being involved in the farming community, I have personally witnessed Riverview's commitment to supporting the local community, prioritizing employee safety, and building solid plans for environmentally sustainable operations. Their facilities have extremely clean standards and healthy animals.

As a farmer, I believe that more livestock like cows are good for the land, environment, and economy. For example, when I grow a corn crop, the corn can be used locally to feed cows instead of having to truck it to a different destination. Then, instead of having to purchase synthetic commercial fertilizer from overseas, I can use all natural dairy manure from just down the road to fertilize next years crop. On our farm we have seen significant improvements in our soil health by using dairy manure instead of synthetic commercial fertilizer. All manure from the animals is collected and stored until an appropriate time to apply it in the fall. Riverview uses some of the most advanced methods and equipment available to carefully apply this manure to farmers fields and mitigate any pollution or runoff. Many people may not realize that Riverview works hand in hand with their neighbors, big and small, to grow feed, harvest, and apply manure.

As for ground water, we have seen no concerns with water supply in this area, neither do I personally know anyone in this area that is concerned about running out of water. We are fortunate to live in a place in the world with abundant water resources and productive crop land. From what I have observed, Riverview, along with other local farmers, is committed to stewardship and sustainability of the land and these resources while providing healthy and affordable food for anyone who eats.

Angela Lund **Letter 169**

Please do not them expand! Not good for water and air pollution!

Thank you

Angela Lund

Vern Simula **Letter 170**

I urge the requirement an EIS!

For a project of the size proposed, the UNPRECEDENTED SCALED should make the necessity of an EIS an absolute requirement.

I do not object to Riverview expanding its operation, but I question the wisdom of doing it in ONE LIMITED LOCATION! Others have detailed other more specific concerns.

Emily Johnson **Letter 171**

I live in Stevens County, where the proposed Riverview Dairy expansion would be located. Given the scale of this expansion, I feel the project should undergo a full Environmental Impact Statement to ensure there is transparency around potential environmental impacts.

Tracy Otten **Letter 172**

RE: Proposed Riverview Dairy Expansion

We must require a full Environmental Impact Statement for the proposed Riverview Dairy expansion before it is allowed to move forward. I am a resident of Stevens County MN, where the expansion would be located. I am concerned about its scale as the project would more than double the size of Riverview's dairy operation in our county, with the final size being almost twice as large as the next largest livestock operation in our state in terms of animal units. A project of this unprecedented scope demands particular care in reviewing its impacts, which a full Environmental Impact Statement would provide. In addition, it is important for the EIS to consider the total projected size of Riverview's Stevens County dairy operations, including existing animal units, not just the expansion. Total size matters because the larger the total size, the larger the potential impact if something goes wrong. For example, Riverview's Feb. 2025 manure spill in Kandiyohi County likely spilled approximately the same amount of manure in 5 days that an average sized MN dairy farm would produce in 6 months, based on early reports.

Please do the report before allowing this proposal to proceed.

Kristen Ringham **Letter 173**

I vehemently oppose this project!! Huge feedlots are terrible not only for the land, but for our family farms as well. Furthermore, a quick look at their other feedlots shows they have been liable for over-pumping ground water, manure lagoon failures and various other infractions. Our clean water in Minnesota is one of our greatest resources and treasures. Are we going to squander it on a huge operation that gives little, if anything, back to our local economy and that pollute and degrades all the things we as Minnesotans hold most dear? One would hope not!! Give a resounding NO!! to this permit and project.

Caroline Collet **Letter 174**

I'm local to Morris, and regularly use the Pomme de Terre river bike paths and dog park. I'm concerned about the impact such a large operation would have on the environment that is currently an important part of my day-to-day life. I'm also very proud of the work the university does with regards to land

stewardship, and I'm not sure this is in line with the best interests of the people who live in this area and rely on this land/ecosystem.

If built, the Riverview operation would be allowed to pump up to 226 million gallons of water per year from an off-site well. For reference, the City of Morris, which is home to over 5,000 people, is permitted to pump up to 300 million gallons of water a year. Once constructed, the facility would produce 202,744,000 gallons of liquid manure and wastewater a year and 26,400 tons of solid manure a year.

The Minnesota Department of Natural Resources has not yet completed a mapping of Stevens County's groundwater resources and aquifers for their County Geologic Atlas Series. In fact, they have not even begun the hydrological survey of the county. It is irresponsible to other water users and residents of the area to move forward with this permit without a full understanding of the potential impacts.

The Pomme de Terre watershed, where this expansion is proposed, is already considered a sensitive watershed. The MPCA already lists the two closest waterways to the facility, the Pomme de Terre River and an unnamed creek, as impaired, and this proposal would only exacerbate the impairment.

Justin McGuire **Letter 175**

It is vital that the Riverview Dairy be required to submit an environmental impact statement. It is nearly twice as big as any current operations in the state, and its environmental harm would be enormous. Here's what we know now.

Massive water use: Riverview would pump up to 226 million gallons/year from an off-site well—nearly as much as the entire City of Morris (permitted for 300 million gallons/year for 5,000+ residents).

Huge waste output: The facility would generate about 202.7 million gallons of liquid manure and wastewater annually, plus 26,400 tons of solid manure.

Unknown groundwater impacts: The DNR hasn't begun the hydrologic survey or completed the County Geologic Atlas for Stevens County, so aquifers and groundwater resources aren't mapped—making it risky to permit large withdrawals now.

Sensitive, already-impaired waters: The expansion sits in the Pomme de Terre watershed, designated sensitive; the nearest waters—the Pomme de Terre River and a nearby unnamed creek—are already listed as impaired. The project would likely worsen these impairments.

Advancing permits without a full understanding of groundwater and water-quality risks is irresponsible. It is critical that the MPCA require a full Environmental Impact Statement.

Julie Kill **Letter 176**

20,000 + cattle!

There were approximately 8,000 cattle at this dairy to begin with and they want to add up to 18,555 MORE. see FB post

"As of early 2026, Riverview LLP has applied for a permit to construct a new dairy facility in Minnesota that would hold approximately 18,855 dairy cattle, which would bring the total to 26,397 animal units

This project is notable for being the first in Minnesota to hold over 20,000 animal units in a single facility" Face book

Just the Size of this proposed operation expansion should cause serious pause and REQUIRE that a thorough investigation be completed including emergency situations, WATER USAGE, WATER ACCESS,

AQUIFER AVILABILITY, Affects on other Aquifers, individual wells, surface water quality in the whole area of Stevens county. Just the amount of water that this operation will need supplied to it ALONE SHOULD be enough to automatically require a FULL Environmental Impact Study on this Operation.

see below

If each cow drinks 30-50 gallons of water per day *26397 cows* 365 days in a year: 289,047,150 to 481,745,250 Gallons of water use just for drinking water for the cattle for a year. if it is really hot or dry outside the number can double to 60-100 Gallons. add washing water, cleaning water and possible irrigation for crops to feed all of these cattle from all over the place and this is a MAJOR ENVIRONMENTAL IMPACT possibly for the whole county.

@120-150 lbs of feces and urine PER COW/ PER DAY *26397 =3167640 to 3,959,550 pounds of waste to remove PER DAY-calculation done at 120 and 150 lbs. (source=dairyland initiative)

the proximity to the Wetlands, drainage ditches, creeks in the area as well as the topography on the area should also cause a red flag.

What has happened to water availibility in the area from the previously permitted well that is off site and that is currently being used as a water source for the dairy? Water Quality?

Do we know precisely what aquifer is being utilized for that well? Has the aquifer been thoroughly studied? (recharge rate?, aquifer size? Depth? extent?) How long can the aquifer sustain this type of usage? What will happen if there is a drought? have wells in the area been monitored for depth data or water quality? We have been having flooding also lately, what happens in a huge flood to runoff,this spring the county ditch system was overwhelmed and it took until late fall for some areas to drain off. Where will the manure and urine go if the tanks are full and they cannot get into the fields?

As citizen in Stevens county as well as a citizen in the state of Minnesota, I firmly believe that before the Minnesota Pollution Control Agency gives any permission at all for this facility they Require a FULL Environmental Impact Study. The effects on wells, sanitation, contamination and the huge number of animal units should require and EIS Study alone.

PLEASE do what is right and require a full environmental impact study.

Thank you for your time.

Jennifer Mashuga **Letter 177**

Letting this be built is a huge mistake. It is nearly twice as big as any current operations in the state. It would be using massive amounts of water: Riverview would pump up to 226 million gallons/year from an off-site well—nearly as much as the entire City of Morris. The facility would generate about 202.7 million gallons of liquid manure and wastewater annually, plus 26,400 tons of solid manure. We don't know the groundwater impacts. The DNR hasn't begun the hydrologic survey or completed the County Geologic Atlas for Stevens County, so aquifers and groundwater resources aren't mapped—making it risky to permit large withdrawals now. The waters nearby are already listed as sensitive or damaged. The project would likely worsen these impairments. The Riverview Dairy project must be required to get an Environmental Impact Statement.

Dori Coler **Letter 178**

This project should have extensive studies done to determine the environmental impact. Water use, run off, air quality, abatement of noise, water, air etc emissions. Traffic and road maintenance and the impact on transportation adjacent water ways with increased salt/sand and emissions from trucking.

The huge amount of water taken from the water table and the treatment necessary to prevent damage to wetlands, lakes and rivers. This significant increase in size should require all possible reviews and testing, not least of which would be a thorough, detailed and independently resourced Environmental Impact statement.

Allan LaValier **Letter 179**

I am writing to comment on the draft of the Environmental Assessment Worksheet for the proposed West River Dairy Expansion.

This Dairy, if the expansion is allowed, would be nearly double the size of the next largest operation in our state in terms of animal units.

The dairy industry is already, due to the presence of massive operations, pushing small and medium-sized farms out of business and off the land.

Though an Environmental Impact Statement is what is needed for the West River Dairy Expansion, history indicates that operators withdraw their application when asked to undergo one from the MPCA.

The sheer amount of water that would be allowed to be used from an offsite well of 226 million gallons along with the generation of 202,744,000 gallons of liquid manure and wastewater and the 26,400 tons of solid manure makes this operation's environmental impact staggering and deleterious to the adjacent community.

Barring no mapping of the Stevens County's groundwater resources or hydrological survey of the county this project must not be allowed before preparations are made as to its long term environmental impact.

Mckayla Kaardal **Letter 180**

No

Mike Odell **Letter 181**

Hello, I spend time in this area, and I am concerned with the proposed size and impact of this operation. This proposed development should get an environmental impact statement to ensure that harm isn't caused to the environment. I understand that this development would drastically increase water use, produce huge amounts of waste, potentially impact groundwater, and create an unpleasant odor. Requiring a full EIS seems very important.

Tracy Schad **Letter 182**

Requiring an Environmental Impact Statement for Riverview Dairy is essential. The proposed facility would be nearly double the size of any existing operation in the state, posing serious environmental risks.

Water demand: Riverview plans to draw up to 226 million gallons annually from an off-site well — comparable to nearly the entire water supply permitted for the City of Morris.

Waste volume: Operations would produce roughly 202.7 million gallons of liquid manure and wastewater per year, along with approximately 26,400 tons of solid waste.

Unmapped groundwater: Stevens County lacks a completed Geologic Atlas, and the required hydrologic survey hasn't started — meaning aquifer impacts from large withdrawals remain unknown.

Vulnerable waterways: The site drains into the Pomme de Terre watershed, a designated sensitive area. Both the Pomme de Terre River and a nearby creek are already classified as impaired and could face further degradation.

Issuing permits before these critical data gaps are filled is premature. The MPCA must require a full Environmental Impact Statement before this project moves forward.

Anthony Anker **Letter 183**

I am writing in strong support of the West River Dairy Expansion. Having worked alongside Riverview at several locations as a custom manure applicator, I have seen firsthand the high standards they hold themselves and their partners to — standards that consistently exceed what state regulations require.

Every Riverview site I have worked at has been clean, well-organized, and professionally managed. Their commitment to environmental stewardship is evident in every aspect of their operations, from how they handle manure application to how they engage with the surrounding community. They take seriously their responsibility to local infrastructure and invest in maintaining and improving it.

Riverview has also been a genuine benefit to local farmers. By creating reliable markets for crops and providing quality manure to improve soil health and fertility, they strengthen the agricultural community as a whole. Having pumped for both Riverview and other dairies, I can say with confidence that Riverview sets the bar for how a dairy operation should be run.

Beyond agriculture, this expansion will bring meaningful economic opportunity to rural Minnesota — a region where attracting committed, community-minded businesses is no small challenge.

Riverview has a proven track record of donating to local causes and investing in the communities where they operate.

I am proud to live and work in a community with Riverview and wholeheartedly support the expansion of West River Dairy.

Sincerely,

Anthony Anker

Audrey Gunn **Letter 184**

The very least, an Environmental Impact Statement from a party that is not invested in this project needs to be provided. It is irresponsible to other water users and residents of the area to move forward with this permit. There is already increased pressure on water systems. The threat of water contamination is guaranteed based on previous records. Concentrated animal feeding operations degrade everyone involved, including the environment. The profits are not worth the depletion and degradation. Please cease and desist.

Leslie MacKichan **Letter 185**

I have canoed on the Pomme de Terre River - while it is in a lovely setting, the water quality is already "iffy" (I was glad that we never capsized the canoe). Please ensure that a thorough environmental impact assessment is completed and interpreted before this project is authorized.

Seraphina Ridgeway **Letter 186**

It is vital that the Riverview Dairy be required to submit an environmental impact statement. It is nearly twice as big as any current operations in the state, and its environmental harm would be enormous.

Massive water use: Riverview would pump up to 226 million gallons/year from an off-site well—nearly as much as the entire City of Morris (permitted for 300 million gallons/year for 5,000+ residents).

Huge waste output: The facility would generate about 202.7 million gallons of liquid manure and wastewater annually, plus 26,400 tons of solid manure.

Unknown groundwater impacts: The DNR hasn't begun the hydrologic survey or completed the County Geologic Atlas for Stevens County, so aquifers and groundwater resources aren't mapped—making it risky to permit large withdrawals now.

Sensitive, already-impaired waters: The expansion sits in the Pomme de Terre watershed, designated sensitive; the nearest waters—the Pomme de Terre River and a nearby unnamed creek—are already listed as impaired. The project would likely worsen these impairments.

Advancing permits without a full understanding of groundwater and water-quality risks is irresponsible. It is critical that the MPCA require a full Environmental Impact Statement.

Jerry Loxtercamp **Letter 187**

I'm a custom manure pumper from central mn, I've pump manure on farms all over mn,sd,nd,mi,ia,mt,in, I've toured farms all over the country. I've never seen an operation as clean and well run as a riverview dairy.

Alexander Grabowska **Letter 188**

An environmental review assessing the potential impacts of this expansion are essential. I am not in favor of the expansion regardless, but an accurate and thorough review of how this expansion will impact land, water, and wildlife across our communities is the bare minimum for helping us to understand how significant and extensive the harm will be. Any possible efforts to delay, discredit, expedite, or avoid a review will show how much Riverview values the communities it inhabits.

A business decision rooted in extracting and consolidating wealth into the hands of a few at the expense of all is not enough justification to move forward. Until the cows are compensated for the abuses they are forced to suffer (obviously incompatible with the business model), an equal amount of money and effort goes into restoring the land that has been polluted, and the millionaires that are profiting off of these abuses equitably re-distribute the excess wealth they've made to the people and communities that make their business possible, this expansion will only cause more long-term harm to the majority of people, land, nd non-human animals in our part of the state.

Mike Bieniek **Letter 189**

Please, Do Not let this happen:

Massive water use: Riverview would pump up to 226 million gallons/year from an off-site well—nearly as much as the entire City of Morris (permitted for 300 million gallons/year for 5,000+ residents).

Huge waste output: The facility would generate about 202.7 million gallons of liquid manure and wastewater annually, plus 26,400 tons of solid manure.

Unknown groundwater impacts: The DNR hasn't begun the hydrologic survey or completed the County Geologic Atlas for Stevens County, so aquifers and groundwater resources aren't mapped—making it risky to permit large withdrawals now.

Thank you for your attention,

Mike Bieniek

Judith Flicker **Letter 190**

I am very concerned about negative impacts expansion will impose upon our already fragile environment. Stevens County has the Pomme de Terre River, various lakes, and wetlands that that provide homes to a wide variety of birds and animal life. Citizens, such as myself, enjoy the wildlife and the natural habitats they occupy. Environmental impact and conservation must be taken in to consideration before any expansion is approved.

Brent Koehl **Letter 191**

My name is Brent Koehl and I have been a lifelong resident of the Horton Township area in Stevens County. I have been actively farming for 20 years growing corn and soybeans. My farm is located approximately two miles from the current West River Dairy site and the proposed expansion. Throughout my entire farming career, I have worked directly with Riverview's West River Dairy—supplying feed and receiving manure as fertilizer. I am writing this letter to express my strong support for the proposed dairy expansion project currently under MPCA review. I believe this project will continue to benefit our local agricultural community, our land, and our water resources.

Water Quantity and Aquifer Sustainability

As a nearby well owner, water quantity is critically important to me, my family, and my operation. I have personally analyzed decades of groundwater monitoring data from the Horton DNR Test Wells that are located directly where water will be drawn to supply West River Dairy. We have compared those water level readings, done by the Minnesota DNR, against annual precipitation records from the Morris WCROC weather station. The results are clear: water levels in our local aquifer are driven overwhelmingly by natural precipitation patterns, not by agricultural water use. The data shows a statistically significant correlation between precipitation and water levels, with the strongest relationship appearing in a two-year rolling average of precipitation ($r = 0.656$, $p < 0.0001$, $R^2 = 0.43$). In practical terms, this means that roughly 43% of the variation in aquifer levels can be explained by rainfall alone—and the remaining variation is likely attributable to other natural hydrological factors. There is no evidence in the data that current water usage has negatively impacted the aquifer. Our area sits atop one of the best naturally recharging aquifers for agricultural use in the region, and the monitoring data spanning over 40 years confirms its resilience.

To put the proposed water usage in perspective: Riverview's expansion plans call for a maximum of 226 million gallons of water annually. Consider that a single square mile of land in our area receives approximately 452 million gallons of water each year from rainfall alone, based on the Morris average of 26 inches of annual precipitation. That means the dairy's entire annual water demand is roughly equivalent to the rain that falls on just half of one square mile—a modest amount relative to the scale of precipitation and recharge occurring across this landscape. Minnesota's water appropriation permitting process is rigorous, prioritizes domestic and household water use, and requires a demonstrated sustainable water source before any permit is issued. I have full confidence that water quantity can be managed responsibly as this expansion moves forward.

Please refer to Figure 1 below, which illustrates the relationship between water levels and annual precipitation at the Horton DNR Test Wells over the past four decades. The underlying data used in this analysis was sourced from publicly available NOAA precipitation records and Minnesota DNR groundwater monitoring reports.

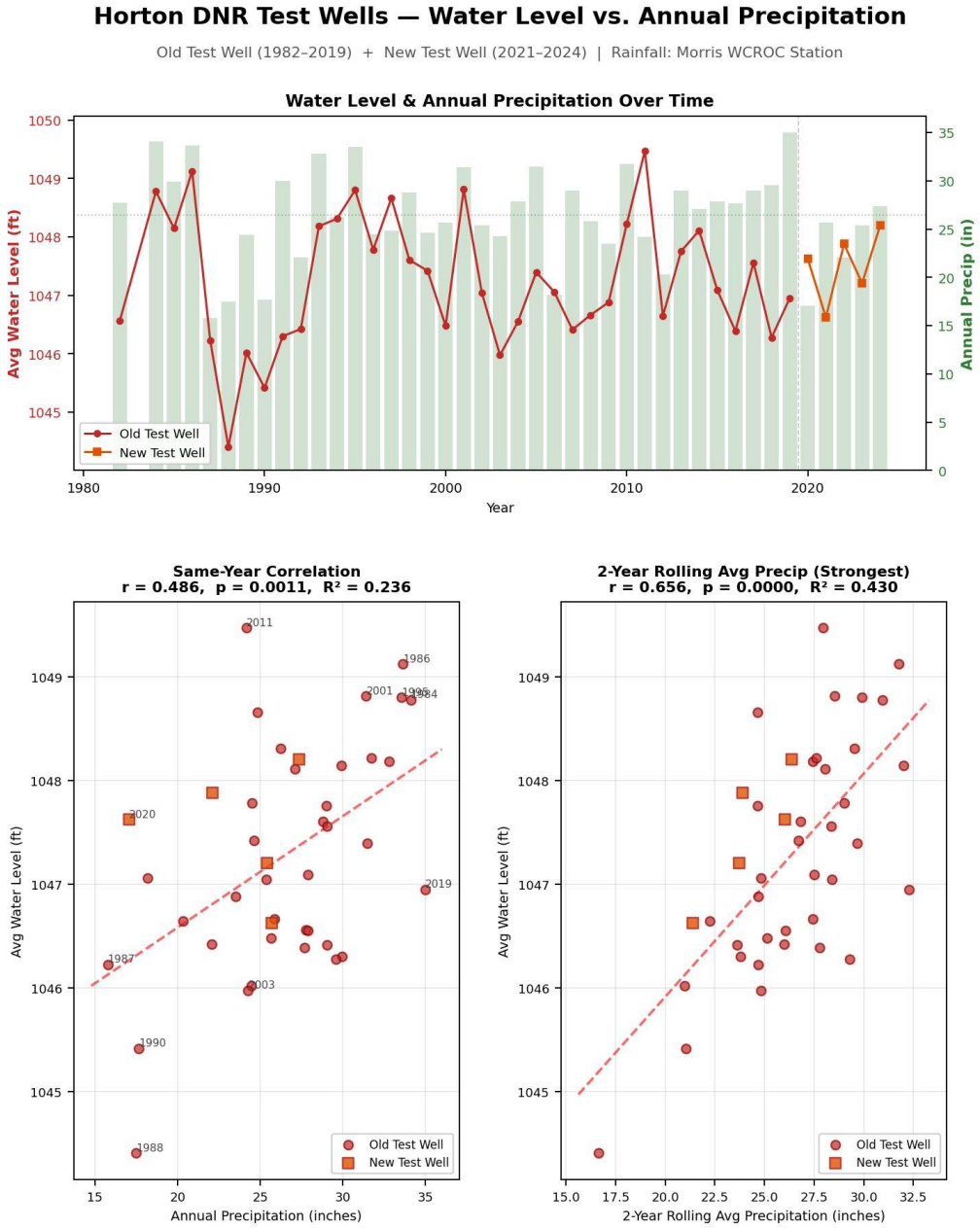


Figure 1. Horton DNR Test Wells – Water Level vs. Annual Precipitation (1982–2024)

The Agronomic Benefits of Manure

One of the most significant benefits of working with West River Dairy is the ability to sell silage and alfalfa to the operation and receive manure back in return. This exchange is not just economically efficient; it provides agronomic and environmental benefits that go beyond what commercial fertilizers alone can achieve. A 20-year study conducted by Iowa State University found that cropland fertilized

with manure had significantly better measures of soil quality—including higher particulate organic matter—compared to fields treated with commercial nitrogen at equivalent rates. Additionally, nitrate-nitrogen losses in tile drainage were 7 to 16 percent lower from manured plots than from commercially fertilized plots. Manure also increased soil organic carbon at multiple depths, increased total nitrogen, and improved the soil's ability to withstand erosion. Research at North Dakota State University's Carrington Research Extension Center found that manure applied at just 40 pounds of nitrogen per acre performed comparably to—and in some cases outperformed—80 pounds per acre of commercial nitrogen, while also producing significantly higher soil organic matter levels.

For my operation, receiving manure from West River Dairy is not just a convenience; it is a cornerstone of my soil management strategy.

Sources:

Hoover, N.L., Law, J.Y., Long, L.A.M., Kanwar, R.S., & Soupir, M.L. (2019). "Long-term impact of poultry manure on crop yield, soil and water quality, and crop revenue." Journal of Environmental Management, Vol. 252. Iowa State University.

Wiederholt, R. (2008). "Manure Good for Crops, Soil." Long-term Cropping Systems Trial (est. 1987), Carrington Research Extension Center, North Dakota State University.

Organic Crop Production and the Critical Need for Local Manure

It is important to understand that the ability to grow certified organic crops in this area depends heavily on access to local manure sources. Under the USDA National Organic Program (NOP) regulations, most synthetic fertilizers are prohibited in organic crop production (7 CFR 205.105). Organic farmers must instead rely on non-synthetic nutrient sources—primarily animal manure, compost, and legume cover crops—to maintain soil fertility and meet crop nutrient demands. In practical terms, this means that without a nearby livestock operation like West River Dairy, organic producers in our area would need to source manure from distant barns and facilities. That manure would have to be trucked in over long distances, stockpiled on-site, and spread at a later time—adding significant cost, logistical complexity, fuel consumption, and road traffic. Having a local dairy that produces manure much closer to cropland eliminates these inefficiencies and makes organic production viable and economically sustainable for area farmers.

Community and Economic Impact

Beyond the agronomic and environmental merits of this project, the West River Dairy expansion would bring meaningful economic benefits to our rural community. The expansion would create jobs, bring more families and students to our towns and schools, and strengthen the local agricultural economy through increased demand for locally grown feed crops. Riverview has been an important partner to area farmers for years, and their presence supports our community in ways that extend well beyond economics. In all my years farming near this site, I have found Riverview to be a responsible neighbor and operator. They run a clean, well-maintained facility, and they take their environmental responsibilities seriously.

For all of the reasons stated above—the demonstrated sustainability of our local aquifer, the proven agronomic benefits of manure, the critical role of local manure in supporting organic crop production, and the positive economic impact on our community—we fully support the West River Dairy Expansion.

Billy Schwartz **Letter 192**

A project this size, is so very difficult to judge the impact on the natural resources. There is no way this project should be allowed because of the massive size and impact this many animals will have in that area. In MN, I feel we try very hard to keep our natural resources in high regard.

Diane Anspach **Letter 193**

As a property owner in Stevens County, my vote is "No!" This will impact our water, wildlife areas, farmers, and our community!

Katherine Johnson **Letter 194**

It is vital that the Riverview Dairy be required to submit an environmental impact statement. It is nearly twice as big as any current operations in the state, and its environmental harm would be enormous. Here's what we know now.

Massive water use: Riverview would pump up to 226 million gallons/year from an off-site well—nearly as much as the entire City of Morris (permitted for 300 million gallons/year for 5,000+ residents).

Huge waste output: The facility would generate about 202.7 million gallons of liquid manure and wastewater annually, plus 26,400 tons of solid manure.

Unknown groundwater impacts: The DNR hasn't begun the hydrologic survey or completed the County Geologic Atlas for Stevens County, so aquifers and groundwater resources aren't mapped—making it risky to permit large withdrawals now.

Sensitive, already-impaired waters: The expansion sits in the Pomme de Terre watershed, designated sensitive; the nearest waters—the Pomme de Terre River and a nearby unnamed creek—are already listed as impaired. The project would likely worsen these impairments.

Advancing permits without a full understanding of groundwater and water-quality risks is irresponsible. It is critical that the MPCA require a full Environmental Impact Statement.

Joshua Truong **Letter 195**

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Max Guo **Letter 196**

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Advancing permits without a full understanding of groundwater and water-quality risks is irresponsible. It is critical that the MPCA require a full Environmental Impact Statement.

Sally Fernholz **Letter 197**

Expansion makes no sense considering the environmental consequences and future health of the environment. Rural area resources such as water and man power are finite and cannot be taken for financial gain.

Carmen Fernholz **Letter 198**

The future of rural Minnesota does not rest with corporate takeover of the dairy industry. Family farms not religious affiliated structures with lots of tax exemptions and significant amounts of capital. This corporate takeover is the quickest way to undermine our democracy as it takes away the owner/operator independence needed to maintain versatility and diverse thinking in our government. Disenfranchising family farms is the quickest way to destroy rural Minnesota and rural America.

Mary Beam **Letter 199**

I am from Benson and graduated from the UM of Morris. I am wholeheartedly against building an extension to the already excessively large West River Dairy operation in Steven's County.

Sadie Schrader **Letter 200**

Immediately DEMAND a full ENVIRONMENTAL IMPACT STATEMENT from Riverview Dairy.

Advancing any permit for Riverview Dairy without full understanding of the frighteningly DEVASTATING GROUNDWATER and WATER-QUALITY risk is unconscionable.

The Riverview Dairy controlled animal feeding operation would be nearly DOUBLE the size of the LARGEST current operation in our state. It's potential environmental DESTRUCTION is MASSIVE.

Riverview would use HUNDREDS of MILLIONS of gallons of water per year.

Riverview would dump HUNDREDS of MILLIONS of gallons of liquid manure and wastewater per year PLUS TENS of THOUSANDS of TONS of solid manure.

The DNR has NO SURVEY or completed County Geologic ATLAS for Stevens County, so aquifer and groundwater resources are UNKNOWN.

Nearest waters—the Pomme de Terre River and a nearby unnamed creek—are already COMPROMISED and listed as IMPAIRED.

REQUIRE a full ENVIRONMENTAL IMPACT STATEMENT from Riverview Dairy immediately.

Lexi Fischer **Letter 201**

No to expansion. Protect our land and smaller farmers against big corporations.

Julie Knopp **Letter 202**

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Advancing permits without a full understanding of groundwater and water-quality risks is irresponsible. It is critical that the MPCA require a full Environmental Impact Statement.

Angelica Agents **Letter 203**

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Advancing permits without a full understanding of groundwater and water-quality risks is irresponsible. It is critical that the MPCA require a full Environmental Impact Statement.

Anna Overby **Letter 204**

Please make Riverside Dairy farm submit to an environmental impact study. Factory farming is shown to increase use of water, runoff & other harmful chemicals in the water stream. It is vital we measure this be for building

Brinna Langford **Letter 205**

Hi, the Pomme de Terre River runs through my property, I have 3 acres on one side, 7 on the other. The river is already quite contaminated come early summer, I fear this would make it much worse. I want my kids and I to be able to swim in it all summer! PLEASE PLEASE PLEASE do an environmental review, at a minimum, before considering allowing another huge farm.

Thank you!

Lisa Koehler **Letter 206**

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Thank you.

Brenna Munoz **Letter 207**

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Advancing permits without a full understanding of groundwater and water-quality risks is irresponsible. It is critical that the MPCA require a full Environmental Impact Statement.

Victoria Piotter **Letter 208**

Please do not allow this dairy center to be built in the purposed location. It is irresponsible and could lead to catastrophic environmental damages for generations. Please let us clean up our precious waters!

I reside in Winona MN but this issue takes place in my home town area. I remember playing in streams on the farm as a child. Making sure our waters are safe for our children and wildlife should take priority!

Alexandria Muff **Letter 209**

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Advancing permits without a full understanding of groundwater and water-quality risks is irresponsible. It is critical that the MPCA require a full Environmental Impact Statement.

Julia Cedergren **Letter 210**

Riverview Dairy must submit an environmental impact statement! Stop trying to ruin our beautiful planet!!!

Mitch Trumble **Letter 211**

Good morning,

My name is Mitch Trumble. I am writing to you in regards the the West River Dairy expansion project proposed for Stevens county where I live.

I have no financial investment in Riverview dairy and perhaps that is to my loss, however I do have a concern that this company is doing irreparable harm to the small farms and future farms of our area. The cost of land has been driven up incredibly high and the pockets of Riverview are very deep, no small farm can compete when it comes to land and rent prices and this is not improving. If the surrounding farms do not sell crops to the dairy for feed and in turn, BUY back liquid manure they are on the loosing

end of farming next to a corporate farm that will simply out bid them on land and rent until they have it for them selves.

I am not accusing the company of malicious intent, I believe that to them "its just good business". My children will never be able to farm in the future due to the inflated costs, particularly of land in our home area, due to the Spring Valley/Riverview competition.

The second concern I have is the smell, I do not live close enough to the West River Dairy for that to be a personal issue but I am about 2 miles from the original Riverview Dairy and the smell is very noticeable. During fall when liquid manure is being applied the county stinks as a whole, the well water smells of rotten eggs and this has not been getting better.

I feel the monopoly of Riverview is hurting small family farms if they do not want to participate in the game with Riverview and sell them commodities to stay on good terms. Large corporations like Riverview are doing a disservice to the farming community in my opinion. We have enough dairy products in Stevens county, I don't see how adding 11,000 more mouths will help the small guy out. I did not post comments on the public sight as I feel a target would be on my back and most small farmers I have spoken with have the same reservations about publicly questioning this expansion.

Thank you

Crystal Poppe **Letter 212**

It is vital that the Riverview Dairy be required to submit an environmental impact statement. It is nearly twice as big as any current operations in the state, and its environmental harm would be enormous. Here's what we know now.

—Massive water use: Riverview would pump up to 226 million gallons/year from an off-site well-nearly as much as the entire City of Morris (permitted for 300 million gallons/year for 5,000+ residents).

-Huge waste output: The facility would generate about 202.7 million gallons of liquid manure and wastewater annually, plus 26,400 tons of solid manure.

—Unknown groundwater impacts: The DNR hasn't begun the hydrologic survey or completed the County Geologic Atlas for Stevens County, so aquiters and groundwater resources aren't mapped-making it risky to permit large withdrawals now.

—Sensitive, already-impaired waters: The expansion sits in the Pomme de Terre watershed, designated sensitive; the nearest waters-the Pomme de Terre River and a nearby unnamed creek-are already listed as impaired. The project would likely worsen these impairments.

Advancing permits without a full understanding of groundwater and water-quality risks is irresponsible. It is critical that the MPCA require a full Environmental Impact Statement.

Patti Vega **Letter 213**

Mn does not want or need more rampant polluters. If this project comes to our state we request and expect a pollution mitigation plan.

Marjie Carr-Oxley **Letter 214**

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Lynne Riley **Letter 215**

Please require an environmental impact statement with time for public comments from community members who will be directly impacted by this operation.

We can't continue to rubber stamp every request by agribusinesses to maximize their profits. As a state agency, your priority is the well-being of Minnesotans. Thank you.

Jaimee Frank **Letter 216**

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Marjie Carr-Oxley **Letter 217**

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Sawyer Buhman **Letter 218**

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Advancing permits without a full understanding of groundwater and water quality risks is irresponsible. It is critical that the MPCA require a full environmental risk impact statement.

Erin Jimcosky **Letter 223**

Minnesota doesn't need more environmental destruction. Require an environmental impact study or just don't approve of it. If we don't protect our state, we will lose what makes it great.

Marjie Carr-Oxley **Letter 224**

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Paul Carlson **Letter 225**

As Superintendent of Hancock Public School, I am pleased to express my support for the West River Dairy Expansion. Our district's success is connected to the strength and stability of the area we serve, and this project represents a meaningful investment in both. The expansion of West River Dairy will bring valuable economic growth to our region, supporting local families and strengthening the tax base that helps sustain high quality educational opportunities for our students.

Agriculture has been a cornerstone of our community's identity, and continued investment in this sector ensures that our students can look forward to a future with robust career pathways close to home. Beyond the economic benefits, Riverview has consistently demonstrated a commitment to being a responsible community partner. Their support for youth programs, hands on learning experiences, and agricultural education has enriched our schools and helped students develop real world skills. The expansion will only deepen these opportunities. I look forward to the positive impact this will have on our students, families, and the broader area.

Marjie Carr-Oxley **Letter 226**

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Sloan Parker **Letter 227**

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Reid Gosmire **Letter 228**

Please please please require a full environmental impact statement!

Kaitlyn OConnor **Letter 229**

Please require Riverview Dairy to conduct a full environmental impact statement

Nicola Philpott **Letter 230**

The Riverview Dairy project must be required to get an Environmental Impact Statement. Its environmental harm would be enormous.

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ohn Schreier **Letter 232**

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Xander Godfrey-Singh **Letter 233**

The amount of ground water waste, water usage, and other polluting factors is a poor use for this land. Please reconsider this.

Ryan Meehan **Letter 234**

I'm concerned about this project and how it interacts with surface and ground water in our state.

Ed Brands **Letter 235**

Two quick points:

1) Where is the water coming from for this expansion? From the spotty aquifer beneath the existing dairy? From a "retired" water use permit from the ethanol plant in Morris? The ethanol plant still uses water from the same aquifer, but it gets the water from the city instead of directly from the wells it used. The Pomme de Terre aquifer in Morris is also the city's drinking water source. It is not clear that this aquifer can support a giant dairy operation in addition to the existing demands.

2) A roughly 20,000 cow dairy will require approximately 30 square miles of land to feed the dairy animals and to absorb their manure. Combined with the other two large dairy sites operated by Riverview in Stevens County, Riverview's operations will occupy more than 10% of the land in the county.

Karen Arnold **Letter 236**

Please review the impacts of this expansion carefully. Water is a precious commodity.

Kevin Koehl **Letter 237**

To: Minnesota Pollution Control Agency (MPCA)

Subject: Support for West River Dairy Expansion in Stevens County

Dear MPCA Review Team,

My name is Kevin Koehl, and I am writing to express my support for the proposed Riverview Dairy expansion in Stevens County. Projects like this represent an important opportunity for rural communities in western Minnesota to strengthen their agricultural economy while supporting responsible production practices.

First, the expansion would contribute positively to local job growth. Dairy operations of this scale require a wide range of skilled and semi-skilled employees, including positions in herd management, animal care, equipment operation, maintenance, and transportation. These jobs provide stable employment opportunities in rural areas where maintaining a strong workforce is critical to long-term economic stability.

In addition to on-farm employment, dairy expansion supports value-added agricultural processing in our region. Riverview is constructing the Stevens Milk Plant near Morris, a facility that will process approximately four million pounds of milk each day and produce products such as non-fat dry milk and skim milk powder. This plant alone is expected to employ dozens of people and represents a significant investment in Stevens County’s agricultural infrastructure. Facilities like this keep more of the value of agricultural production in our region while creating skilled manufacturing jobs tied directly to Minnesota agriculture. The West River Dairy Expansion will compliment this plant as well.

The project also supports the broader production agriculture system that is central to Stevens County. Dairy operations create strong demand for locally produced feed crops such as corn silage, alfalfa, and small grains. This demand provides reliable market opportunities for area farmers and encourages diversified crop rotations. When livestock and cropping operations work together, they strengthen the overall resilience and profitability of the local agricultural economy.

Another important benefit is the value of dairy manure as a nutrient resource. When properly managed, manure serves as an e□ective organic fertilizer that improves soil fertility and supports crop production. When applied under nutrient management plans, manure returns nitrogen, phosphorus, potassium, and organic matter back to the soil. This helps reduce reliance on commercial fertilizers while improving soil health and productivity for local farmers.

Agricultural investments of this scale also strengthen the local tax base and rural infrastructure. Economic activity generated by expanded agricultural operations contributes to counties, townships, and school districts. The addition of employees and their families support local schools, housing demand, and small businesses. Maintaining strong school enrollment and vibrant rural communities depends on continued economic activity, and agriculture remains a foundational driver of that activity in Stevens County.

I appreciate the MPCA's role in ensuring that agricultural development occurs in a responsible and environmentally sound manner. With appropriate oversight and modern management practices, I believe the West River Dairy expansion can provide meaningful economic and agricultural benefits to Stevens County while meeting environmental standards.

Thank you for considering this perspective during your review process.

Sincerely,

Kevin Koehl

Melissa Harper-France **Letter 238**

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Sarah Hernández **Letter 239**

There needs to be a thorough review of the long term impacts.

Jolene Turner **Letter 240**

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Randi Jorgensen **Letter 241**

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Jennifer Nowatzki **Letter 242**

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Dionne Porter **Letter 243**

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Ren Ze **Letter 244**

Animal agriculture wreaks havoc on the environment especially factory farms. I'm asking that a thorough environmental impact assessment is done before any consideration to allow this facility to be built.

Will Carlen **Letter 245**

Please require an environmental impact statement for this new factory farm, the largest in the state. The people deserve to know how this farm will impact our lands, waters, and the ecosystem as a whole.

Kristin Bertram **Letter 246**

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Alicia Sandor **Letter 247**

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Pixie Green **Letter 248**

West River dairy must be required to provide an environmental impact statement! The expansion of factory farming in Minnesota will have devastating consequences on our lakes and our ground water, endangering people for generations to come. You must move to protect the people of Minnesota rather than the interests of big dairy.

Grace Davies **Letter249**

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Advancing permits without a full understanding of groundwater and water-quality risks is irresponsible. It is critical that the MPCA require a full Environmental Impact Statement.

Carter Voorde **Letter 250**

As someone who lives in Stevens County and will be affected by this project, I insist MPCA require a full Environmental Impact Statement before the project can go forward. This is a hugely transformative proposal that would double Riverview's operations in our county, which is not something to take lightly. It is the least that can be done to do a FULL Environmental Impact Statement in order to fully understand the impacts of this change.

A project of this unprecedented scope demands particular care in reviewing its impacts, which a full Environmental Impact Statement would provide. In addition, I believe it is important for the EIS to take into account the total projected size of Riverview's Stevens County dairy operations, including existing animal units, not just the size of the expansion. Total size matters because the larger the total size, the larger the potential impact if something goes wrong. For example, Riverview's Feb. 2025 manure spill in Kandiyohi County likely spilled approximately the same amount of manure in 5 days that an average sized MN dairy farm would produce in 6 months, based on early reports.

Hayley Saccoman **Letter 251**

We don't want more pollution from a giant factory farm in MN. This is not the direction we need to go. Our environment is at a terribly perilous point in time and we need to prioritize the health of everyone before this giant farm that abuses animals as a business. Hard no from me as a small business owner.

Shanta Mayweather **Letter 252**

We the people of Minnesota do not want factories replacing farms. We don't want our food grown inside buildings, and labs. Listen to the people, the consumers, the indigenous communities, and most importantly nature. Please allow the planet to provide we don't need human intervention anymore.

Kathy Burt **Letter 253**

This project should require an environmental impact statement. The size of this operation will have a negative effect on the surrounding area and beyond. Bigger is not better when resources will be gobbled up. This operation should not go forward.

Bonnie Morgan Norgren **Letter 254**

I COMPLETELY OPPOSE this request for expansion!! The environmental impact will be negatively huge and detrimental to many valuable lakes and connecting rivers in both Stevens and Grant counties. Approving this expansion would be actionable for a Class Action lawsuit. Please, please DENY this request and protect our valuable lakes and rivers. Protect our ground water! This is exactly the opposite direction for The land of 10,000 Lakes. DENY THIS REQUEST!!

Pamela Gades **Letter 255**

Do the EIS study. Go forward with that. Once you have all of the results from the study, then make a decision.

Shanta Mayweather **Letter 256**

It is vital that the Riverview Dairy be required to submit an environmental impact statement. It is nearly twice as big as any current operations in the state, and its environmental harm would be enormous. Here's what we know now.

* Massive water use: Riverview would pump up to 226 million gallons/year from an off-site well —nearly as much as the entire City of Morris (permitted for 300 million gallons/year for 5,000+ residents).

* Huge waste output: The facility would generate about 202.7 million gallons of liquid manure and wastewater annually, plus 26,400 tons of solid manure.

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Advancing permits without a full understanding of groundwater and water-quality risks is irresponsible. It is critical that the MPCA require a full Environmental Impact Statement.

Anne Moreno **Letter 257**

Please don't allow this project to move forward without an environmental impact review.

Thank you,

Anne

Debra Luetmer **Letter 258**

Our water resources are too valuable not at ensure that they will be used wisely. A full, comprehensive review needs to be completed.

Tawnya Gelle **Letter 259**

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Tierney Graf **Letter 260**

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Sensitive, already-impaired waters:

The expansion sits in the Pomme de Terre watershed, designated sensitive; the nearest waters-the Pomme de Terre River and a nearby unnamed creek-are already listed as impaired.

The project would likely worsen these impairments.

Advancing permits without a full understanding of groundwater and water-quality risks is irresponsible. It is critical that the MPCA require a full Environmental Impact Statement.

Ann Williams **Letter 261**

Please do not allow this expansion. The huge amounts of water required is not sustainable in today's world.

Jenifer Culbertson **Letter 262**

I have family and friends in Morris and this would impact their enjoyment of their homes. Concerns about water shortages, increased manure (smell and pollution) are concerning . It is vital that the Riverview Dairy be required to submit an environmental impact statement. It is nearly twice as big as any current operations in the state, and its environmental harm would be enormous. Here's what we know now.

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Tanna Rens **Letter 263**

I could not caution you more to not allow this. These large scale dairy farms are ruining our rural farming community. They (unfortunately) put one up close to our home and it has essentially ruined our once peaceful farm. We can rarely have our windows open due to the horrible smell when they're separating manure. The amount of flies that we have is absolutely disgusting and we can't even enjoy being outdoors. They are pushing every small dairy farm out of business. When is enough enough for them?

Wendy Pilot **Letter 264**

Riverview Dairy must be required to complete a full environmental impact statement. This facility would be nearly twice the size of any other dairy operation in Minnesota, and the potential damage to our environment is too serious to ignore. Here is what we already know. Water use: Riverview plans to pump up to 226 million gallons of water per year from an off-site well. To put that in perspective, the entire City of Morris with over 5,000 residents is permitted to use 300 million gallons per year. Waste production: The facility would produce roughly 202.7 million gallons of liquid manure and wastewater every year, along with 26,400 tons of solid manure. Groundwater risks: The DNR has not yet completed a hydrologic survey or the County Geologic Atlas for Stevens County, meaning we do not have a clear picture of local aquifers and groundwater. Approving large water withdrawals before that work is done is a serious gamble. Already-struggling waterways: This project sits within the Pomme de Terre watershed, which is already designated as sensitive. Both the Pomme de Terre River and a nearby unnamed creek are currently listed as impaired. Adding this facility would likely make things worse. Moving forward with permits before we fully understand the risks to groundwater and water quality is reckless. The MPCA must require a complete Environmental Impact Statement before this project goes any further. Sincerely, Wendy P

Michael Finn **Letter 265**

An expansion of this magnitude proximity must justify the completion of an environmental assessment. Minnesota's land, water, and wildlife are one of our greatest assets and worth protecting against the potential risks of storage and distribution of manure, runoff, and other contaminants. Thank you for your attention to this matter

Claire Kaiserman **Letter 266**

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Dominic Decker **Letter 267**

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Advancing permits without a full understanding of groundwater and water-quality risks is irresponsible. It is critical that the MPCA require a full Environmental Impact Statement.

Rachel Coler Mulholland **Letter 268**

I am deeply concerned to learn that MPCA is even considering granting a permit to Riverview Dairy for their planned expansion without an EIS. A dairy of this proposed scale does not yet exist in Minnesota, much less nested amongst so many protected wildlife areas and near such a vital watershed. Given Riverview's recent history of manure spills in Minnesota, along with the damage they've caused in other municipalities with over-pumping and water table depletion, it behooves the MPCA to require a full environmental review of any proposed expansion that INCLUDES the existing dairy in the equation (not just the expansion). Please consider the health of the land, the flora and fauna, and the PEOPLE who live in this area - myself and my children included. Thank you for your time.

Alexandra Beane **Letter 269**

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Kelsey Hambor **Letter 270**

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Meghan Manahan **Letter 271**

I am writing to request that the Riverview Dairy be required to submit an environmental impact statement. It is nearly twice as big as any current operations in the state, and its environmental harm would be enormous, including massive water use, huge waste output, unknown groundwater impacts, and potential harm to the Pomme de Terre watershed, designated as sensitive.

Melody Kitchen **Letter 272**

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What

Janice Kostad **Letter 273**

Please review this project and protect our natural resources. Please also review and consider the consequences to our local economy if we allow such a large facility.

Karrie Vrabel **Letter 274**

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Winnie Cheung **Letter 275**

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Kayla Jacobson **Letter 276**

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Lia Saaskilahti **Letter 277**

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Rodden Turner **Letter 278**

An EAW must be done to assess environmental impact. Please don't sell out MN residents because of mislaid policies, this is unnecessary expansion. Additionally, factory farming on this scale is immoral.

Sheila Nelson **Letter 279**

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Emily Rosenmeier **Letter 280**

This is a terrible plan, and absolutely must include an EIS, as well as some study of the impact it would have on the surrounding communities. Small dairy farms MN are already struggling, and this proposal would put many of them out of business and create an unwanted monopoly on milk production, as well as create a potential environmental danger.

Jodi Gruhn **Letter 281**

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John Sheehan **Letter 282**

When is it going to end? If the pollution control agency doesn't think it's a good idea why allow it? Shouldn't this require a more extensive review than an EAW? I have invested millions in RE projects and an EAW is not a big deal and this project is huge. I would think the ground water pollution would be unbelievable and the use of all of that water from an "offsite well"? What the does that mean? Where is the well, what aquifer will it draw from and who will that effect? I'm tired of this crap. Projects like this will have a negative effect on my grandchildrens future and further destroy the family farm. That takes the competetivness out of business. Food companies are already screwing us.

Heather Waye **Letter 383**

I understand that Riverview has applied for an expansion that would result in an operation double the size of the next largest livestock operation in Minnesota (in terms of number of animals). The proposed site in Stevens County, where I live, will be very close to more than a few protected waterfowl and wildlife production areas. Riverview has a history of manure spills in our area and inappropriate use of water resources in Arizona. This proposed project will have a major impact throughout our county, the Pomme de Terre watershed, and communities and habitats downstream. Therefore, this proposed project must be required to undergo a full and thorough Environmental Impact Statement.

Anna Borell **Letter 284**

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Kurtis Koehl **Letter 285**

I am writing in support of the West River Dairy Expansion. Having lived in Stevens County for all of my 40 years, I have had the opportunity to work for and with Riverview. I live and farm in between two of the Stevens County dairies, and our farm is able to source manure from these dairies for organic crop production. Having Riverview in my backyard has given myself and my kids opportunities that would likely have otherwise not existed. We are able to be involved in forage harvesting and manure application, both of which allow us to better utilize our equipment for our farm.

For those of us that live here, water use and water quality are of utmost importance. I have confidence in Minnesota's water appropriation and permitting process along with MPCA requirements, that water use and water quality can be managed effectively as this project moves forward. Living less than two miles from one of the dairies, I have seen no negative impacts on my water quality.

Living in rural MN, I expect slight inconveniences at times as farmers go about providing food for all of us, and Riverview's attention to this is impeccable. Riverview does a phenomenal job of maintaining roads, dust control, and reducing odor during field operations.

I believe this project will benefit the area for years to come, that is why I support it.

Thank you.

Kurtis Koehl

Steph Kuehn **Letter 286**

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Cari Lombardi **Letter 287**

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Advancing permits without a full understanding of groundwater and water-quality risks is irresponsible. It is critical that the MPCA require a full Environmental Impact Statement.

Mark Berkson **Letter 288**

Greetings,

I am writing because I am deeply concerned that another CAFO (factory farm) is going to be created in Minnesota. This is the last thing we need, not only because of the devastating environmental impact these facilities have, but also because of the documented mistreatment of animals. Above all else, an environmental impact report must be submitted and audited by an independent organization of experts. The industry itself cannot be trusted.

It is vital that the Riverview Dairy be required to submit an environmental impact statement. It is nearly twice as big as any current operations in the state, and its environmental harm would be enormous. Here's what we know now.

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Thank you,

Mark

Amy Kinneman **Letter 289**

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-Sensitive, already-impaired waters: The expansion sits in the Pomme de Terre watershed, designated sensitive; the nearest waters-the Pomme de Terre River and a nearby unnamed creek-are already listed as impaired. The project would likely worsen these impairments.

Advancing permits without a full understanding of groundwater and water-quality risks is irresponsible. It is critical that the MPCA require a full Environmental Impact Statement

Linda Hanke **Letter 290**

Please do not approve this EAW! This will negatively affect the environment in the surrounding areas. And the amount of water needed would be horrific. This must not get approved. Thank you.

Mark Kaelke **Letter 291**

Riverview LLP's proposed expansion of operations at the West River Dairy should receive the highest level of review possible, by both MPCA and DNR, to assure their activities will not negatively impact the quality or quantity of nearby surface waters, acquifers, wildlife, vegetation, soils, and people. Permits for this expansion should not be issued unless negative impacts to these resources can be avoided and Riverview should be required to monetarily insure against spills and other accidents which may occur as a result of their operations.

Lisa A **Letter 292**

Please call for an environmental impact study. As an agency that is called to control pollution, you must take this seriously and do what is required of you. Lives are at stake. Water pollution is at risk so is methane pollution. Factory farming is often cruel besides. Do your jobs please and consider the pros and cons in terms of who benefits and who suffers from rushing this through. How will this affect Minnesotans quality of life? How will it harm us? How will it affect the environment? How will it benefit? How will it harm? Think 7 generations. Be smart, have a heart

Amanda Huggett **Letter 293**

As an animal lover in Minnesota, PLEASE, do not add a massive factory farming operation to be added here or anywhere. It is bad for the environment, it is bad for animals, and it is bad for people. Here's what we know now.

—Massive water use: Riverview would pump up to 226 million gallons/year from an off-site well—nearly as much as the entire City of Morris (permitted for 300 million gallons/year for 5,000+ residents).

—Huge waste output: The facility would generate about 202.7 million gallons of liquid manure and wastewater annually, plus 26,400 tons of solid manure.

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Advancing permits without a full understanding of groundwater and water-quality risks is irresponsible. It is critical that the MPCA require a full Environmental Impact Statement.

Roxanne Friedenfels **Letter 294**

No to the West Dairy River expansion. It will be environmentally harmful.

Lori Clark **Letter 295**

Farming operations like this are simply TOO BIG! Too big for the land, too big for the neighbors, too big for the water infrastructure, and WAY TOO BIG to not require a EIS.

PLEASE care for the citizens and the environment before the corporations and pause long enough to address the issues an EIS covers. Thank you for always protecting our environment FIRST.

Thomas Hoch **Letter 296**

This project expansion is an environmental disaster in the making. What we SHOULD be focused on is how to transition dairy away from operations such as these to one that more appropriately uses agriculture. Plant-based products could not only protect our environment but would eliminate the extreme animal cruelty inherent in these operations. Just take a look at their website: https://riverviewllp.com/ . Animals placed on a merry-go-round for their entire adult lives? Really? And the public is left to pick up the pieces from these disastrous CAFOs.

Candace Marx **Letter 297**

How will they dispose of the manure? what about Pollution from this facility (chemicals in the manure, water polution, The amount of water they will need (effect on ground water, etc,), Air pollution, Smell, how will they dispose of dead cows & calves? There are so many factors to consider - we need an enviormental Study before any construction. Please checkdo this first!

Loren Stoner **Letter 298**

I am writing as a concerned citizen and health care provider. CAFOs are resource-heavy, produce less-than-healthy animals, and contribute to significant pollution in the United States. Minnesota is already losing dozens of dairy farms annually due to inconsistent and often below-cost-of-production milk prices. Massive dairy operations, like the one Riverview is proposing to build, have glutted the market and tightened Big Milk's stranglehold on the industry, allowing it to push small and medium-sized family farms out of business and off the land. This operation would only exacerbate the situation and accelerate the loss of dairy farms in our state, decimating Main Street economies.

The Pomme de Terre watershed, where this expansion is proposed, is considered a sensitive watershed. The MPCA already lists the two closest waterways to the facility, the Pomme de Terre River and an unnamed creek, as impaired, and this proposal would only exacerbate the impairment.

No feedlot has ever undergone an Environmental Impact Statement (EIS) in Minnesota. Each time the MPCA has determined that an operation should undergo one, the operator that requested the permit has withdrawn their application. And all of those operations that were determined to need an EIS were significantly smaller than Riverview's proposed operation will be.

If built, the Riverview operation would be allowed to pump up to 226 million gallons of water per year from an off-site well. For reference, the City of Morris, which is home to over 5,000 people, is permitted to pump up to 300 million gallons of water a year. Once constructed, the facility would produce 202,744,000 gallons of liquid manure and wastewater a year and 26,400 tons of solid manure a year.

It is absolutely reasonable to do a full environmental impact study regarding this proposal. Thank you for your consideration.

Elizabeth Brandt **Letter 299**

There is no way this action benefits small dairy farmers, is a positive environment for the animals and is healthy for the environment.

This must not be allowed to continue.

The smell alone would be unbearable.

Shelly Bell **Letter 300**

It is vital that the Riverview Dairy be required to submit an environmental impact statement. It is nearly twice as big as any current operations in the state, and its environmental harm would be enormous. Here's what we know now.

Massive water use: Riverview would pump up to 226 million gallons/year from an off-site well—nearly as much as the entire City of Morris (permitted for 300 million gallons/year for 5,000+ residents).

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Advancing permits without a full understanding of groundwater and water-quality risks is irresponsible. It is critical that the MPCA require a full Environmental Impact Statement

Leland Stoe **Letter 301**

I am a fly fisherman and outdoorsman. I was on Rush Creek near Lewiston with my 6-yr-old grandson and my son three weeks before the massive 2021 fish kill, where approximately 2,500 trout were killed over a one-mile section just upstream from where we had our magical outing. On that day, my grandson presented a #18 dry fly to the fish by himself and fooled his very first trout. He netted the fish himself while broadly smiling with pride.

The fish kill resulted from a combination of 1) low stream level in late summer 2) large rainfall 3) poor farming practices. There was (and is) a CAFO of about 1,500 cows near the headwaters of Rush Creek in Winona County. Basically, storm runoff transports these toxins into the water at higher concentrations when stream flows are lower (especially as summer progresses) and therefore provide less dilution of the toxins. And large storms are increasingly becoming the norm.

The Driftless Area in SE MN (in places like Lewiston, where Rush Creek is) has a "Swiss cheese" geology, which is why we have cold water spring creeks in the area. Water from the surface can reach the aquifer in 0-3 days.

We learned this the hard way with the 2021 Rush Creek fish kill.

The Central Sands area (like the Willmar area) is also has a very sensitive geology, where surface water can quickly reach aquifers. We cannot afford to find out the hard way with this massive CAFO proposal permitting 18,855 dairy cattle on a single site. Being over ten times the size of the CAFO near the headwaters of Rush Creek, the environmental risks are clear.

We cannot, in good conscience, approve a CAFO of 18,855 dairy cattle before performing an Environmental Impact Statement (EIS).

If the analysis shows that a CAFO of this size would be safe, so be it. But moving forward without and EIS is risking the environment and human health. We must require an EIS for a proposal of this magnitude.

Douglas Nopar **Letter 302**

I am concerned about air quality , and its effects on workers and neighbors, both the gases from storage facilities, and the air quality effects from the spreading of liquid manure. Of equal concern is water quality , and the effects of liquid manure and excess nitrogen fertilizer application on nitrogen levels in groundwater (as well as phosphorus impacts on surface waters).

An environmental impact statement needs to be done to not only examine air and water quality, but to also assess the impacts of this proposed facility on the economic viability of small and mid-size dairies in the entire state. Lastly, Riverview's track record of exploiting its immigrant work force must also be reviewed for cases of wage theft, failure to provide worker's compensation benefits to farm workers, and failure to pay overtime wages. Operations such as this proposed operation are a blight on

Minnesotas farm and rural economy . We need the state of Minnesota to protect us from these facilities, and not allow them.

Birgitta Anderson **Letter 303**

I believe that a more in depth study into the environmental impact of a production of this size. This is new territory for MN and its citizens deserve the time and attention to their communities that an in depth study provides.

Em Perttu **Letter 304**

It is vital that the Riverview Dairy be required to submit an environmental impact statement. It is nearly twice as big as any current operations in the state, and its environmental harm would be enormous. Here's what we know now.

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Advancing permits without a full understanding of groundwater and water-quality risks is irresponsible. It is critical that the MPCA require a full Environmental Impact Statement.

Abby A **Letter 305**

Riverview Dairy should be required to submit an environmental impact report!!

Thank you!!

Steve Thompson **Letter 306**

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Advancing permits without a full understanding of groundwater and water-quality risks is irresponsible. It is critical that the MPCA require a full Environmental Impact Statement.

Dean E. Peterson **Letter 307**

Dear Mr Peterson:

The following are my comments that I would like posted for the EAW being conducted for the West River Dairy expansion in Stevens County.

I am not an environmentalist nor do I understand the entire process. I am not an owner/shareholder of Riverview. I just wanted to expound on the people and the organization behind Riverview Dairy LLP. I desire that the public knows and understands the integrity of the people behind this project. I feel there are several misconceptions about who Riverview is and what they stand for.

I have now known four generations of the founding family of Riverview. I lived in the Morris area from 1986 to 1998. This family was one of my customers in the business that I worked for. I spent many hours working in and around their farms south of Morris.

I have never worked for nicer people. I know they would never invest in something that could be of harm to their adjoining neighbors. They consider their neighbors their partners. Their desire is to add value to their surrounding communities. I appreciate all the kids that have been added to our schools because of the new employment at Riverview.

I want to share what their Core Values are that are posted in all their work places:

Strong Work Ethic	Proverbs 6:6-8
Integrity	Luke 12:2
Keep it Simple	Matthew 22:37-40
Candor	1 Thessalonians 5:14
Spirit of Humility	James 4:6

The consolidation and growth of any business is an issue today in all areas of our country's commerce. It doesn't matter what industry your involved with, consolidation is what it takes to survive and be competitive. Sadly the days of small family farms with a hundred dairy cows are over.

I would encourage anyone to visit any of the Riverview milking facilities. You will notice there is no smell and you cannot find a cleaner operation. These guys know how to manage their facilities!

I appreciate and respect the process to get these permits and I thank you for the opportunity to comment here.

Sincerely,

Dean E. Peterson

Janet Thompson **Letter 308**

It is vital that the Riverview Dairy be required to submit an environmental impact statement. It is nearly twice as big as any current operations in the state, and its environmental harm would be enormous. Here's what we know now.

Massive water use: Riverview would pump up to 226 million gallons/year from an off-site well—nearly as much as the entire City of Morris (permitted for 300 million gallons/year for 5,000+ residents).

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Advancing permits without a full understanding of groundwater and water-quality risks is irresponsible. It is critical that the MPCA require a full Environmental Impact Statement.

Celeste Knoff **Letter 309**

Minnesota Pollution Control Agency,

It is vital that the Riverview Dairy be required to submit an environmental impact statement. It is nearly twice as big as any current operations in the state, and its environmental harm would be enormous. Here's what we know now.

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Advancing permits without a full understanding of groundwater and water-quality risks is irresponsible. It is critical that the MPCA require a full Environmental Impact Statement.

I care deeply about the environmental impact of this CAFO. I care deeply about keeping Minnesota and its water clean and sustainable for future generations.

Thank you.

Celeste Knoff RN, MAN, MBA, CNE

Jeffrey Borchert **Letter 310**

Hello. I feel NO person or company should have this many animals, for many reasons. Impact of land around it. Animal safety due to equipment failure or help issues. I own land near the project both north (Alberta) and to the south (south of Oliver lake), not close but very possible having an impact. There are many USFWS properties nearby as well. This does nothing to help locals either. They have a track record of manure spills. I really believe a project of this size needs EIS study done. I actually believe they may have too many cows already. Jeff Borchert.

Austin Voltin **Letter 311**

We don't want of need this!

Faye Duvall **Letter 312**

Please consider the soil and your neighbors. This large number of animals in one location is not healthy for the environment.

Marz Beckman **Letter 313**

No project of significant size such as this should be allowed in a community without an environmental impact study. We can destroy the environment easily but we can't restore it without a great deal of money. Do the right thing.

Kim Fortin **Letter 314**

It is essential that the Riverview Dairy be required to submit an environmental impact statement. It is nearly twice as big as any current operations in the state, and its environmental harm would be enormous. Here's what we know now:

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Todd & Cheryl Jackson **Letter 315**

When is enough enough ??? There is already an abundance of dairy cows cattle in this area of MN. This will be one more nail in the coffin for the small dairy producer.

Audrey Kingstrom **Letter 316**

I can't imagine that such a large operation is good for the environment or the surrounding rural neighborhood. You must at least do an environmental review. While I don't live in that area (I live in the

city now), I grew up in west central Minnesota and my brother now operates an industrial hog operation on what used to be our family farm. Not only is it cruel to the animals to be confined as they are, but the manure lagoons reek and make living in the area so unpleasant. Plus the manure concentration on the fields and the inevitable contamination of waterways are a travesty to the environment.

I urge you to take a closer look at this proposal for the West River Dairy Expansion -- and deny the request. We need to move to more sustainable and regenerative agriculture in this state -- and stop these huge livestock operations!

Karen Ahrens **Letter 317**

I am terrified by the Riverview proposal. Living nearby the Daley Farms in the karst topography of southeast Minnesota, I feel the anxiety of these neighboring communities. These monstrous CAFOs demonstrate selfish disregard for the health, safety and economic conditions of everyone, even their own families. These industrial farms will leave a "legacy" of greed, toxic well water,deserted towns and human suffering.

This is beyond opinion. They are undisputable facts.

Kim Hiltner **Letter 318**

I am writing to express my concerns with Riverview, LLP's proposal to build the first livestock operation in Minnesota to hold over 20,000 animal units. The MPCA must recognize the fundamentally new nature of this threat. This proposal must be required to undergo a full Environmental Impact Statement (EIS) on its impacts on water quality and quantity, local roads, and existing independent family dairy farms to be fully analyzed before the project is allowed to seek a permit. Minnesota is is already losing dozens of dairy farms annually due to inconsistent and often below cost-of-production milk prices. Agricultural consolidation is pushing small and medium-sized family farms out of business and off the land. We must require an EIS before this proceeds.

Emily Marsolek **Letter 319**

It is vital that the Riverview Dairy be required to submit an environmental impact statement. It is nearly twice as big as any current operations in the state, and its environmental harm would be enormous. Here's what we know now.

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Advancing permits without a full understanding of groundwater and water-quality risks is irresponsible. It is critical that the MPCA require a full Environmental Impact Statement

Allie Arthur **Letter 320**

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Mary Vlazny **Letter 321**

An EIS will allow the proposal's negative impacts on water quality and quantity, local roads, and existing independent family dairy farms to be fully analyzed before the project is allowed to seek a permit. This is what the MPCA is for, to assess the potential for harmful impacts to our local environments, both ecological and social. According to the documents filed by Riverview, the proposed operation would require:

To supply water for the operation, the facility will be allowed to pump 226 million gallons from an off-site well per year. For reference, the City of Morris, which is home to over 5,000 people, is permitted to pump up to 300 million gallons of water a year.

Liquid manure storage encompassing 250 million gallons of waste.

13,200 acres of farmland for manure application.

Riverview has a recent history of a manure spill in western Minnesota. In Arizona, the company recently agreed to pay $11 million to residents affected by the dairy's over-pumping.

The proposed Stevens County site sits within five miles of eight different protected waterfowl and wildlife production areas and is part of the Pomme de Terre River watershed, just 25 miles from its confluence with the Minnesota River. A facility of this scale located in such a vulnerable area calls for a thorough environmental review.

Just as importantly, an EIS of the West River Dairy Expansion proposal would address socio-economic impacts. Minnesota is already losing dozens of dairy farms annually due to inconsistent and often below cost-of-production milk prices. I have watched this happen in my own county here in Minnesota and the local push-back necessary to prevent the exploitation of resources. Massive dairy operations, like the one Riverview is proposing to build, have glutted the market and tightened Big Milk's stranglehold on the industry, allowing them to push small and medium-sized family farms out of business and off the land. This operation would only exacerbate the situation and accelerate the loss of dairy farms in our state, decimating Main Street economies in the process.

Robert Rinkenberger **Letter 322**

To Charles Peterson and the Minnesota Pollution Control Agency,

Hi my name is Robert Rinkenberger, I have lived in Stevens County for 67 years. I live 3 miles as the crow files from West River Dairy. You wouldn't even know the facility is there except for a little more traffic during harvest. I have been on the Township Board as supervisor since 1996. We have not had any

major problems with the roads with the extra traffic during harvest. And what does pop up Riverview is easy to talk to and will take care of any issues that arise immediately.

Riverview does an excellent job of odor control, manure management and keeps the site very clean. It gave me the opportunity to diversify crops, that I didn't have the ability to have done before they started West River. I have read some of the other comments and it seems like some people did not read the EAW for this project because their statements don't line up with what's on file. For one Riverview has been great neighbors to work with, although they do buy land, like everybody else, they also help smaller guys expand their land base. As far as the use of water, I believe the MPCA and the DNR have done their due diligence in protecting the water resources and quality. It also gave myself, my children and grandchildren the opportunity for supplemental income, such as hay, silage and straw hauling. Riverview also does many community projects and provide educational opportunities for many young people in our area, where they can learn all aspects of the business which is many. I am only a neighbor not an investor and I have no monetary value in the dairy other than I get the opportunity to work for them time to time. I completely support the expansion of West River Dairy. Thank you for your consideration and I hope they will get the permits needed.

Thomas Sybrant **Letter 323**

This project is too large for the area. The pollution impact has not been studied and presented. This is about greed, not the health of the animals or community. Thank you.

Malee Johnson **Letter 324**

It is vital that the Riverview Dairy be required to submit an environmental impact statement. It is nearly twice as big as any current operations in the state, and its environmental harm would be enormous. Here's what we know now.

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Advancing permi ts without a full understanding of groundwater and water-quality risks is irresponsible. It is critical that the MPCA require a full Environmental Impact Statement.

Gretchen Goodman **Letter 325**

Surely an expansion of this size and scope warrants an Environmental Impact Study! The people of Stevens county, and indeed of all Minnesota, deserve this. Our environment, and its ability to sustain itself, needs more than just rubber-stamp approvals.

Gretchen H Goodman

Danielle White **Letter 326**

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Sumi Srinivasan **Letter 327**

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Advancing permits without a full understanding of groundwater and water-quality risks is irresponsible. It is critical that the MPCA require a full Environmental Impact Statement

Holly Swiglo **Letter 328**

I urge you to oppose the expansion of West River Dairy, due to the large environmental impacts and health impacts on local communities.

Ann Peckskamp **Letter329**

It is vital that the Riverview Dairy be required to submit an environmental impact statement. It is nearly twice as big as any current operations in the state, and its environmental harm would be enormous. Here's what we know now.

—Massive water use: Riverview would pump up to 226 million gallons/year from an off-site well—nearly as much as the entire City of Morris (permitted for 300 million gallons/year for 5,000+ residents).

—Huge waste output: The facility would generate about 202.7 million gallons of liquid manure and wastewater annually, plus 26,400 tons of solid manure.

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—Sensitive, already-impaired waters: The expansion sits in the Pomme de Terre watershed, designated sensitive; the nearest waters—the Pomme de Terre River and a nearby unnamed creek—are already listed as impaired. The project would likely worsen these impairments.

Advancing permits without a full understanding of groundwater and water-quality risks is irresponsible. It is critical that the MPCA require a full Environmental Impact Statement.

Maurice Spangler **Letter 330**

This huge expansion of factory dairy farming poses risks for environmental pollution, massive amounts of water and financial risks for smaller dairy farmers. Please do an Environmental Impact Statement and give a very careful, thoughtful assessment of this project.

Taylor Borgman **Letter 331**

This huge expansion of factory dairy farming poses risks for environmental pollution, massive amounts of water and financial risks for smaller dairy farmers. Please do an Environmental Impact Statement and give a very careful, thoughtful assessment of this project.

Jazmin Goire **Letter 332**

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Deborah Liang **Letter 333**

Riverview Dairy must be required to submit an environmental impact statement. It is nearly twice as big as any current operations in the state, and its environmental harm would be enormous. Current concerns:

—Massive water use: Riverview would pump up to 226 million gallons/year from an off-site well—nearly as much as the entire City of Morris (permitted for 300 million gallons/year for 5,000+ residents).

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Advancing permits without a full understanding of groundwater and water-quality risks is irresponsible. It is critical that the MPCA require a full Environmental Impact Statement.

Ana Shickich **Letter 334**

After learning about this proposal, I believe it is essential that Riverview Dairy be required to submit an environmental impact report. It is nearly twice as big as any current operations in the state, and its environmental harm would be enormous. Current concerns:

—Massive water use: Riverview would pump up to 226 million gallons/year from an off-site well—nearly as much as the entire City of Morris (permitted for 300 million gallons/year for 5,000+ residents).

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Advancing permits without a full understanding of groundwater and water-quality risks is irresponsible. It is critical that the MPCA require a full Environmental Impact Report.

Michael Kennedy **Letter 335**

This project, due to its unique size and impact, requires a mandatory EIS. Anything less would be setting a precedent in our state that threatens all future land use for dairy operations by ignoring massive impacts on already fragile natural resources.

Jennifer Love **Letter 336**

Farming cows is a huge contributor to global warming and environmental damage. Please do not expand, even with the most up to date farming practices, this is not good for our climate as a whole nor for the protected and already struggling Pomme de Terre watershed.

Cassie Dudley **Letter 337**

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Advancing permits without a full understanding of groundwater and water-quality risks is irresponsible. It is critical that the MPCA require a full Environmental Impact Statement.

Brook Pederson **Letter 338**

As a homeowner who can't drink their well water due to the high nitrate concentration in it. It is absolutely abhorrent to see and hear such a violation of nature being proposed. I've never understood why humans are so hell-bent on creating food in such a terrible way. This is a horrific idea. It's terrible for humans. It's terrible for animals and it's only good for a few Farmers Pocketbooks!

Kirstan Ketter **Letter339**

It is vital that the Riverview Dairy be required to submit an environmental impact statement. It is nearly twice as big as any current operations in the state, and its environmental harm would be enormous. Here's what we know now.

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Advancing permits without a full understanding of groundwater and water-quality risks is irresponsible. It is critical that the MPCA require a full Environmental Impact Statement.

Emily B **Letter 340**

Aside from environmental concerns wich are innumerable, factory farming is a disgustingly cruel practice. It should be illegal it is animal cruelty it is human cruelty.

It is vital that the Riverview Dairv be required to submit an environmental impact statement. It is nearly twice as big as any current operations in the state, and its environmental harm would be enormous. Here's what we know now

22

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Jeremy Culver **Letter 341**

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Advancing permits without a full understanding of groundwater and water-quality risks is irresponsible. It is critical that the MPCA require a full Environmental Impact Statement.

Laura Aldrich-Wolfe **Letter 342**

The proposed project requires a full environmental impact statement. Even without one, it is obvious that this project is incompatible with a state that values its lands and waters. CAFOs enrich a few at the expense of many, bringing minimal economic benefits and very high environmental costs.

Faustine Micheyl Moran **Letter 343**

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Kelley Parker **Letter 344**

It is vital that we require this riverview dairy expansion project to run an environmental impact study before it's approved.

Kaitlin Kramer **Letter 345**

The West River Dairy Expansion would result in enormous environmental harm to its surroundings; massive water use and waste output would be highly detrimental to the groundwater reserves and the Pomme de Terre watershed where the expansion would sit.

Bonita Underbakke **Letter 346**

The EAW is merely assurance by the proposer that all is well. The Riverview Expansion project needs a thorough Environmental Impact Study to recognize risks across the board, and how, if possible, to prevent permanent damages.

A healthy rural future is essential; myopic focus on short-term profits is predictably destructive.

Laura Haule **Letter 347**

It is inconceivable that a dairy operation of this size will not heavily impact soil, water, and air quality in the surrounding area. Riverview Dairy should be required to submit an environmental impact statement. It will drain local water resources and create hundreds of millions of gallons of wastewater annually. Groundwater impacts are unknown. This should not go forward without knowing environmental impacts. Water resources in the area are unknown, so permitting a heavy water user does not sound appropriate. A full environmental Impact Statement should be required.

Dylan Summerville, Summerville Electric **Letter 348**

Letter of Support for West River Dairy Expansion

Vendor of Riverview Dairy

Subject: Support for West River Dairy Expansion

My name is Dylan Summerville Owner of Summerville Electric based out of Breckenridge MN. We currently have two dairies owned and operated by Riverview in our county. I am writing here today for my support for West River Dairy Expansion.

In working with Riverview LLP through the years, from wiring new facilities to daily service work they have been a great customer to work for. They value their employees within Riverview and truly value their outside relationships whether they be venders, local farmers, neighbors and the local communities. They are very proactive in their daily operations to make their dairies efficient, modernized and immaculately clean. Working alongside them firsthand makes it clear that their commitment and dedication to their facilities do not go unnoticed. They work hard to keep these spaces safe, well-maintained, and accountable--reflecting values that many in our community appreciate and rely on.

Riverview has been a huge partner with Summerville Electric, not only helping our operation for Electrical, but has helped our business grow. In working with them it has allowed us to find other ways to grow our business such as providing services within their daily operations and by starting other businesses and employing additional people. Working with Riverview, they maintain high expectations and strong standards—not only for themselves, but for everyone around them. These core values have helped strengthen not only their own work, but also the people they collaborate with, including vendors, local farmers, and the surrounding communities, making all of us stronger and better together.

Riverview is always looking at the economic impact they can make on a community. They are very involved in community actions, and very actively looking to employ residents to contribute to their dairy and farming operations. Riverview embraces opportunity for those around them and focuses on the word team (Community). I firmly believe the West River Dairy expansion will continue to reflect the same level of care, professionalism, and positive impact they have provided and will continue to strive for within their operations.

Sincerely,

Dylan Summerville

Paige Van Pelt **Letter 349**

If this doubling of the size of Minnesota's current CAFO capacity can be approved without a full environmental review process, we are truly in trouble. I find it creepy that agricultural interests in our state would try to slide this under the door rather than achieve a legitimate approval. Operating in this fashion betrays the trust of the public and weakens our state.

Jack Judkins, Grandpa Roy's Pickles **Letter 350**

Industrial scale agriculture has been an environmental disaster, to say nothing about animal welfare (cruelty). Listen to the folks most affected. Deny the Riverview permit.

Katie Hauge **Letter 351**

This is just simply horrible... as a small family farmer who is hoping to keep our little farm going, we need to stop more expansion from the corporate farms! We are being swallowed up by these giant corporate farms, wells are a problem, river pollution is a problem. If this passes it's because the pockets are too deep!

Peg Furshong **Letter 352**

Do you ever say no? How many is too many cows? How much does this operation actually pay for their water - all that water for the cows and to grow the feed? This is North America's largest dairy operation - the largest - The Minnesota River Basin is overrun with manure from CAFO's - and you are continuing to permit more facilities. This proposed project expansion is on sensitive ground - there are wetlands just to the south of the proposed site. What we know about wetlands is that they are a complex network of capillaries and underground water pathways that goes significantly beyond what we can see above ground - This proposal needs a comprehensive EAW and the impacts to local well water and the Pomme de Terre River.

What is the threshold for saying no - just because someone wants to built it - doesn't meet that we have the land and water to support it. The impacts on the surrounding area is significant. This operation has become a monopoly in the dairy industry and has put many small family farms out of business. At some point the well being of the greater community and the future of our water, air and soil health should outweigh the economic interests of this company.

Respectfully,

P & S Petrich

Lauren Robinson **Letter 353**

It is vital that the Riverview Dairy be required to submit an environmental impact statement. It is nearly twice as big as any current operations in the state, and its environmental harm would be enormous. Here's what we know now.

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Advancing permits without a full understanding of groundwater and water-quality risks is irresponsible. It is critical that the MPCA require a full Environmental Impact Statement.

Lisa Cain **Letter 354**

Due to past problems with water access for neighbors, possible degradation of our water quality, and just the sheer size of the proposed dairy, I believe very thorough studies should be done before this project would even be considered. Our way of life and that of our wetlands too are at stake.

This is too large an operation for our area.

Thank you for your time in reading my comments.

Lisa Cain

Gage Norton **Letter 355**

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Advancing permits without a full understanding of groundwater and water-quality risks is irresponsible. It is critical that the MPCA require a full Environmental Impact Statement.

Patrick Brueske **Letter 356**

Hello.

This comes strongly urging an environmental impact study for the proposed West River Dairy Expansion in Stevens County, Minnesota.

Thank you for giving a read and for next steps being taken for addressing this.

Respectfully,

Patrick Brueske

Becca Golden **Letter 357**

These mega-dairies are one of the worst things to happen to Chippewa and Swift County. They are nothing more than massive land grabs by a small group of people who claim these operations "help the community," when in reality it's simply greed feeding greed.

What they don't tell the public is the real cost--paid by local taxpayers:

1. Damaged roads: Rural roads are deteriorating under the weight of constant heavy truck traffic, leaving counties to foot the repair bill.

2. Subsidized labor: These operations bring in H-2A workers and then receive subsides for their food, housing, and wages--another hidden benefit that doesn't help the community at all.

3. Strained schools: Our school districts are overwhelmed, especially as they work to support students whose families come to the dairies and who are still learning English.

Take a step back and ask: Who actually benefits?

From where I live, it's clear that the dairies and the large farming operations tied to them are trying to grab and control every acre possible. They are not your friends or your neighbors; they are businesses determined to expand at any cost.

On top of that, they work to place their people on township boards, planning and zoning boards, and other local government committees--giving them influence at every level while the broader community pays the price.

Mega-dairies don't strengthen our counties--they hollow them out.

Stuart Knappmiller **Letter358**

Growing up on a 28 cow 228 acre farm, I saw our livestock use Stumptown Creek as a toilet. Our septic tank flowed water into the pasture near a tree I stayed away from.

20 years later, we had no livestock near the creek, a new up to date field for our waste. It would seem to me 26,000 cattle might do more damage than our 28 cows. Dad applied anhydrous ammonia on our neighbor's corn fields. He needed the money to buy the land. That polluted our well water.

Do an EIS.

Carlos Gutierrez **Letter 359**

I am a Stevens County resident, and I am in favor of the expansion of West River Dairy. I am familiar with Riverview's farms, and I know they always try to do things the right way. Riverview provides jobs in our area. They also care about protecting the environment and taking care of their neighbors and communities where they operate. West River is a clean farm with manure properly handled and contained. this manure is used on fields near the dairy after silage harvest and following state requirements. I know some guys who help apply manure for Riverview and they have to follow a lot of rules and do inspections. I am not an expert in government and permitting but I know that the state reviews just about every aspect of projects like this. It has been about two years since I first heard about this expansion for Riverview and I believe they've been working on permitting all this time. Please give West River a permit for the expansion.

Thank you

Dawn Cook Ronningen **Letter 360**

This is a horrid idea. Please I want to see a complete environmental study and economic assessment.

This needs to be done before any further advancement of the project.

Itzel Herrera **Letter 361**

It is vital that the Riverview Dairy be required to submit an environmental impact statement. It is nearly twice as big as any current operations in the state, and its environmental harm would be enormous. Here's what we know now.

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Advancing permits without a full understanding of groundwater and water-quality risks is irresponsible. It is critical that the MPCA require a full Environmental Impact Statement.

Sarah Winikoff **Letter 362**

I think that the proposed project should be rejected.

As a PhD aquatic ecologist and freshwater biologist, I see the proposed project as a threat to public health in the nearby communities.

Confined animal operations have long been known to degrade surface and groundwater supplies by increasing the incidence of fecal coliform, increasing nitrogen and phosphorous loading, and increasing the concentration and prevalence of antibiotic resistant bacterial communities.

I have further concerns about how the proposed project will influence water availability to nearby communities as climate change continues to alter water availability in space and time.

Finally, I see the proposed project as a potential threat to community health because a confined animal operation of this size increases the risk of rapid pathogen spread should one of the emerging viruses establish within the herd (e.g., avian influenza). Not only would this hurt the cattle in such an operation, but concentrating animals in these quantities increases the risk of spread to human populations as well.

In conclusion, I am opposed to an animal confinement operation of this size and magnitude anywhere, but particularly in a small rural community when there has been little or no environmental impact assessment.

Barbara Burke **Letter 363**

The Riverview expansion should require a full EIS.

GHG testing and estimating that was done as part of the Environmental Assessment Worksheet was based only on the number of cows they intend to add, not including the base amount of cows they already have. This leaves an incomplete picture of the true costs to the environment, the community, the water, and the land.

Riverview has a recent history of manure spills in western Minnesota.

The Environmental Assessment Worksheet prepared for this project claims that the project will overall reduce GHG emissions because they will not be using anhydrous ammonia on the fields that have manure being spread on them. This grossly undercounts the true emissions of an operation of this scale and must be reviewed further in a full Environmental Impact Statement.

Darlene Eckert **Letter 364**

It seems that Minnesota's ground water is under attack from all sides. Mining, ai farms and big ag businesses. The quantity of water they will use and pollute is unacceptable. Can they treat and reuse the treated water instead of using fresh water? This seems like the perfect way to introduce nitrates into large areas of our groundwater . Will that mean users of groundwater in areas where waste is spread will need to upgrade their home wells or home treatment systems? I am also concerned by the smell. Driving through areas with huge feedlots really stink even in cities near huge feedlots by like Colorado going out of Denver and North Platte, Nebraska. If you're going to spread liquid manure over huge areas then huge areas will stink.

Basically I am saying that this does not benefit the community, small farmers or other water users. I don't think this would be acceptable unless they come up with an environmentally sound method to manage manure that doesn't contribute to nitrate contamination in local wells.

Helene Murray **Letter 365**

A dairy of this size has the potential to have severe, adverse environmental impacts. An EIS is needed to determine to what extent this facility will have on the environment and area.

Jody Snow **Letter 366**

As a Morris, Minnesota resident for almost 20 years, I would like to voice my opposition to the expansion project proposed. The leadership of the LLC exploits workers, breaks contracts, and are not good stewards of the land they currently possess. They will cut corners to make more of a profit. The amount of resources required for such an expansion will put the entire community at risk, people I worked with and care about.

I encourage you not to approve it!

Jan Kaeter **Letter 367**

I oppose any opperation of this size with the volume of water used and the affects it would have on the local aquafers to the amount of waste produced not to mention the methane gas released. This opperation is not a farm it is an industrial plant not unlike an oil refinery and should have a rigorous environmental impact study before any permit is even considered.

Ann DuHamel **Letter 368**

As a resident of Stevens county for almost 17 years, I am EXTREMELY concerned about this proposed expansion, and how it will impact both the quality of life for the people who live here as well as the environmental impacts for water, flora, and fauna in the area.

I wholeheartedly agree with the Land Stewardship Project that a full Environmental Impact Statement must be completed, because of these reasons:

- GHG testing and estimating as part of the Environmental Assessment Worksheet was based only on the number of cows Riverview LLP intends to add, not including the base amount of cows they already have. This leaves an incomplete picture of the true costs to the environment, the community, the water, and the land.

- This proposed operation is the first of its size in Minnesota. It would be nearly DOUBLE the size of the next largest livestock operation in our state in terms of animal units. This makes it a fundamentally new

and particularly powerful threat to Minnesota farmers and rural communities. The MPCA should give it scrutiny as such.

- Riverview has a recent history of manure spills in western Minnesota. (YIKES!) In Arizona, the company recently agreed to deliver $11 million to residents affected by the dairy's overpumping.

- The proposed Stevens County site sits within five miles of eight different protected waterfowl and wildlife production areas and is part of the Pomme de Terre River watershed, just 25 miles from its confluence with the Minnesota River. A facility of this scale located in such a vulnerable area calls for a thorough environmental review.

- Minnesota has lost 528 dairy farms in the last 4 years, and what's even more concerning, has lost 1,987 dairy farms since 2017. Our state is losing dozens of dairy farms a year due to inconsistent and often below cost-of-production milk prices. This disaster in price is largely caused by massive dairy operations, being able to glut the milk market with cheaper-to-produce milk, making it hard for smaller family farms to compete. As a descendant of Minnesota dairy farmers, this expansion seems contrary to the spirit of supporting our hard-working citizens and farmers.

- The Environmental Assessment Worksheet prepared for this project claims that the project will overall reduce GHG emissions because they will not be using anhydrous ammonia on the fields that have manure being spread on them. This grossly undercounts the true emissions of an operation of this scale and must be reviewed further in a full Environmental Impact Statement.

Thank you for your consideration!

Elena Machkasova **Letter 369**

As a resident of Morris, MN, I am very concerned about the environmental effects of the proposed Riverview Dairy expansion. The project of such scale has a potential to negatively effect the environment in a variety of ways.

The proposed location is within five miles of eight different protected waterfowl and wildlife production areas and is part of the Pomme de Terre River watershed, just 25 miles from its confluence with the Minnesota River. A possible manure spill would be devastating to the livelihood of nearby population, farms, and wildlife. The changed landscape would also affect plants and insects habitats and may create a potential for animal and plant diseases spreading to nearby family farms and other small agricultural businesses. The consequences of building such an unprecedented project need to be thoroughly evaluated.

The project of this size must undergo a full and thorough Environmental Impact Statement. This is a matter of highest importance for Morris and its surrounding areas.

Sincerely,

Elena Machkasova

Heather Stefanek-Peters **Letter 370**

As a resident of Stevens County MN, where the proposed Riverview Dairy expansion would be located, I am concerned about its environmental impact and would like the MPCA to require a full Environmental Impact Statement before the project can go forward. This project would more than double the size of Riverview's dairy operation in Stevens County, with the final size being almost twice as large as the next largest livestock operation in our state in terms of animal units. A project of this unprecedented scope demands particular care in reviewing its impacts, which a full Environmental Impact Statement would

provide. In addition, I believe it is important for the EIS to take into account the total projected size of Riverview's Stevens County dairy operations, including existing animal units, not just the size of the expansion. Total size matters because the larger the total size, the larger the potential impact if something goes wrong. For example, Riverview's Feb. 2025 manure spill in Kandiyohi County likely spilled approximately the same amount of manure in 5 days that an average sized MN dairy farm would produce in 6 months, based on early reports.

Jim Bambenek **Letter 371**

For the health and safety of our environment, water, clean air and soil health, please say no !

Anna Larsson **Letter 372**

The Riverview Dairy must be required to submit an environmental impact statement. This proposed farm is almost twice as big as any current Minnesota dairy operation. It will cause enormous environmental damage. I am an environmental educator, and here are the main concerns I have about this farm.

• Poo-lution The 11,000 proposed new cattle will create almost as much biological waste as all the people in Saint Paul. And this waste doesn't get treated in a sewage treatment facility. Instead, it gets sprayed on nearby fields. The Pomme de Terre watershed is designated "sensitive," and the Pomme de Terre River is already listed as "impaired". Adding this much waste to the watershed will almost certainly worsen the situation.

• Water Use The farm will pump up to 226 million gallons of water per year from the aquifer. Is this a little or a lot relative to what the area can handle? I don't know, and neither does anyone else. The DNR hasn't analyzed what this means in the context of what the environment can handle. It is irresponsible to permit such large withdrawals without knowing if the system can handle it. What we do know is that throughout the US, groundwater resources have been declining. This is an issue that needs to be evaluated before the project moves forward.

Advancing permits without a full understanding of water-quality and groundwater risks is irresponsible. It is critical that the MPCA require a full Environmental Impact Statement.

Dairy consumption in the US is flat. The only way adding a dairy of this size makes sense is if they are expecting to push other, family-scale dairies out of business, or if they are planning to export their products to other countries. Neither reason is justification for harming our beautiful, clean Minnesota environment.

Rhyan Schicker **Letter 373**

Thank you for reading my comment. I am extremely worried and frustrated by the Riverview Dairy proposal to install the largest CAFO MN has ever seen in the area where I live, work and recreate on the local waterways.

MN has a climate action plan with tangible goals set for 2030 and beyond. This proposal would move us against those goals as the emissions from the cows, the usage of water and the transportation of cattle would cause significant impacts to the state. The water usage outline by Riverview is as much as the town of Morris is allowed- so where is that water coming from? Are we willing to empty our already limited aquifers in the name of a mega corporation over our own residents? At the very least we need an environmental impact statement so we can make sure we are aware of the risks, and who the risks will affect were something to go wrong or over pumping to occur. Riverview has a history of over

pumping and is currently facing a multi million dollar pay out to residents they affected by over pumping in AZ- a state so obviously in need of proper water usage as they are currently experiencing water shortages, how would we trust them to follow rules set in MN? (Inside Climate News; Arizona Comes to Agreement With Major Dairy Farm to Cut Groundwater Pumping That Is Draining Wells)

Riverview also had a recent MN spill in this area with limited transparency on results and impacts to the surrounding residents.

I work with farmers everyday. The amount of small farms in MN, especially small dairies has seen a devastating downfall. MN is supposed to be a state the leads the way in climate action, sustainability and care of residents. It is really hard to see how this huge feedlot is good for anyone other than Riverview. When is enough enough? We are going to continue losing small farm families and residents in our small towns, which are in need of revitalization efforts- not support for huge mega operations whose use of resources greatly overshadows the need of local residents and businesses.

Due to the unprecedented size of the facility, an Environmental Impact Statement should be done. It's what's right for our communities. MPCA needs to find a way to start putting the needs of our communities over the needs of a small percentage of large corporations and saying no to projects that go against our state climate action plan, our natural resources and wellbeing of our communities.

Please consider the need for a EIS.

Thank you for hearing my concerns,

Rhyan Schicker

Carole Fernholz **Letter 374**

In my opinion, this is far too many animals proposed in this project and must have a thorough environmental review! These massive dairy operations have glutted the market and tightened their hold on the industry. This project would push more family farmers out and decimate our main street businesses. Inconsistent and below cost of production prices are affecting smaller family farms. The area where this operation is proposed is already considered a "sensitive watershed." This massive dairy project would only do more damage. There NEEDS to be an EIS (Environmental Impact Statement) done before they are allowed to go forward.

Thank you.

Mariah McMahon **Letter 375**

It is vital that the Riverview Dairy be required to submit an environmental impact statement. It is nearly twice as big as any current operations in the state, and its environmental harm would be enormous. Here's what we know now.

Massive water use: Riverview would pump up to 226 million gallons/year from an off-site well—nearly as much as the entire City of Morris (permitted for 300 million gallons/year for 5,000+ residents).

Huge waste output: The facility would generate about 202.7 million gallons of liquid manure and wastewater annually, plus 26,400 tons of solid manure.

Unknown groundwater impacts: The DNR hasn't begun the hydrologic survey or completed the County Geologic Atlas for Stevens County, so aquifers and groundwater resources aren't mapped—making it risky to permit large withdrawals now.

Sensitive, already-impaired waters: The expansion sits in the Pomme de Terre watershed, designated sensitive; the nearest waters—the Pomme de Terre River and a nearby unnamed creek—are already listed as impaired. The project would likely worsen these impairments.

Advancing permits without a full understanding of groundwater and water-quality risks is irresponsible. It is critical that the MPCA require a full Environmental Impact Statement.

James Harkness **Letter 376**

I am strongly opposed to moving forward with this proposed expansion without a much more comprehensive environmental and socioeconomic review. Riverview's plan would blanket a huge area with manure, and I do not see sufficient evidence that it will neither create severe air and water pollution, the latter especially during extreme weather events. I am alarmed at the apparent assumption that there is no need to look seriously at the risk to the Pomme de Terre and Minnesota River watersheds. This company does not have a good record, so assurances about solid and liquid waste management practices ring hollow to me!

The water demand is also excessive.

Cary Anderson **Letter 377**

It is vital that the Riverview Dairy be required to submit an environmental impact statement. It is nearly twice as big as any current operations in the state, and its environmental harm would be enormous. Here's what we know now.

* Massive water use: Riverview would pump up to 226 million gallons/year from an off-site well—nearly as much as the entire City of Morris (permitted for 300 million gallons/year for 5,000+ residents).

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* Sensitive, already-impaired waters: The expansion sits in the Pomme de Terre watershed, designated sensitive; the nearest waters—the Pomme de Terre River and a nearby unnamed creek—are already listed as impaired. The project would likely worsen these impairments.

Advancing permits without a full understanding of groundwater and water-quality risks is irresponsible. It is critical that the MPCA require a full Environmental Impact Statement.

Tyler Scott **Letter 378**

3/12/26

Dear MPCA,

I have lived withing a ¼ mile of another Stevens County Riverview dairy for the last 10 years. In that time, we've had no water quality or supply issues with our well. Riverview excels in neighbor relations, maintain A dust control on roads, resolving concerns promptly, and minimizing odor.

My experience in the dairy industry is that Riverview is top-tier in cleanliness and site upkeep.. Dairy manure not only sustains soil health but also helps retain carbon locally, a natural and sustainable

approach to helping the environment. I feel that Riverview adds a lot to our community which has provided opportunity for that next generation to live in this area.

I encourage the MPCA to prioritize feedback from those of us living near these operations, not from those afar. I support the West River Dairy Expansion in Stevens County.

Sincerely,

Tyler Scott

Cora Gertjejanssen **Letter 379**

I am writing to plead that an environmental assessment be required for a project of this size. It is well known that feedlots have detrimental effects on the environment, such as potential manure spills or mismanagement and intensive water usage. We have a duty to protect our wildlife and natural resources from unintended consequences of large operations such as these. Not to mention, the impact on our small farmers - this will be driving more and more small farmers out of business and taking away their acres of land, when we as a state have a responsibility to support them and not hand over their businesses to corporations. Please consider doing a full environmental review of this proposed expansion and I thank you for your time.

Ramona Heitmann **Letter 380**

I am strongly opposed to the expansion of Riverview Dairy. The operation is already large and has caused problems with both groundwater extraction beyond what the current wells can handle sustainably and the waste generated also has caused issues. The other wells in the area are at risk due to overuse.

The air pollution caused by an expansion is also problematic. Such a large operation is not conducive to animal welfare nor human health. I strongly encourage the MPCA to deny the application for expansion.

Anna Mehlhoff **Letter 381**

It is vital that the Riverview Dairy be required to submit an environmental impact statement. It is nearly twice as big as any current operations in the state, and its environmental harm would be enormous. Here's what we know now.

Massive water use: Riverview would pump up to 226 million gallons/year from an off-site well—nearly as much as the entire City of Morris (permitted for 300 million gallons/year for 5,000+ residents).

-Huge waste output: The facility would generate about 202.7 million gallons of liquid manure and wastewater annually, plus 26,400 tons of solid manure.

-Unknown groundwater impacts: The DNR hasn't begun the hydrologic survey or completed the County Geologic Atlas for Stevens County, so aquifers and groundwater resources aren't mapped—making it risky to permit large withdrawals now.

-Sensitive, already-impaired waters: The expansion sits in the Pomme de Terre watershed, designated sensitive; the nearest waters, the Pomme de Terre River and a nearby unnamed creek, are already listed as impaired. The project would likely worsen these impairments.

Advancing permits without a full understanding of groundwater and water-quality risks is irresponsible. It is critical that the MPCA require a full Environmental Impact Statement.

Mary Longfellow **Letter 382**

Do the right thing for your future self and your prodigy. We shouldn't need to convince you this is simply bad form and isn't needed. The pressure on you and us by corporate entities has to stop. It's destructive and inhumane. Do the right thing instead. It will build your character and you'll thank yourself later.

Gayl Gustafson **Letter 383**

Please get an environmental impact evaluation on this CAFO expansion before permission to build is given

Brooke Reynolds **Letter 384**

It is vital that the Riverview Dairy be required to submit an environmental impact statement. It is nearly twice as big as any current operations in the state, and its environmental harm would be enormous. Here's what we know now.

Massive water use: Riverview would pump up to 226 million gallons/year from an off-site well—nearly as much as the entire City of Morris (permitted for 300 million gallons/year for 5,000+ residents).

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Sensitive, already-impaired waters: The expansion sits in the Pomme de Terre watershed, designated sensitive; the nearest waters—the Pomme de Terre River and a nearby unnamed creek—are already listed as impaired. The project would likely worsen these impairments.

Advancing permits without a full understanding of groundwater and water-quality risks is irresponsible. It is critical that the MPCA require a full Environmental Impact Statement.

Michelle Gobely **Letter 385**

Please require an EIS for this outrageously sized proposed dairy! Thank you!

Andrew Steiner **Letter 386**

To Whom It May Concern,

My name is Andrew Steiner, and I am writing as a local resident, a high school agricultural educator, and a small business owner in the Morris area. I have toured Riverview facilities several times over the years and regularly bring high school students to visit their dairy operations as part of our agricultural education program. I also know many Riverview employees and managers personally. Based on my experiences and what I have seen firsthand, I support this project and believe the Environmental Assessment Worksheet (EAW) process is sufficient. I do not believe a full Environmental Impact Statement (EIS) is necessary.

One thing that has been disappointing to see during the comment period is how many opinions seem to come from people who are unfamiliar with the area or with Riverview's operations. Riverview has built a very strong reputation in our community. Their facilities are well run, and they have always been willing

to host tours and answer questions. Every time I have visited with students, the facilities have been clean, organized, and clearly managed with professionalism and attention to detail.

Some of the concerns raised about manure management also appear to overlook the fact that these systems are already heavily regulated. Projects like this must operate under MPCA feedlot permits and detailed manure management plans. In this case, the proposed facility includes more than a year of manure storage capacity and access to far more acres for manure application than are actually required. Those requirements exist specifically to protect water quality and ensure nutrients are applied responsibly.

I would also encourage reviewers to look carefully at the actual water monitoring data for the watershed. Monitoring in the Pomme de Terre River watershed has shown that overall water quality conditions and biological health have remained relatively stable over the past decade, even though agriculture has been a major land use in this region for generations. Concerns about impacts to waters such as the Pomme de Terre River, Drywood Creek, and Muddy Creek should be evaluated in the context of this long-term data.

Another concern raised by some commenters involves water use. Groundwater withdrawals for projects like this are reviewed and permitted by the Minnesota Department of Natural Resources. That process exists specifically to ensure aquifers are used sustainably. It is important to remember that many other industries and communities also rely on groundwater, and all of them are regulated through the same permitting process.

Beyond the environmental review, it is also important to recognize the role Riverview plays in our local economy. As a small business owner, I see firsthand how much large employers like Riverview contribute to the stability of rural communities. Their operations support local suppliers, contractors, and many other small businesses throughout the region.

Riverview has also been extremely supportive of agricultural education. As a teacher, I think it is important for students to see what modern agriculture actually looks like. Riverview has consistently opened their doors to students so they can learn about animal care, technology, and the science behind food production. Those opportunities are incredibly valuable for young people who are interested in agriculture and environmental careers.

In closing, I encourage the agencies reviewing this project to rely on the available data and the existing regulatory process. From what I have seen personally and from what the monitoring data shows, the EAW has already provided a thorough review of potential environmental impacts. For those reasons, I believe the EAW is sufficient and that preparation of a full Environmental Impact Statement is not necessary.

Sincerely,

Andrew Steiner

Tanner Davison **Letter 387**

Riverview dairy should be granted the permit for expansion. As a farmer that has worked with them on other dairies they have always done what they said, and make things fair and right when circumstances change. As the Mayor of Wendell they have been very generous with the community, supporting multiple fundraising events for city improvements and were a main reason our fire department was able to cover the costs of expensive upgrades with our fire turnout gear.

They have been a great and welcomed addition to our area.

As far as running a dairy, I challenge you to find one that is better run. They as always clean and pleasant looking, there is very rarely an odor. The only smell is usually for a few days when they are doing field manure application, and that is a welcomed event by any and all farmers that are able to receive the application.

I have had many interactions with many of their employees on all levels of their operations, and they are all good people. They work hard and love what they do. It is amazing to have a business that is able and willing to grow in our small communities. We should welcome it and help facilitate it. This is why I support their expansion efforts, Thank You!

Francisco Guadarrama Capitaine **Letter 388**

To whom it may concern.

I want to express my support to the West River Dairy Expansion project; I have known about Riverview for over 6 years. This includes touring their farms in different states.

This opportunity has given me an insight of Riverview, the more I know about who Riverview really is, the more I realized it is something good and not only for the employees or vendors who work directly but also for the communities, townships and counties where Riverview operates.

No matter the circumstances Riverview sites comply with the regulations, laws and even go beyond, sites are clean, organized, with minimal flies, minimal odor even during manure pumping season in the fall.

After harvest and pumping season, the roads are always taken care of, and it is always about people.

Thanks,

Francisco Guadarrama Capitaine

Jodi Williams **Letter 389**

It is vital that the Riverview Dairy be required to submit an environmental impact statement. It is nearly twice as big as any current operations in the state, and its environmental harm would be enormous. Here's what we know now.

* Massive water use: Riverview would pump up to 226 million gallons/year from an off-site well—nearly as much as the entire City of Morris (permitted for 300 million gallons/year for 5,000+ residents).

* Huge waste output: The facility would generate about 202.7 million gallons of liquid manure and wastewater annually, plus 26,400 tons of solid manure.

* Unknown groundwater impacts: The DNR hasn't begun the hydrologic survey or completed the County Geologic Atlas for Stevens County, so aquifers and groundwater resources aren't mapped—making it risky to permit large withdrawals now.

* Sensitive, already-impaired waters: The expansion sits in the Pomme de Terre watershed, designated sensitive; the nearest waters—the Pomme de Terre River and a nearby unnamed creek—are already listed as impaired. The project would likely worsen these impairments.

Advancing permits without a full understanding of groundwater and water-quality risks is irresponsible. It is critical that the MPCA require a full Environmental Impact Statement

Joyce Borgerding **Letter 390**

Minnesota's water is the most important resource we have! I've moved from western Wisconsin in this past year, so I know first hand the effects of CAFOs. Don't let corporate money get in the way of protecting water for all.

Tayler Williamson **Letter 391**

It is extremely important to me that the Riverview Dairy be required to submit an environmental impact statement. It is nearly twice as big as any current operations in the state, and its environmental harm would be enormous. Riverview, in addition to the devastating ethical and inhumane nature of dairy farming would have a negative impact on the surrounding natural environment in the form of millions of gallons of water used, enormous waste output in a critical migratory bird habitat, and groundwater impacts that have not yet been evaluated by the DNR via a hydrologic survey and we don't know what impact such massive water withdrawals would have on aquifers. If this expansion were to happen, there would be catastrophic impact to sensitive waters in the Pomme de Terre watershed. Continuing this effort without a full understanding of water quality and habitat impacts is wrong and not right for Minnesota. I demand that the MPCA require a full environmental impact statement for review. I again reiterate that this is in effort to mitigate additional damages that would be brought to the surrounding animals and environment in addition to the already treacherous atrocities committed each day against the cows subject to dairy farming.

Please do the right thing here.

Paul Golden **Letter 392**

Dear Mcap,

As a very concerned citizen who lives and farms by one of their sites other then this one I can't emphasize enough that they need to be stopped from further expansion at this site and other sites in the future

1- I'm very concerned about our environment and our water quality and supply from the stain they put on everything.

2- I know there has been manure spills that have been cleaned up before they are reported to the MPCA.

3- I have watched what use to be a very peaceful and safe area to live and farm in to become a very unsafe area to live and farm in because of them. Our rural area is deteriorating very from fast from them now and our quality of the environment also.

4- The traffic increase from them is really high and basically hazardous. State highways 29 and 40 have heavy traffic use from them all the year along.

5- The manure smell at many times is really bad at times of the year and can be smelt from a distance of 4-5 miles away.

When they are hauling the solids manure as they call it from their sites I have saw over the years there is dry manure being spilled all over the roadways from the trucks that are hauling it.

6- I can't emphasize enough about our environment and our water supply and our quality of water. Both are very precious resources.

7- I see the bad side and ill side of these large dairies everyday now by living and farming by one. I'm all for livestock and farming/ag in general but this isn't farming or milking cows at all.

8- They need to be required to do a EIS.

Who is really benefiting from these large scale dairies from this entity?

As a very concerned citizen I can't empathize enough that this has to be stopped before it's all too late for everyone and our environment. I'm afraid it's already too late almost.

Sincerely a very concerned citizen,

Paul Golden

Kelle Green **Letter 393**

They say an ounce of prevention is worth a pound of cure. Riverview, LLP's operation has the potential to pollute nearby already-fragile waterways. And a proposal that would generate over 200 million gallons of liquid manure and wastewater annually–plus 26,400 tons of solid manure–should be examined with great care.

The DNR hasn't begun the hydrologic survey or completed the County Geologic Atlas for Stevens County, so aquifers and groundwater resources aren't mapped—making it risky to permit large withdrawal.

Advancing permits without a full understanding of groundwater and water-quality risks is irresponsible.

We Minnesotans take pride in our clean environment and this factory farm has the potential to create long-term, negative consequences to our land and water. It is critical that the MPCA require a full Environmental Impact Statement.

Jenell Holden **Letter 394**

I'd rather see more community gardens

Edi Thorstensson **Letter 395**

A dairy of this size should be required to meet high standards, both in production and environmental stewardship. It should be required to file an EIS and to maintain the highest standards in its operation. I frankly am concerned that, because of its size and influence, ir won't.

Jenell Holden **Letter 396**

It is vital that the Riverview Dairy be required to submit an environmental impact statement. It is nearly twice as big as any current operations in the state, and its environmental harm would be enormous. Here's what we know now.

Massive water use: Riverview would pump up to 226 million gallons/year from an off-site well—nearly as much as the entire City of Morris (permitted for 300 million gallons/year for 5,000+ residents).

Huge waste output: The facility would generate about 202.7 million gallons of liquid manure and wastewater annually, plus 26,400 tons of solid manure.

Unknown groundwater impacts: The DNR hasn't begun the hydrologic survey or completed the County Geologic Atlas for Stevens County, so aquifers and groundwater resources aren't mapped—making it risky to permit large withdrawals now.

Sensitive, already-impaired waters: The expansion sits in the Pomme de Terre watershed, designated sensitive; the nearest waters—the Pomme de Terre River and a nearby unnamed creek—are already listed as impaired. The project would likely worsen these impairments.

Advancing permits without a full understanding of groundwater and water-quality risks is irresponsible. It is critical that the MPCA require a full Environmental Impact Statement.

Ben Knelman **Letter 397**

It is vital that the Riverview Dairy be required to submit an environmental impact statement. It is nearly twice as big as any current operations in the state, and its environmental harm would be enormous. Here's what we know now:

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Advancing permits without a full understanding of groundwater and water-quality risks is irresponsible. It is critical that the MPCA require a full Environmental Impact Statement.

K Shomion **Letter 398**

Stop! No body wants this. Ruining our water, land and environment!!!

Disgusting

Caitlin Rathbone **Letter 399**

I would like to require an environmental assessment for this project. The harms that factory farming has on people and the environment are massive and it wouldn't be in the best interests of anyone to have this farm.

Amy LeBeau **Letter 400**

t is vital that the Riverview Dairy be required to submit an environmental impact statement. It is nearly twice as big as any current operations in the state, and its environmental harm would be enormous. Here's what we know now.

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Advancing permits without a full understanding of groundwater and water-quality risks is irresponsible. It is critical that the MPCA require a full Environmental Impact Statement.

Please don't allow this project to move forward without an environmental impact review.

Thank you,

Amy LeBeau

Tim Ahrens **Letter 401**

The MPCA's repeated refusal to order EIS reviews for extremely largescale feedlot projects is an absolute failure to honor the intent and purpose of MEPA, and the protections it provides. If you don't believe me, ask John Herman and Chuck Dayton.

Environmental Impact Statements under the law are simply more extensive reviews that projects of this complexity must warrant, and applicants must undergo. Proposals even beyond the multi-thousand animal unit scale, and into the tens of thousands of animal unit scale will soon end up exposing the negligence of the agency in failing to order EIS level reviews when they are so blatantly warranted. Facilities of this magnitude in other states have literally displaced material human populations through their depletion of aquifers, surface water bodies, and other environmental harms. If a failure to thoroughly study this proposal leads to a similar outcome in Minnesota, I believe the systemic history of mismanaged environmental review processes by the MPCA will be drawn to the surface. The thousands of documented pleas the MPCA has received from Minnesota residents to honor entitled protections under MEPA may finally command the attention they have always deserved. Natural resources in America's West are depleting at a level that makes the future construction of facilities such as proposed unviable in those regions. The "shit-storm" is coming to Minnesota. Our only shelter, we as residents, and the MPCA as the accountable authority, will be a new adherence to intended conventions of Minnesota Environmental Review regarding NPDES permits, specifically ordering EIS statements when they are appropriate.

Thank you for your time. I always look forward to reading the creative responses left to my comments in your "findings of fact."

Jon Moser **Letter 402**

I am Jon Moser, we live and farm 3 miles East of West River Dairy. We are not financially involved with Riverview. We do support the 11,000 cow expansion of West River Dairy.

Riverview has been a leader in dairy production in many areas.

In my 40 plus years of farming in Stevens County, I have never had issues working with them. They have proven to me to be very credible in their dealings. We use them for another marketing option for crops, and in return, we are able to purchase manure to be used as fertilizer for our growing crops. It is a win-win situation for sustainable agriculture.

As a close neighboring farm family, I do support expanding West River Dairy. This gives an even greater opportunity for us. I do not support an Environmental Impact Study for the expansion, and Riverview has shown to be an incredibly responsible producer and neighbor, and has the track record to prove it.

Respectfully submitted-

Jon Moser

Jane Dow **Letter 403**

Please do not permit this dairy farm for expansion. This large a number of cattle is environmentally a disaster, totally inhumane to the animals and unhealthy for the community where it is located.

This large a facility is totally unacceptable. I think you know that too so don't permit it. Thank you.

Hannah Bernhardt **Letter 404**

I am a farmer and this size project will absolutely have an outsized environmental impact on Minnesota's water, soil, and air. I work closely with my county Soil and Water Conservation District and am Minnesota Agricultural Water Quality Certified because it is the responsible thing to do. We have the right to farm, but I know that how I farm affects my neighbors. I expect reasonable regulation of any industry that impacts public health and well being. Thank you.

Holly Grise **Letter 405**

It is vital that the Riverview Dairy be required to submit an environmental impact statement. It is nearly twice as big as any current operations in the state, and its environmental harm would be enormous. Here's what we know now.

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-Sensitive, already-impaired waters: The expansion sits in the Pomme de Terre watershed, designated sensitive; the nearest waters-the Pomme de Terre River and a nearby unnamed creek

—are already listed as impaired. The project would likely worsen these impairments. Advancing permits without a full understanding of groundwater and water-quality risks is irresponsible. It is critical that the MPCA require a full Environmental Impact Statement.

Morris is an important community that has touched many more lives than just the people currently living there. Every town sees people coming and go, especially college towns. They deserve an independent environmental impact study to be done to see what the estimated impact to the surrounding community would be if this unprecedentedly large farm were opened. No matter how small or large a community is, every single one deserves an environmentally safe place to live.

Kevin Hohn **Letter 406**

Riverview Dairy must be required to submit an environmental impact statement. A farm that large will cause serious environmental issues including massive water use and possible poisoning of groundwater.

Marshall Hoffman **Letter 407**

As a resident of Stevens County, I am very troubled by the possible expansion of the West River Dairy. The sheer enormity of this proposed expansion warrants a full Environmental Impact Statement. The City of Morris is already effected by the smell of the dairy, especially on summer days, and doubling the herd will only make this problem worse. And that's not even touching on the millions of gallons of manure waste that would be generated. I am also against the conglomeration in the ag industry and the squeezing out of smaller family farms, the backbone of rural Minnesota, with anti-competitive practices. The expansion also seeks to use a tremendous amount of the area's water. Riverview already has a track record of questionable ethical practices regarding the use of water and overpumping at their Arizona operation. The amount of pumping they want to do annually in West Central Minnesota would equal about 75% of the amount of water that is pumped for the entire city of Morris. There are also a number of wildlife protection areas nearby the dairy and manure spills -- which Riverview has had in recent years in this area -- would be disastrous for these lovely areas. Our family has taken walks and enjoyed these protected areas over the years and we would not want to see it harmed or damaged. In short, a full Environmental Impact Statement must be required before this proposal by Riverview moves forward.

Sharon Fortunak **Letter 408**

The MPCA must require a full EIS!

Negatives of this proposal--massive water use, huge wastewater output, ground water impacts, sensitive, already impaired waters.

Julia Hoffman **Letter 409**

I am a resident of Stevens County. I am very troubled by the possible expansion of the West River Dairy. The size of the proposed operation is too big for our community. MPCA needs to scutinize the environmental, hydrological, pollution and economic effects on our community. This proposal by Riverview, LLP, must undergo a full Environmental Impact Statement (EIS).

Riverview has a recent history of manure spills in western Minnesota. In Arizona it paid $11 million to residents affected by dairy water overpumping. The proposed Stevens County site sits within 5 miles of eight different protected waterfowl and wildlife areas and is a part of Pomme De Terre River Watershed, 25 miles from its confluence with the Minnesota River. A facility of this scale located in such a vulnerable area calls for a thorough environmental review.

The city of Morris has already a smell of manure from existing West River Dairy on many days of the year. Building CAFO that will hold over 20,000 animal units will make this problem worse. I am against squeezing out small farmers and replacing them with huge dairy conglomerates. Small farmers know how to be better stewards of the land than massive dairy operations.

I am also concerned about water overuse and contamination of surrounding areas by millions of gallons of manure waste disposal.

In summary, I am calling for a full Environmental Impact Statement before the Riverview expansion proposal moves forward.

Winston Kaehler **Letter 410**

The proposed expansion of the West River Dairy is a bad idea.

Renee Obrecht-Como **Letter 411**

It is vital that the Riverview Dairy be required to submit an environmental impact statement. It is nearly twice as big as any current operations in the state, and its environmental harm would be enormous. This expansion would also further erode the ability of small dairies to survive. Having grown up in Marshall, MN, with friends who worked dairy farms, it is heartbreaking to witness the destruction of their way of life in favor of mega operations that are brutal for workers, animals, surrounding communities, and the environment. Here's what we know now:

—Massive water use: Riverview would pump up to 226 million gallons/year from an off-site well—nearly as much as the entire City of Morris (permitted for 300 million gallons/year for 5,000+ residents).

—Huge waste output: The facility would generate about 202.7 million gallons of liquid manure and wastewater annually, plus 26,400 tons of solid manure.

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—Sensitive, already-impaired waters: The expansion sits in the Pomme de Terre watershed, designated sensitive; the nearest waters—the Pomme de Terre River and a nearby unnamed creek—are already listed as impaired. The project would likely worsen these impairments.

Advancing permits without a full understanding of groundwater and water-quality risks is irresponsible. It is critical that the MPCA require a full Environmental Impact Statement. Thank you for your consideration.

Dean Vital **Letter 412**

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Francy Jenko **Letter 414**

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Sara Bosley **Letter 415**

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Theresa Salchert-Keller **Letter 416**

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Rachel Day **Letter 417**

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Mark Paquette **Letter 418**

THE RIVERVIEW DAIRY PROJECT MUST BE REQUIRED TO GET AN ENVIRONMENTAL IMPACT STATEMENT. And they must be prevented from wrecking our water and air.

Mary Abel **Letter 419**

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Advancing permits without a full understanding of groundwater and water-quality risks is irresponsible. It is critical that the MPCA require a full Environmental Impact Statement.

Karen Nelson **Letter 420**

Please do all necessary steps to make sure water and environmental concerns are addressed before allowing Riverview Dairy from expanding. Minnesota's water and environment are under threat with this project. Protect Minnesota's environment for future generations.

Amy Leinen **Letter 421**

It is vital that the Riverview Dairy be required to submit an environmental impact statement. It is nearly twice as big as any current operations in the state, and its environmental harm would be enormous. Here's what I have learned-

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It is critical that the MPCA require a full Environmental Impact Statement.

Thank you

Leslie Kaup **Letter 422**

I don't live near this proposed project, but I do live in a rural area, and I grew up in a different rural area, and I understand what large animal confinement operations can do to a community. First of all, the animals suffer. Stressed and crowded animals do not give healthy milk. Air and water quality suffer. Kids can't play outside because of the stench. Property values decrease.

I am asking that the MPCA require a full Environmental Impact Statement for the West River Dairy expansion. At a time when federal environmental regulations are being rolled back, we need to step up and make sure that Minnesota remains a state that takes care of our lands. This project would set a dangerous precedent in our state. Rural communities deserve clean air and clean water and safe and healthy foods.

Ian Radtke-Rosen **Letter 423**

This proposed operation is the first of its size in Minnesota. It would be nearly double the size of the next largest operation in our state in terms of animal units. This makes it a fundamentally new and particularly powerful threat to Minnesota farmers and rural communities.

Minnesota is already losing dozens of dairy farms annually due to inconsistent and often below cost-of-production milk prices. Massive dairy operations, like the one Riverview is proposing to build, have glutted the market and tightened Big Milk's stranglehold on the industry, allowing them to push small and medium-sized family farms out of business and off the land. This operation would only exacerbate the situation and accelerate the loss of dairy farms in our state, decimating Main Street economies in the process.

No feedlot has ever undergone an Environmental Impact Statement (EIS) in Minnesota. Each time the MPCA has determined that an operation should undergo one, the operator that requested the permit has withdrawn their application. And all of those operations that were determined to need an EIS were significantly smaller than Riverview's proposed operation will be.

If built, the Riverview operation would be allowed to pump up to 226 million gallons of water per year from an off-site well. For reference, the City of Morris, which is home to over 5,000 people, is permitted to pump up to 300 million gallons of water a year. Once constructed, the facility would produce 202,744,000 gallons of liquid manure and wastewater a year and 26,400 tons of solid manure a year.

The Minnesota Department of Natural Resources has not yet completed a mapping of Stevens County's groundwater resources and aquifers for their County Geologic Atlas Series. In fact, they have not even begun the hydrological survey of the county. It is irresponsible to other water users and residents of the area to move forward with this permit without a full understanding of the potential impacts.

The Pomme de Terre watershed, where this expansion is proposed, is already considered a sensitive watershed. The MPCA already lists the two closest waterways to the facility, the Pomme de Terre River and an unnamed creek, as impaired, and this proposal would only exacerbate the impairment.

Cristina Ortiz **Letter 424**

As a local resident and community member, I'm very concerned about the potential environmental impacts of a project of this size. This project would apparently more than double the size of Riverview's

dairy operation in Stevens County, with the final size being almost twice as large as the next largest livestock operation in our state in terms of animal units. A proposal of this type seems worthy of some careful consideration about its possible impacts. Riverview had a previous manure spill in 2025 and we should be mindful of what could happen when things do not go exactly according to plan with an operation of this size.

Sherri Thissen **Letter 425**

12:09

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Advancing permits without a full understanding of groundwater and water-quality risks is irresponsible. It is critical that the MPCA require a full Environmental Impact Statement.

Ashley Kittelson **Letter 426**

Please require Riverview Dairy to submit an environmental impact statement. It is nearly twice the size of current operations in the state, and the environmental damage could be enormous. The water usage would dramatically increase with unknown groundwater impacts as the DNR hasn't mapped groundwater resources in Stevens County. The nearby Pomme de Terre River are already listed as impaired. The tremendous increase in liquid manure could further damage the river's ecosystem.

Advancing permits without a full understanding of the groundwater and water-quality risks is irresponsible. It is critical that the MPCA require a full Environmental Impact Statement.

Margi Preus **Letter 427**

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—

If you live near, studied in, or spend time around Morris, include that in your comment.

Nicole Frank **Letter 428**

I do not agree with allowing expansion. At the very least the likely impacts to to be assessed and reported for informed decision making. This needs to be a decision based on community wellbeing and health.

Nicole Frank

Stephen Leinen **Letter 429**

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Suzanne Lommen **Letter 430**

Please STOP this massive, inhumane treatment of animals and environment! Please STOP the West River Dairy Expansion.

- Suzanne Lommen

Karen Watson **Letter 431**

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Tim Phillips **Letter 432**

I attended college at the University of Minnesota Morris, and I believe it is vital that the Riverview Dairy be required to submit an environmental impact statement. It is nearly twice as big as any current operations in the state, and its environmental harm would be enormous. Here's what we know now.

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Ray Canapini **Letter 433**

Do not expand this farm! The environmental damage would be horrible.

John Clifton **Letter 434**

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Mark Robinson **Letter 435**

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Caitlin Clemens **Letter 436**

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Jennifer Fox **Letter 438**

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Erika Nelson **Letter 439**

It is vital that the Riverview Dairy be required to submit an environmental impact statement. It is nearly twice as big as any current operations in the state, and its environmental harm would be enormous. Many communities living within the vicinity of CAFOs have poor health outcomes as a direct result of the waste escapes into the air and ground water. As a former public health professional I know these impacts will be vast and will negatively impact the health of communities for generations.

Theresa Zingery **Letter 440**

For the safety of all, the Riverview Dairy project must be required to get an Environmental Impact Statement.

Jennifer Hill **Letter 441**

I don't understand how this could move forward without an EAW to inform decision makers on impacts to neighbors, the community at large, and the local watershed (possibly even beyond). Environmental externalities can no longer be ignored while while corporations extract wealth from our communities.

Norm Gross **Letter 442**

As a small family my farmer I would like to see more energy and $ go into keeping families on the land and keep rural America alive and vibrant. These huge corporation farms harm MN, the land and the local communities.

Paul Adams **Letter 443**

We farm right next to Riverviews North Ottawa dairy and it has been a good experience. We use manure from the dairy to fertilize our corn silage ground and we have had a very positive effect on yield and have been using less commercial fertilizer as a result. Farmers here are requesting more manure than the dairy can provide every year so the demand is there.

There is very little smell when applying manure because it is directly incorporated and a cover crop is usually applied to address any erosion concerns.

The DNR has strict rules on water usage that both farmers and the dairy must follow. There is concern about the amount of water being pumped for the dairy, but my own farm has irrigation systems that can legally pump about 50 million more gallons than the dairy is requesting and that is done in probably a 2 month window, not over the course of a year.

People have to remember that 1 inch of water on one acre of land is 27,185 gallons.

Riverview has supported our local schools and fire departments and brought more jobs and residents to our small farming community. I support the dairy expansion.

Owen Tesson **Letter 444**

I would like to express my opposition to this project. The threat to local Waters both above and below ground must be considered, as well as what will happen to dispose of the massive amount of feces and waste created.

Cathy Dolan **Letter 445**

I am requesting you do an Environmental Impact Statement Study of the River West Dairy Expansion. I support the Land Stewardship Projects concern about this proposed huge farm and it's impact on the land, people, cows, and community. Consider ALL effected by this decision. Small is Beautiful!

Lindsay Henkemeyer **Letter 446**

Factory farms go against everything the Minnesotan people and communities stand for. They believe in community, environment, health and wellbeing. Large scale factory farms are terrible for environment, animals, and surrounding family farms - family farming is what our agriculture is built on and we need to do better in making it easier for small farms family farms to keep their land, to grow, to thrive. When they thrive we thrive. No one wants a creepy sad industrial farm in our beautiful state.

John Marks **Letter 447**

The West River Dairy Expansion proposal must have a full Environmental Impact Assessment. The way of life which the citizens of Minnesota value is based on clean water and clean air.

Concentrating so many dairy cows in one place will result in environmental damage. This high cost is not worth the end result- a high volumn of low-quality milk.

Maria Weir **Letter 448**

Hi, I am very concerned about this expansion. Please find my comments below.

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Advancing permits without a full understanding of groundwater and water-quality risks is irresponsible. It is critical that the MPCA require a full Environmental Impact Statement.

Ilga Polleitis **Letter 449**

An EIS is a must for something this huge and impactful.

Barbara Haag **Letter 450**

To Whom It May Concern,

My family home and surrounding land on Frog Lake (Gorter Lake on a map), with familial ownership dating back to the early 1920's to present, sits one mile north of the Riverview LLP dairy. I voiced my

concern when it was originally planned and talked to the MPCA at that time, as well. Despite my disapproval and that of many others in the community, the dairy operation went forward. My concerns over the water table and the tremendous amounts of animal waste are still at the forefront of my mind, especially since they have increased their capacity from their original plan and now have much larger wants. They have outbid the small farmer to gain more land when land is sold.

What are the working conditions in their barns and what wages do they offer that causes them to bypass American workers and seek cheaper labor and veterinarians from Mexico?

Our beautiful lake, Frog Lake, next to where my late parents' home sits and that I now own, is a wonderful place for waterfowl and game. Artists, naturalists, and conservationists have visited, written about, and painted the wildlife that are regular visitors to the lake, farm and prairie lands in the area. Because of those people and the wildlife, this area has become known to people around the state of Minnesota and the country. The abundance of varied waterfowl is amazing. What is not amazing is the odor that is carried on the wind from the Riverview Dairy (West River Dairy) one mile away. The odor is so offensive at times that you can't stay in the area. Enjoying the outdoors or having your windows open is impossible.

Most people don't know that the life of a dairy cow at a place like Riverview's is cut short by living all their life on a concrete slab, never being outside to graze in the pasture, and being milked 2 or 3 times per day. Have they not learned anything about how a dairy farm should be operated?

My parents left their home to me when they passed away as a place where my children and grandchildren could come to enjoy the beauty of the surrounding area and the family ties that connect us to this land. My brother continued farming this land after our dad passed away and he has now passed that legacy to his son and two grandsons. The Riverview Dairy (West River Dairy Expansion), just one mile away from where they live and farm, will be an even bigger threat to their health and livelihood if this operation increases capacity.

Let me end by saying this: When money is your god, your hunger to obtain it overtakes your ability for sound reason and compassion.

Sincerely,

Barbara (Holslin) Haag

Kendra Nielsen **Letter 451**

Dear Members of the MPCA,

It is hard to know where to begin when you are trying to save a place that is part of your own childhood and the area where your mother and extended family were raised and where some still live. When I say "save" that is not an overstatement. West River Dairy, overseen by Riverview LLP, and its proposed expansion threatens the health of the land, the water, the wildlife, and the people who live and visit in the surrounding area. Let me correct that slightly by saying it has ALREADY threatened those things and people since its inception, but now GRAVELY threatens the land, the water, the wildlife inhabitants and the people.

I truly believe it is greed that has been the motivation behind this dairy and the almighty dollar is now threatening an expansion of gross proportions. Gross in every sense of the word. I visit the area where my mom grew up - just one mile away from West River Dairy - several times a year, as do several of my siblings and their families. Every time, since the day the dairy operation began, we have to cross our fingers that the smell from the dairy doesn't hinder or completely wreck our plans during our time at

Frog Lake (Gorter Lake on the map) while visiting family nearby and staying at what was my grandparents' home which my mom owns now. The lights from the dairy can be easily seen across the field at night, that's how close it is.

My grandfather, Alfred Holslin, bought farmland back in the early 1920's and was married and began raising a family in the 1930's in the area that I am talking about that is so near the West River Dairy and proposed expansion. That legacy of farming was passed down to my uncle, Maurice Holslin, and continues to be carried on by my cousin, Mark Holslin, and his sons, Justin and William Holslin. Not only does an operation like West River Dairy and its overseer, Riverview, LLP, threaten the things I previously mentioned, but it also has a choke hold on the family farms in America. The average farmer can't compete with corporate or factory farms when it comes to buying land to expand their own operations. When I think about a Concentrated Animal Feeding Operation (CAFO), such as what is being proposed to expand, I think about my grandpa Al Holslin and how upset he would be over the confinement of such a large amount of animals for "maximizing efficiency" and in knowing what kind of decimation these operations cause to the land, the water, the animals, and the people exposed to it. This dairy and the proposed expansion is crushing my grandfather's dream for future generations. This is just one story. There are more.

Please listen. Don't allow the expansion to go forward.

Sincerely,

Kendra (Haag) Nielsen

Rhona Wilson **Letter 452**

An EIS should be ordered for this project due to its massive size, which is *11 times* larger than the minimum threshold for an EAW, its likely impacts on ground water and surface water, and the amount of greenhouse gases that are likely to be emitted. The estimated GHG of 66,324 tons per year is speculative and incomplete. A full EIS is necessary to determine the true impacts of this proposed operation.

Bridget Shankey **Letter 453**

It is vital that the Riverview Dairy be required to submit an environmental impact statement. It is nearly twice as big as any current operations in the state, and its environmental harm would be enormous. Here's what we know now.

Massive water use: Riverview would pump up to 226 million gallons/year from an off-site well—nearly as much as the entire City of Morris (permitted for 300 million gallons/year for 5,000+ residents).

Huge waste output: The facility would generate about 202.7 million gallons of liquid manure and wastewater annually, plus 26,400 tons of solid manure.

Unknown groundwater impacts: The DNR hasn't begun the hydrologic survey or completed the County Geologic Atlas for Stevens County, so aquifers and groundwater resources aren't mapped—making it risky to permit large withdrawals now.

Sensitive, already-impaired waters: The expansion sits in the Pomme de Terre watershed, designated sensitive; the nearest waters—the Pomme de Terre River and a nearby unnamed creek—are already listed as impaired. The project would likely worsen these impairments.

Advancing permits without a full understanding of groundwater and water-quality risks is irresponsible. It is critical that the MPCA require a full Environmental Impact.

Mary C. Voight

I grew up in Morris and attended high school with the Riverview owners.

Do your job as pollution control agents for Minnesota taxpayers and prevent the massive and unnecessary expansion of a greedy operation by irreligious people that will pollute the air and soil you protect.

It does not serve the residents of Stevens County nor the land.

Rachel Nielsen **Letter 455**

My concerns regarding this project center on animal welfare and environmental impact. CAFOs pose well known and documented environmental risk not just due to manure management but as a result of destruction of grazing land and wildlife habitat.

Housing nearly 20,000 cows in such a small area is also an obvious animal welfare issue. Cows are biologically designed to graze, not to feed on grains in confinement. This poses many known health risks to the animals and is inherently cruel; collectively we should be moving away from this model of dairying.

Allowing this project to go forward would benefit only the company who will profit from the destruction of the land, the inhumane treatment of the animals, and the many risks to the environment (immediate, long term, and downsteam), and provide no to very little benefit to the people living in its vicinity or Minnesotans at large.

It would be very impressive should Riverview Dairy choose to move to a grazing model of dairy farming, which honors the lives of the cows and benefits our shared environment.

These are my own words.

Thank you for considering them.

Sincerely,

Rachel Nielsen

John Pierce **Letter 456**

Riverview Dairy must submit an environmental impact statement.

Dairy operations are notorious for water consumption AND for point source water pollution. Without an EIS, we will not know the potential harms to weigh against economic benefits.

Deborah Camasta **Letter 457**

Large scale factory farming is detrimental to society, small farms and ecosystems.

Lisa Goddard **Letter 458**

It's vital that the Riverview Dairy be required to submit an environmental impact statement. It is nearly twice as big as any current operations in the state, and its environmental harm would be enormous. Here's what we know now:

Massive water use: Riverview would pump up to 226 million gallons/year from an off-site well—nearly as much as the entire City of Morris (permitted for 300 million gallons/year for 5,000+ residents).

Huge waste output: The facility would generate about 202.7 million gallons of liquid manure and wastewater annually, plus 26,400 tons of solid manure.

Unknown groundwater impacts: The DNR hasn't begun the hydrologic survey or completed the County Geologic Atlas for Stevens County, so aquifers and groundwater resources aren't mapped—making it risky to permit large withdrawals now. A completed hydrologic survey and geologic atlas will also help understand if the large amount of liquid manure and other pollutants could contaminate drinking water sources.

Sensitive, already-impaired waters: The expansion sits in the Pomme de Terre watershed, designated sensitive; the nearest waters (the Pomme de Terre River and a nearby unnamed creek) are already listed as impaired. The project would likely worsen these impairments.

Advancing permits without a full understanding of groundwater and water-quality risks is irresponsible. It is critical that the MPCA require a full Environmental Impact Statement.

Nathan Huerkamp **Letter 459**

Let's conduct some due diligence.

It is vital that the Riverview Dairy be required to submit an environmental impact statement. It is nearly twice as big as any current operations in the state, and its environmental harm would be enormous. Here's what we know now.

Massive water use: Riverview would pump up to 226 million gallons/year from an off-site well—nearly as much as the entire City of Morris (permitted for 300 million gallons/year for 5,000+ residents).

Huge waste output: The facility would generate about 202.7 million gallons of liquid manure and wastewater annually, plus 26,400 tons of solid manure.

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The project would likely worsen these impairments.

Advancing permits without a full understanding of groundwater and water-quality risks is irresponsible. It is critical that the MPCA require a full Environmental Impact Statement.

Christopher Loetscher **Letter 460**

The proposed Riverview CAFO threatens soil, water, and air quality, human health, and independent family dairy farms. A proposal of this magnitude, with its attendant threats, requires a full Environmental Impact Statement (EIS). I worked for the Diocese of New Ulm for 25 years, directing the Social Concerns and Family Life Offices. Over those years I witnessed farm crises, the erosion of rural communities, the concentration of agricultural production into fewer and fewer hands, the pollution of water, soil and air by large-scale hog and dairy operations. The Diocese of New Ulm is a fifteen county area. The Minnesota River runs diagonally through the area. How will the Riverview proposal affect the watershed feeding the Minnesota River? How will it affect the water and air quality of neighboring

towns, the health of neighbors, including students attending the University of Minnesota, Morris? A full EIS is needed.

George John Dubie **Letter 461**

PLEASE, PLEASE, Do not allow the mega-huge dairy farm in Stevens County. We don't need more environmental damage. These can be smaller and spread out more land wise. Thank You!

John Velie **Letter 462**

The owners of West River Dairy must be required to file an EIS. They must prove that the massive amount of manure this operation will produce will not negatively impact the groundwater systems in the area and they must prove they have a sanitary plan for disposing of all the dead animals this operation will produce.

Leslie McInenly **Letter 463**

Please do not approve this project without an EIS. I am concerned about water usage and waste management. I also have concerns about the size of these farming operations and related health of the animals.

Greta Conroy **Letter 464**

Housing this many dairy cows in one area would produce a very large amount of manure. If not carefully managed, manure runoff will contaminate nearby groundwater, rivers, and lakes with nitrogen and phosphorus. Along with its environmental impacts large dairy operations can also reduce quality of life in the surrounding areas. Manure produces strong odors and release gases that affect local air quality. The expansion will increase truck traffic, noise, and other disturbances in the community. This project will harm the environment and reduce the quality of life of Steven's County residents. The residents that you are expecting to sacrifice their quality of life will have no control over how noise and manure are managed, nor will they benefit from this expansion.

John Doe **Letter 465**

I would like comment in favor of Riverviews expansion. I do not live near a current Riverview dairy but I have seen there operation and the benefit it provides for the local community and economy.

Riverview provides a big economic booster for areas they operate in bringing in new crops and markets for area farmers. In return these farmers use manure replacing there need for synthetic fertilizers. I believe this I a "win-win" situation for everybody involved. I agree that we should try and save smaller family dairy's but that has become simply not viable in today's economy and I feel like the positives for this expansion out weight negatives

Sophie Hannig **Letter 466**

It is vital that the Riverview Dairy be required to submit an environmental impact statement. It is nearly twice as big as any current operations in the state, and its environmental harm would be enormous. Here's what we know now.

Massive water use: Riverview would pump up to 226 million gallons/year from an off-site well—nearly as much as the entire City of Morris (permitted for 300 million gallons/year for 5,000+ residents).

Huge waste output: The facility would generate about 202.7 million gallons of liquid manure and wastewater annually, plus 26,400 tons of solid manure.

Unknown groundwater impacts: The DNR hasn't begun the hydrologic survey or completed the County Geologic Atlas for Stevens County, so aquifers and groundwater resources aren't mapped—making it risky to permit large withdrawals now.

Sensitive, already-impaired waters: The expansion sits in the Pomme de Terre watershed, designated sensitive; the nearest waters—the Pomme de Terre River and a nearby unnamed creek—are already listed as impaired. The project would likely worsen these impairments.

Advancing permits without a full understanding of groundwater and water-quality risks is irresponsible. It is critical that the MPCA require a full Environmental Impact Statement.

Joe Storlien **Letter 467**

To the MPCA review committee,

The proposed expansion of West River Dairy near Morris raises significant concerns about the environmental and community impacts associated with such a large-scale livestock operation. Increasing the herd to nearly 19,000 cows would create one of the largest dairy facilities in Minnesota and dramatically increase the volume of manure generated and stored on site. Managing and land-applying hundreds of millions of gallons of manure each year presents meaningful risks to soil health, groundwater, and nearby waterways if nutrients are over-applied or if storage systems fail.

The project's projected water use—hundreds of millions of gallons annually—also raises important questions about the long-term sustainability of groundwater withdrawals in westcentral Minnesota, particularly during drought conditions. Given the proximity of the operation to sensitive watersheds and conservation lands, there is a legitimate concern that nutrient runoff or other environmental impacts could affect nearby ecosystems and wildlife habitat.

In addition to environmental considerations, the scale of the project could alter the character of the local agricultural economy by further concentrating dairy production into very large operations, potentially placing additional pressure on smaller regional farms. Rural residents may also experience quality-of-life impacts associated with increased truck traffic, odors, and other by-products of an industrial-scale livestock facility.

Given the size and potential cumulative impacts of this project, it would be prudent to require a more comprehensive environmental review to ensure that all long-term effects on water resources, ecosystems, and rural communities are carefully evaluated before any expansion moves forward.

I grew up in southwest Minnesota and am a proponent of the agriculture community. I chose a career path as a soil scientist because of my love for agriculture and rural communities. This is not a pro- or anti-agricultural issue when weighing this decision. This is a common sense issue and is a fundamental question of what the future of agriculture could or should be. The proposed expansion of West River Dairy does not align with a long-term vision for a resilient and sustainable agricultural community in west-central Minnesota. Sustainable agriculture depends on systems that distribute opportunities broadly, protect shared natural resources, and support diverse, locally rooted farms. Expanding a single dairy operation to nearly 19,000 cows moves in the opposite direction by concentrating production, environmental risk, and economic power into one large corporate entity.

Rather than strengthening the fabric of rural agriculture, projects of this scale often accelerate consolidation and make it more difficult for smaller and mid-sized family farms to compete or remain

viable. This model reflects the priorities of industrial agriculture and corporate capitalism—maximizing scale and efficiency—rather than building a diversified agricultural landscape that supports farmers, communities, and ecosystems over the long term.

If we are serious about the future of agriculture in Minnesota, we should be investing in systems that promote stewardship of soil and water, strengthen regional food economies, and create opportunities for many farmers rather than concentrating production in a few massive facilities. A project of this scale raises important questions about whether our agricultural development choices are guided by long-term sustainability or by short-term economic gain. At the very least, this project requires an EIS to give local residents a say in what kind of agriculture dominates their community.

Sincerely,

Joe Storlien, PhD

Jennifer Vogt-Erickson **Letter 468**

Dear MPCA,

I am writing in regard to water quality threats that a very large confinement dairy operation would pose to Stevens County.

My connection to the area is that I graduated from the University of Minnesota-Morris in 1998. I was once startled to encounter cows standing in the Pomme de Terre River as I canoed around a bend in the river with a friend. Manure dropping directly in the river is not great, and that was a small herd.

I also grew up on a farm myself and am familiar with many of the issues facing farmers and rural communities. Concentration in agriculture has greatly reduced the number of farms and led to consolidation of schools, hospitals, and businesses in rural areas in my lifetime.

The proposed expansion would be like having 180 conventional dairy farms concentrated in one place, but it's only promising about 40 extra jobs. The potential for a hazardous release of manure would be much greater, and the people hired to work on the farm do not have the same incentive to care for the land, animals and facilities the way that an owner-operator would. Climate change may also make flooding events more severe. All of these factors increase the risk of environmental damage posed by this project.

Because of the elevated environmental risk this project would impose on Stevens County, I ask that Riverview be required to do a full Environmental Impact Statement.

Sincerely,

Jennifer Vogt-Erickson

Sarah Backman **Letter 469**

Hello, as a neighbor in Darnen township, I support this project for the expansion. I do not support overreach by the MPCA or the government, imposing burdensome regulations and expenses that do not support the project's growth. This project is an asset to Stevens County and has support to move forward.

Kurtis Wulf **Letter 470**

To whom it may concern,

I am a neighbor who lives and farms in the area around the West River Dairy. Each interaction that I have had with Riverview has been filled with integrity and a genuine concern for my well being as well as a desire to care for the environment. With this in mind and the extensive permitting process set forth by the state, I support the expansion of the West River Dairy. I welcome more growth in our community! As a local school board member I am excited for the potential to increase our enrollment with this project. I have had a front row seat watching operations of West River Dairy since its inception and have always been impressed with the courtesy of employees and owners alike. Riverview also uses best practices when it comes to manure application, dust suppression and other duties associated with running a dairy farm. I encourage MPCA to approve this permit and allow growth in my community!

Thank you, Kurt

Cory Skaurud **Letter 471**

We have been working with River View for 6 years now. Since the very beginning they have been an outstanding company to be involved with. They are made up of very smart, passionate, and forward thinking people. Their company is always looking at ways to be more efficient and sustainable with their resources. They are willing to change their operations in ways that others wouldn't in order to build their dairies for a sustainable future. All of their locations that I have visited are always in a neat and clean order. Community involvement is a big part of their philosophy, they provide opportunities and economic benefit for surrounding neighbors and communities. If there is anyone you want building more dairies in MN, River View should be at the top of the list. I fully support the West River Expansion. Thank You

Brian Lacey **Letter 472**

Letter of support for Riverview Dairy Expansion

*West River Dairy Expansion

My name is Brian Lacey. My farm is in Lawrence Township/Grant County since the 1960's. My farm location is 7.9 miles from the North Ottawa Dairy. I have been able to watch Riverview Dairy at its Morris, Campbell and North Ottawa Dairies' locations for many years.

From my farm site location where I have been able to see how the dairy is managed. The site is very well maintained and the facility is run in a very professional manner. Truck traffic has been handled responsibly, and local roads are kept in very good condition. As for my wells and drinking water, I haven't noticed any changes. I do have my well tested every so often over the years.

Riverview has maintained open and professional communication with our community and surrounding area.

North Ottawa Dairy plays an important role in the local economy by providing steady employment opportunities. I recognize that Riverview Dairies are a vital part of our community (and area) and that the awareness is reflected in how the facility is maintained and operated. Also, as a local farmer, I do recognize the major impact to my neighbor's local farm commodity sales. With the dairy purchasing my neighbors' crops of shelled corn, silage and alfalfa it is a huge impact because they can keep their crops local. No major shipping cost. The Dairy also helps provide the local farmer with an agronomist, who helps with healthy farming practices to the environment and the local communities.

Based on my experiences as neighbors and farmer, I support the Riverview expansion and believe it will continue to reflect the same level of care and professionalism. The Dairy supports local farmers, jobs, and businesses.

For these reasons, we support the expansion.

Sincerely,

Brian Lacey

Coby Backman **Letter 473**

I am writing this in support of the West River Dairy expansion.

Riverview Dairy has been a positive addition to our agricultural community. From the ability of local farmers to sell their crop to them, to the nutrient rich manure that is then available to be applied to those acres, Riverview has been an excellent partner to work with.

There's been a lot of comments and concerns on ground water contamination. Having worked with Riverview on manure applications, I can tell you first hand that they observe and follow the guidelines set in place by MPCA. Manure is applied in a responsible and conservative fashion. A drive by any one of their sites should be enough to let anyone know that they are responsible stewards of the land. The sites are clean and well kept with no manure running off into the surrounding farm land.

Water usage is another area that I think is being unfairly criticized. Cows drink a lot of water, but, when we compare it to the city of Morris....? Morris, a town of 5000 people, uses 255.5 million gallons of water per year. In comparison, the expansion of 11,000 cows, more than twice the population of Morris (cows also being 7x the size of a human being), will only be using 226 million gallons per year. I find those numbers quite "interesting".

Riverviews commitment to agricultural and community improvement has been phenomenal over the years and I would encourage MPCA to allow this expansion to take place.

Thank you!

Coby

Angela Lofquist **Letter 474**

An operation like this must require care of our environment and the impacts it will have on it. I am voting for requiring and environmental impact statement from this company sharing how they intend to clean and return water to the aquifers they're pulling out of. How is waste being managed properly? And any other environmental issues that come along with such a large operation without natural buffers. I do not support large corporations taking away jobs and land from small farmers and local communities.

Patricia Burns **Letter 475**

I am opposed to this proposed huge dairy feedlot in Stevens County. What are you thinking of having that many cattle along the river? I grew up in Chippewa County and love cows that funded my college tuition.....but this is unhealthy for them and the people who live in Minnesota. Water contamination is never a good thing. This big a herd is not good.

Ann Johnson **Letter 476**

Please require the massive Riverview Dairy project to get an Environmental Impact Statement. I am elderly and will live near this massive project. Riverview would pump up to 226 million gallons/year from an off-site well - they will take our water! And they will generate huge amounts of waste, with unknown groundwater impacts. Advancing permits without a full understanding of groundwater and water-quality risks is irresponsible. It is critical that the MPCA require a full Environmental Impact Statement. This will affect my health and my drinking water!

Lisa Moldan **Letter 477**

Livestock Confinement operations in this state already have to submit manure (nutrient) management plans and report and pay water usage. I know this for a fact; I am a hog farmer in Southern Minnesota. (And, I grew up a dairy farmer's daughter milking 60-200 cows in a stanchion barn over the course of my childhood.) There is no environmental reason this dairy cannot expand. And to quote a man speculating that this entity HAS to be polluting based on the sheer amount of manure they handle— is utterly pathetic journalism and a social injustice in itself. Go do your homework. Commercial fertilizer prices are record high. There is no incentive whatsoever for farmers to over-apply manure. Furthermore, it is tested for nutrient value and then applied at precision rates with GPS technology.

In a free market economy, EVERY size of business has a place to exist and offer to consumers a flourishing choice of product—provided each entity can operate at a profit for himself. EVERY size of farm offers a market and competition for local agricultural products—corn, soybeans, alfalfa, oat straw, JOBS, equipment repair, etc. etc. The value to the local economy is incalculable.

Smaller dairies can now enter direct to consumer markets and small scale coops to receive a premium price for their products.

Large scale dairies like this one can meet increasing dairy demand to large scale markets like Costco and Walmart.

Why on Earth would we want to cripple our free market choice with regulation and environmental tax? This state is already one of the WORST STATES of our nation for operating a business—horrifically over regulated and micromanaged by the state with nothing to show for it but billions of dollars of fraud. DO NOT encourage any additional study — what a waste of money. Stop crippling agriculture in this state with bureaucracy.

Use common sense. Allow expansion. Allow the free market to work. A next time, do your homework before you write a piece on confinement ag.

Kim Carswell **Letter 478**

I am writing about this proposed expansion. While I do not live in Stevens County I live in Minnesota and view this plan as an incredible precedent going in the wrong direction. The only benefits I see are for the business. The animals, the land, the neighbors, and the water will not benefit from this. And over time I wonder if the quality of the milk will be found to be compromised by this type of farming.

Kim Carswell

B.S.Dairy Husbandry, Michigan State University 1975

Vanessa Sandoval **Letter 479**

My name is Vanessa Sandoval, and I have lived in the Morris area for almost 14 years. In that time, I've had the opportunity to learn more about Riverview's farms and way of doing business. While I have

always been impressed by how impeccable Riverview's farms are, what has impressed me the most is the company's conscientiousness and focus on taking care of people. Riverview provides good paying jobs in rural communities. Riverview, however, is not exclusively concerned with taking care of its employees. I know that Riverview is an active participant in the communities where it operates, often donating to local charities and causes. Riverview is particularly committed to providing opportunities for the next generation, and that is why I struggle with some of the comments that have been submitted during this comment period. It is my belief that Riverview would not pursue an expansion if it led to environmental degradation that could have a detrimental effect on people's lives. I support the West River Dairy expansion, and I hope they receive the necessary approvals.

Thank you!

Ruth Lindh **Letter 480**

Massive industrial dairy operations are a danger to our environment and our rural economy.

Shari Prigge **Letter 481**

I am opposed to this "unprecedented " request that would allow more pollution into the waterways, land, and surrounding areas of beautiful west central Minnesota. This business also appears to be monopolizing the wellbeing of many of our small farmers. Vote NO!

Nathan Kestner, Minnesota Department of Natural Resources **Letter 482**

Dear Charles Peterson,

Thank you for the opportunity to review the West River Dairy Expansion Environmental Assessment Worksheet (EAW). The Minnesota Department of Natural Resources (MN DNR) has reviewed the EAW and offers the following comments related to water appropriation and permitting.

Water appropriation permitting

MN DNR is currently reviewing groundwater appropriation permit application 2025-1502 for 226 million gallons per year (MGY) at a proposed maximum pumping rate of 1000 gallons per minute (gpm) for the West River Dairy Expansion. Please note permit 2025-1502, using well unique well number (UN#) 740629, would (if approved) replace and modify permit 2008-0230.

Water has never been appropriated from the UN# 740629 associated with permit 2008-0230 (proposed to be used for permit 2025-1502). Groundwater availability is moderate to limited in this area. As identified in permit 2008-0230, the groundwater appropriation from this well can directly impact the river and is subject to existing permit conditions based on the river flow.

MN DNR is completing a re-evaluation of stream flow in the Pomme de Terre River. We expect to include permit conditions based on stream flow. Conditions will be modified from those currently included with 2008-0230, which may include restrictions on the ability to appropriate water during summer months. Additionally, we will evaluate the impacts of water appropriation on rare features in the Pomme de Terre River downstream of the appropriation site.

The EAW did not consider impacts from the potential groundwater appropriation at UN#740629 on the Pomme de Terre River in section 12.B.4. Surface Waters. Our review of the aquifer test completed on UN# 740629 suggests that the water table aquifer is strongly connected to the Pomme de Terre River. The long-term average flow in the Pomme de Terre River is likely to be reduced by the average pumping rate of UN #740629. If water appropriation permit 2025-1502 is authorized, permit conditions, including

restrictions on pumping when streamflow is below 10% of the median monthly base flow, are anticipated. Conditions to maintain baseflow will be considered to protect ecology, public health, and the needs of downstream users of higher priority.

The current West River Dairy operation relies on two groundwater appropriation permits associated with the operation:

- **Permit 2004-1023: 95 MGY for livestock watering from four wells located near the current dairy operation. This permit includes groundwater-level monitoring conditions.**
- **Permit 2009-0492: 21.3 MGY for livestock watering and 64.4 MGY for agricultural irrigation from one well located in the proposed expansion project area. This permit may need to be amended to reflect changes in land use.**

The EAW does not describe how the existing permitted wells, particularly the one located on the proposed expansion site (2009-0492), will be integrated with the new facility. If the permit holder requests to increase the volume of permits 2004-1023 or 2009-0492, aquifer testing may be required to ensure sustainable water use.

The EAW indicates in section 12.B.3.d that the wells for the existing facility and the off-site well are located in separate aquifers. The shallow and deep aquifers in this area are part of one connected system, and water availability from these aquifers is limited. The proposed water sources do not constitute a diversified groundwater source approach. Due to the aquifer connections, cumulative existing and proposed water appropriation will be considered during water appropriation permitting.

MN DNR has also received and is reviewing a Dam Safety Permit application, 2026-0133, associated with the water storage ponds identified in item 9 of the EAW. This permit application was received on January 29, 2026.

Sincerely,

Nathan Kestner

Regional Manager, Ecological and Water Resources

Madeline Neenan — Letter 483

Hello,

As a farmer and community member, I am very concerned about the number of gigantic animal operations in our region. The "concentration" aspect of these industrial actors means that they simply cannot spread their manure on enough acres to manage, and if they get close it will mean huge amounts of wear and tear on our roads as heavy trucks filled with manure drive over them. Additionally, it is not clear that in the event of a mass mortality event, the business has access to necessary levels of carcass disposal. This feedlot is already dangerously large, so any additional expansion would put the surrounding community at risk. Further, we do not know what risks this type of operation poses to groundwater.

This expansion requires an EIS by any common sense metric, and the law should be change to make such an assessment automatic when any permit of this size is requested.

Madeline Neenan

Red Wing

Matthew Green **Letter 484**

Hello, I would like to express my support for the West River Expansion. I lived 3 miles from the West River Dairy for 10 years At the age of 18 out of high school and love for farming. Riverview gave me an opportunity for employment for 8 years which in turn gave me the tools and training to start my own farm. They are great people who care about the community and give small farmers like myself a chance to succeed.

Lisa Rogers **Letter 485**

I vote No! It's too big. Please pay attention to other huge feed lots across our country and the negative impact they have on the environment and the people who live nearby. Thank you.

Marcella Bode **Letter 486**

I'm not in favor of expanding the dairy. The effects on the environment would be horrible and the treatment of the animals would be disrespectful. Please do not approve.

Courtney Swenson **Letter 487**

The site is too close to the Pomme de Terre River, the river would likely be polluted by run-off and could alter ecosystem. I vote no to expansion due to proximity to river and risk of pollution.

Nancy Carpenter **Letter 488**

I am a former resident of Morris, MN and oppose this expansion on the grounds that it is 1) unnecessary (except to increase the profits of Riverview Dairy), 2) directly harmful to family dairy farms, and 3) an environmental insult in terms of enormous water use and production of astronomical amounts of manure. The promise of growth (more jobs) in west central MN is miniscule due to the highly automated operations Riverview uses and certainly does not outweigh the harm to the natural prairie ecosystem. The "need" for more dairy could and should be met by greater support for our family farms, which are considerably less harmful to the environment. An environmental impact statement for such a gross expansion should be required for any operations this large, at minimum. Irregardless of Riverview's past performance, their desire to be considerate and responsible neighbors cannot compensate for a massive environmental impact.

Edie Thiel **Letter 489**

My name is Edie Thiel. On March 10, 2026, I submitted a comment regarding the Riverview expansion project near Morris, MN. When I submitted my comment, I did not have all of the information to make an informed opinion; therefore, the data and information within my opinion comment is not accurate, and I would like my comment removed from the record.

Susan Frenzel **Letter 490**

The manure containment system for this expansion is sufficient "except in conditions of weather extremes." Today's March 18, 2026, Star Tribune weather report by Paul Douglas states: "Welcome to the United States of Weather Extremes."

Even before the dairy expands, it's a reality and a given that the manure containment systems will fail, because they aren't built for weather extremes, and weather extremes are a fact of life now.

I'm 72, and in my lifetime, MN lakes and rivers have gone from being swimmable and fishable to being covered with blue-green algae from overflow of fertilizer from fields and animal factory farms. That's the case from ice out in spring to the freeze in winter. There aren't a few weeks of good swimming anymore in summer.

The MPCA has already allowed the quality of life in Minnesota to be destroyed in favor of profits for animal factory farms. We Minnesotans paid too high a price for thirty cents off a package of meat or a gallon of milk. We lost what makes Minnesota great in our lifetime.

Future generations will be rolling in shit. Thanks a lot, MPCA! You knew what you were doing.

You were not doing your job for the state of Minnesota. And you did a number on us in favor of animal factory farms.

Is your mandate to promote industry over livability?

How about the poor neighbors to the dairy? Can they breathe freely? Can they sell their land for the same amount of money as they would have gotten before the dairy first expanded? What will their land be worth after the expansion?

What's the water table like around the dairy? A.I. data centers will draw down the water table statewide. How about that aquifer under us from the Gulf of Mexico to the Canadian border? Is it drawn down beyond use yet? What do we do when the aquifer is gone, or polluted?

What good is the MPCA to the people of Minnesota?

I hope you'll do your jobs to the best of your ability and disallow an expansion of this animal factory.

Shoppers prefer milk humanely produced. When calves are given cow's blood to drink instead of cow's milk, that's not humane.

Milk produced by cows that are housed skin to skin in dark barns in conditions conducive to turning bird flu or any disease spread among them into an extremely powerful pathogen, endangering human life, we don't want that. You shouldn't either. You are supposed to be protecting us, not pushing the limits of what corporations can get away with, to the detriment of our environment and health.

It's not ok for you to expand West River Dairy. If you approve it anyway, to the detriment of Minnesota, make the dairy ship the manure to farms in other states, instead of dumping it all on this county and this state. How many tons? The animal factory system generates 5 tons of manure per year for every man, woman and child in the U.S.

Susan Frenzel **Letter 491**

The statement on your website above this comment line on March 17, 2026, stated that the manure containment systems for the expansion are sufficient except in the case of extreme storm events.

We are living with global warming, which is rapidly making weather events more extreme and more frequent. There will be an increasing number of extreme storm events. We're seeing them already, year-round. It is no longer possible to swim in most MN waterways due to blue-green algae caused by feces runoff from MN land. It just takes a few flooding events per year to spread feces into waterways.

How will they protect the water table and aquifers from pollution from a 19,000-cow feedlot?

How will they keep the air clean and fresh for the neighbors?

How will they dispose of the manure on an ongoing daily basis in a way that won't burden the county with fecal waste?

Right now, more than 5 tons of animal waste annually is generated for every man, woman and child in the U.S. per Dr. Michael Greger in his 2020 book, "How to Survive a Pandemic."

And even though the MPCA's only concern is pollution, the State has a strong health interest in preventing another pandemic, and businesses have a strong financial interest in preventing another pandemic.

And cow milk isn't even that healthy, due to the pregnancy hormones in it. A huge Swedish nutritional study of tens of thousands of people over decades found that people who drank a cup of milk per day die at a higher rate than those who don't. You can Google it and find it.

Do your job for the people of Minnesota. You don't exist only for the corporations of Minnesota to make a killing off destroying our state.

We don't want to trade fresh air, clean water, swimmable and fishable rivers and lakes, and our health for thirty cents off a carton of milk or off a pound of meat.

Our environment is already destroyed under your oversight. Please don't make it even worse.

Tom Mahoney **Letter 492**

I am concerned about the true environmental impact of the proposed expansion and would like the MPCA to require a full Environmental Impact Statement before the project can go forward.

A project of this scope demands careful and exacting review of cumulative impacts, including existing animal units of all operations within the county and watershed, the increased demand on area water resources with potential threats to existing wells, the additional reduction in regional air quality and the increased threat to protected wildlife and environmental resources located nearby.

I believe the unprecedented scope of this project demands an unprecedented examination of its potential impact.

Mary Nesgoda **Letter 493**

I would like to understand the reason for Riverview LLC desire to put another feedlot in Minnesota. Do they need more money to offset the 11MM judgement in Arizona? Minnesota doesn't need another feedlot. Especially from a company with multiple safety issues. Additionally, before a decision is made an EIS is needed, to determine the effect on nearby protected waterfowl and wildlife production areas.

Susan Frenzel **Letter 494**

If MPCA okays this expansion of the feedlot for the dairy, how will you safeguard the drinking water from nitrates? A.I. says: "Stevens County, like many areas in Minnesota, may face issues with nitrate contamination in groundwater, primarily due to agricultural activities and other human-made sources. Elevated nitrate levels can pose health risks, particularly to infants." and

"Nitrate levels in Stevens County's drinking water have been reported to exceed the Environmental Working Group's health guideline by significant amounts, with some tests showing levels 12 to 31 times above the guideline of 0.14 parts per million. This indicates a serious concern for water quality in the area."

Nitrate pollution in the drinking water is already a problem in Stevens County. Don't make it worse by approving this feedlot expansion.

Air pollution? Water pollution? Pollution of the land from excessive manure?

Please don't degrade our environment even more by doubling the size of the dairy.

Please protect the quality of life of the people of Minnesota. That is your reason to exist. Please honor it.

Corporations must find ways to be profitable without destroying our quality of life. You need to guarantee us a decent quality of life, and the quality of life for the people living within a 10 mile radius of that dairy has been severely degraded.

You are the check on environmental destruction. Please veto this expansion. There is nothing the dairy can do to sufficiently mitigate its danger to the environment b/c it has no protection against extreme weather events, and those are becoming more common and frequent every day.

Michelle Burns **Letter 495**

Minnesota doesn't need another feedlot. Especially from a company with multiple safety issues. Do they need more money to offset the 11MM judgement in Arizona? Additionally, before a decision is made an EIS is needed, to determine the effect on nearby protected waterfowl and wildlife production areas. I am firmly opposed to Riverview LLP feedlot expansion in Minnesota, especially in such a sensitive ecosystem.

Hein Enslin **Letter 496**

My name is Hein Enslin, and I've lived in Stevens County for over five years. As someone who lives near the existing West River Dairy, I take a strong interest in how water resources are managed in our area. Water availability matters not only for agriculture, but also for households like mine, local wells, and the long-term health of the community.

After reviewing the available information, I'm encouraged by the level of thought that has gone into this project. The plans clearly reflect a responsible approach to water use, including conservation-focused practices, monitoring systems, and operational measures aimed at using water efficiently and only as needed.

What gives me additional confidence is Minnesota's strict water use permitting and reporting requirements. Projects of this scale are held to high standards, and ongoing monitoring of groundwater levels and usage provides important safeguards. These layers of oversight help ensure that water use remains sustainable and that both the farm and surrounding community are protected.

Overall, I believe this expansion demonstrates a strong balance between agricultural growth and long-term water stewardship. I support the project and am confident that local water resources can continue to be managed responsibly as it moves forward.

Thank you.

Lisa Notsch **Letter 497**

After having read an article in the Chokio Review, I am appalled at the fact that this expansion wasn't brought to anyone's attention sooner. I also find it ridiculous that this expansion doesn't even require an environmental impact study done, with all the manure this business produces and the runoff etc., it shouldn't be in question that this study should be MANDATORY!!! I also heard that they claim all the

manure will be stored on site... If they consider stored on site to mean in fields such as the one next to our property, then I know that means they will locate a giant pile of manure right in the path of someone's place. Every time that they pile it right to the south of our place the strong south wind we always have during the summer blows that manure dust and debris right to our place. We end up breathing it all in and I also hate to think how it contaminates our garden produce. You can't tell me that's healthy for us or our pets. Also, where is all this water they use for their operation coming from? You can't tell me that excessive water use isn't going to affect the water table for everyone else in the nearby area. I also believe that we should be protecting our natural beauty and resources and there is a wildlife protection area and the Pomme De Terre watershed near that area etc. This shouldn't even be something you feel you can entertain in the slightest. I don't want anyone else having to through the same headaches we've had to go through either. In other words, I'm highly against this expansion.

Alan Nikolai **Letter 498**

This needs an full industrial scale environmental review as it is industrial in size. Clearly 25k+ cattle is a huge sanitation risk. As such, the risk needs a full industrial scale review.

Dustin Walsh **Letter 499**

My name is Dustin Walsh, and I farm in Swift County MN. I grow corn, soybeans, sugar beets and alfalfa, and our family has worked with Riverview for over 20 years.

I receive manure from the dairy as part of my nutrient management plan. Before any application, my fields are soil tested and manure is applied at agronomic rates following state guidelines. From my experience, this is a structured and responsible process.

Manure has improved my soil health, increased organic matter, and reduced my need for commercial fertilizer. The dairy also provides a reliable local market for crops like silage and alfalfa. That partnership supports the long-term sustainability of my farm.

I understand this expansion is being reviewed through the state's environmental process. Based on my firsthand experience working within those rules, I am confident the project can continue to operate responsibly.

I support approval of the West River Dairy expansion.

Respectfully,

Dustin Walsh

Marcia Schroeder **Letter 500**

I live within 5 miles of West River Dairy. I believe that both Riverview and West River are run responsibly with an eye to preserving our environment. However, an expansion of the proposed magnitude requires substantial more environmental resources than are already being used. I favor an environmental impact study. More than doubling the number of cows on a site should not be a default decision by the PCA. Because River View/West River is a responsible company, I think the owners would want to initiate a study to reassure residents like me that the hazardous issues and over taxed resources would be addressed.

Carol Dines **Letter 501**

I am writing to express my shock over the size of the proposed dairy in Morris, and to urge the MPCA to turn down their license to expand. Factory farming pollutes our water systems, and despite extensive storage systems, leaks are inevitable. A dairy of this size will use too much water an inevitably contaminate our air. This kind of factory farm is part of what drives climate change. Moreover, it is the kind of farm that can create a bio-hazard. What if some kind of virus takes hold, and that many cows have to be euthanized. It's a tragedy waiting to happen. Milk is consumed less now, partly because of consumers' concerns about large dairy farms. Why should we risk polluting our land and air to export our milk to other countries? That's what this expansion is about. Please do not allow this dairy to expand. It will only set a new precedent for other dairies around the state who are in competition. We need to fight climate change in all ways, including in our food production systems. Lastly, I'm an animal rights advocate and I can only imagine the kind of lives those cows live, locked inside large barns, their bodies given antibiotics to avoid viruses, milked until they're no longer useful, and then discarded. It's a moral failure in our country.

Thank you,

Carol Dines

Heidi Peters **Letter 502**

I strongly urge the agency to conduct an EIS on this proposed expansion before making a decision for the health of Minnesota's lands, its waters, its people, and its animals that would be at and around this site. Thank you for your consideration and the work that you do to protect our state's amazing resources for this and future generations!

Charles Martelle **Letter 503**

My mother owns acreage in synnes township that a watershed runs through. This land has been rotated between crops and crp since my grandfather purchased the property. Our family believes in conservation, sustainable agriculture, and keeping up good relations with adjoining landowners. I believe if river view moves in and starts using excessive amounts of water and creates unsustainable sewage issues it may negativity effect our land, the wildlife that thrives there, and the small farmers that depend on the land for their income. I have seen a drastic habitat loss in the last decade in this area. Wildlife that was once abundant in a large range is now confined to small pockets of habitat. Our farms are one of those small pockets. I would hate to see a large scale dairy operation ruin any more habitat that is already in such short supply.

Thank you for taking the time to hear my thoughts.

Charlie Martelle

Susan Frenzel **Letter 504**

I submitted this comment on 3/20/26 and you deleted it. I'm resubmitting it.

The MPCA deleted the comment I made on Tuesday, 3/17/26, so, outraged, I followed up with more comments on 3/18 & 3/19. But what I have to say shouldn't be muzzled because it applies to the dangers to Minnesotans of animal/poultry factory farm practices. They have a direct bearing on this expansion request.

And the MPCA is the government bureau with the oversight to regulate animal and poultry factory farms. So take my comment. And act to protect Minnesotans.

I note that the head of the MPCA when the MN public was just discovering 3M's PFAs pollution came to the MPCA from 3M. So perhaps the current leadership at MPCA is from the corporate animal factory farm sector, and they're in a position to try to hide from us the dangers they actually pose to us.

NYT best-selling nutrition expert, Dr. Michael Greger, started out as an epidemiologist. One of the world's leading epidemiologists is Dr. Michael Osterholm, at the University of Minnesota.

In 2020, Dr. Michael Greger published, "How to Survive a Pandemic," about the next pandemic, possibly as soon as within 5 years, that might be a bird flu pandemic, that he predicted would probably be generated in an animal/poultry factory farm. He went in detail in the book about why viruses and bacteria become extremely lethal when generated in a system where the hosts are packed body to body, in dark, airless enclosures. Yes, dark, airless enclosures, packed body to body, causes weight to be put on fastest for poultry, cutting meat production time in half.

Greger told us calves are weaned on cow blood, which is protein nutritious, rather than on milk, which farmers can sell. Cattle (beef and dairy?) are fed chicken manure, which doesn't affect the taste of the meat of the cattle butchered for meat. Cattle are fed highly subsidized corn and soybeans which causes e coli to be produced in their stomachs, and the e coli endangers the consumer when he eats hamburger.

The reason this is relevant to MPCA, pollution control, is that you are the government bureau that can green light or limit animal and poultry factory farms.

Stink, smell and shit aren't the only things you should be paying attention to. The likelihood of animal factory farms generating pandemics is in your wheelhouse, too, within your responsibity.

Dr. Michael Osterholm published a book in December 2025 called, "The Big One," about the upcoming pandemic which might take 1/3 of mankind's lives.

I couldn't bear to finish Dr. Greger's book or to get past a few chapters of Dr. Osterholm's book.

I advise you to talk with Dr. Michael Greger and to Dr. Michael Osterholm about how animal/poultry factory farms can be modified to minimize their generation of pandemics.

As a living being, I ask you to make the factory farms you regulate act humanely toward their living products.

Jacob Strege **Letter 505**

I am against this in all ways. We are driving small farms out of the state. Nobody can compete with these coperations. The environmental impact is terrible and disgusting. The possibility of contamination of the water shed which would destroy how many peoples lives. This cannot happen.

Thank you

Jake

Sharon Kutter **Letter 506**

I strongly urge you to dismiss any plans to proceed with the proposal to dramatically increase the size of the Riverview LLP dairy operation near Morris MN which would be more than 60 times the size of the average Minnesota dairy. Problems with these massive dairy operations center around water and manure. They also drive out smaller family-run dairies which have smaller environmental and community impacts. Giant dairy operations require massive amounts of water and water is our most valuable resource. We must put laws in place to protect the water. Manure in these mega dairies is

collected and diluted into a concentrated liquid sludge that has to be stored or spread on nearby fields which can destroy the soil, water and air.

We used to have a dairy farm but could not stay in operation due to the takeover by mega farms. The mega agriculture industry in nothing but greed and monopoly. They destroy our water, land, air quality, economy and communities. How much have these industries paid to political election campaigns to buy votes that serve their interests? These actions are criminal and should be treated as such.

Again, I strongly urge you to dismiss any plans to proceed with the proposal to dramatically increase the size of the Riverview LLP dairy operation near Morris MN. Do your job.

Karen Renaud **Letter 507**

This proposed operation is the first of its size in Minnesota. It would be nearly double the size of the next largest livestock operation in our state in terms of animal units. This makes it a fundamentally new and particularly powerful threat to Minnesota farmers and rural communities. The Minnesota Pollution Control Agency must recognize the fundamentally new nature of this threat and give this permit greater scrutiny than it ever has to previous proposals. This proposal by Riverview, LLP must be required to undergo a full Environmental Impact Statement (EIS).

An EIS will allow the proposal's negative impacts on water quality and quantity, local roads, and existing independent family dairy farms to be fully analyzed before the project is allowed to seek a permit. According to the documents filed by Riverview, the proposed operation would require:

1. To supply water for the operation the facility would be allowed to pump 226 million gallons from an off-site well per year.

2. Liquid manure storage encompassing 250 million gallons of waste.

3. 13,200 acres of farmland for manure application.

Riverview has a recent history of a manure spill in western Minnesota. In Arizona, the company agreed to pay $11 million to residents affected by the dairy's over-pumping. The proposed Stevens County site sits within five miles of eight different protected waterfowl and wildlife production areas and is part of the Pomme de Terre River watershed, just 25 miles from its confluence with the Minnesota River. A facility of this scale located in such a vulnerable area calls for a thorough environmental review

Just as importantly, an EIS of the West River Dairy Expansion proposal would address socio-economic impacts. Minnesota is already losing dozens of dairy farms annually due to inconsistent and often below cost-of-production milk prices. Massive dairy operations, like the one Riverview is proposing to build, have glutted the market and tightened Big Milk's stranglehold on the industry, allowing them to push small and medium-sized family farms out of business and off the land. This operation would only exacerbate the situation and accelerate the loss of dairy farms in our state, decimating Main Street economies in the process. An EIS must be requied for this project.

Thank You,

Karen Renaud

Boone Carlson **Letter 508**

To the Minnesota Pollution Control Agency,

My name is Boone Carlson, and I serve as Chairman of the North Ottawa Township Board. I'm also a neighboring farmer to the North Ottawa Dairy, operated by Riverview Dairy. I'm writing in support of the proposed West River Dairy Expansion.

Riverview Dairy has been an excellent neighbor and community partner. They maintain their facilities and surrounding farms to a very high standard—everything is kept clean, orderly, and well-managed. The company communicates regularly with the township about road conditions, and they've been proactive in offering help with gravel and maintenance.

On a personal note, they've even assisted me on a few occasions with equipment and manpower for small projects around my farm, which I sincerely appreciate. Their willingness to cooperate and contribute extends beyond operations—they've also established a Dollars for Scholars scholarship for local students, showing real investment in the next generation of our community.

Based on my experience as a township official and a neighboring farmer, I believe Riverview Dairy's expansion will continue to support local agriculture, uphold high environmental standards, and provide benefits to both the township and the broader region.

I respectfully encourage the MPCA to approve the West River Dairy Expansion.

Sincerely,

Boone Carlson

Chairman, North Ottawa Township Board

Tanner Zych **Letter 509**

03-14-2026

West River Dairy Expansion

There should be a Thorough Environmental Impact Statement (EIS) done on this project. This will have an obvious impact on that tract of land and the surrounding community for generations to come. There should be extensive considerations for all corresponding impacts this potential expansion could have on the ground and surface water, air quality, safety concerns for the surrounding community. We have a degrading infrastructure this wont help with that.

We don't need any more corporate farms especially for an industry that isn't needed to be expanded. The Dairy industry is a highly subsidized industry due to the Money Worshipping Corporations that have continually taken advantage of the loopholes and the backing of the federal government to bail them out every time its needed. The time to wake up was 25 years ago I'm afraid.

I've attached with this letter an article that will help explain my prior paragraph.

I hope you make the right decision in this matter.

God Bless and Have a Great Day.

Thanks

Dixie Houser **Letter 510**

To: MPCA

Re: Riverview Proposal - WEST RIVER DAIRY EXPANSION-CAFO Proposal

From: Dixie Houser

Riverview is proposing to pump 226 million gal. of water a year- almost as much as 5,000 people of Morris, that's not counting the numbers of private rural wells probably effected by their proposal. We also know as a fact, they are already in lawsuits for pumping MORE than their application allowed in other states. Their proposal is well above the environmental capacity load.

Waterfowl protected areas are not only important for local economy but is important for migrating fowl on a global scale. It is also representative of the "canary in the coal mines". (what happens to the lower food chain happens to us) These NEED protecting for our own protection. MPCA's mission statement commits to "Protect and IMPROVE the environment and ENHANCES human health by monitoring environmental quality, planning for climate change and ENFORCING regulations to PREVENT (not just monitor) pollution of air, land and water. " Animal numbers has the effect of increasing climate change and Minnesota's climate is one of the fastest changing climates in the nation already.

Riverview has past and current problems in other states of not completing a truly transparent EIS (Environmental Impact Statement). Considering their breaking the conditions of their accepted applications in other states and their current lawsuits; residents from other states are warning Minnesotans.

This creates a monopoly of a mega company that threatens and creates the loss of family farms and local rural economy; causing damages that they try to mitigate by paying out fines and offering jobs. This does not solve environmental problems people will continue to suffer. You do NOT have to live in the area or the Minnesota River watershed to be affected by pollution of groundwater and the aquifer. Aquifers run much further than most people realize, affecting more people than just those who live near by.

I ask you, I plead with you to take seriously your mission and be proactive and not just reactive AFTER the damage is done. We do not want another Water Gremlin type problem that is far reaching.

Thank you,

Dixie Houser

Heather Prunty **Letter 511**

As a biologist, fisherman, and an avid hunter, I strongly oppose this expansion. Large scale dairy farms and feedlots are notorious for contaminating downstream water bodies on a large scale, as well as leaching into the groundwater. This is a much larger footprint than the original plans anticipate. These giant corporations have no problems paying fines, and the problem does not get fixed. Instead, signs are posted warning of the contamination and people can no longer recreate and/or consume fish and waterfowl from the contaminated water bodies.

As an individual, I have friends who own small Minnesota dairy farms. It is their livelihood and has been for generations. Minnesota has already effectively eliminated many small farming operations and, unless their goal is to add small dairy operations to the list, this must not be allowed to happen.

Choose lifelong Minnesotans over Big Ag.

Monica Ledesma **Letter 512**

My name is Monica, and I have been living in Hancock for the past seven years. I live close to Riverview Dairies and have had the opportunity to observe their commitment to operating responsibly within the community. Based on what I have seen, I support the proposed expansion of the dairy farm.

Riverview has demonstrated strong standards when it comes to site cleanliness, organization, and overall management. I have also seen their efforts toward environmental protection and maintaining a well-kept operation, which is important for those of us who live nearby.

In addition to these practices, this expansion would bring positive benefits such as job opportunities, economic growth, and continued support for the local agricultural industry. For these reasons, I believe this project is a positive step forward for our community.

Charles Koehl **Letter 513**

To whom it may concern, my name is Charlie, and I have been in Horton Township for 20 years. I live within 6 miles of West River Dairy.

I have had numerous interactions with the West River Dairy Farm, and so far, they have all been positive. It is a well-supported fact throughout the nearby community that Riverview is a highly professional and community/environmentally conscious organization. The manure from the dairy has made an immensely positive impact on the soil health and erosion control in our region. The crop feeds the cows, and the cows feed the crops through manure; it's a simple yet regenerative system.

I understand the concern some may have regarding this expansion; however, I believe West River Dairy has, and will continue to hold environmental sustainability in the highest priority. Based on my observations from previous Riverview expansion projects, this WRD expansion is likely to bolster the rural community and provide environmentally sustainable solutions for future generations.

I approve the West River Dairy expansion.

Sincerely, Charlie

Connie Maier **Letter 514**

I am writing this in support of Riverview Dairy and the expansion. I grew up in the area and still go out there quite often. Riverview takes great care in their operations. My dad's farm is approximately 3 miles from the expansion site. When we go out there we never smell the barns. They also take great care of their workers. The city of Morris has had a lot of new housing that the company has built. Riverview also does a lot of giving back to the community which many times is unnoticed. I have only heard great things about Riverview.

Rachel McGill **Letter 515**

The West River Dairy Expansion is of a scale that obviously probably impacts its surroundings in a significant way. It is a no-brainer that the environmental impact needs to be understood thoroughly here. Please do so.

Evangeline Moen **Letter 516**

CUI Bono? [Who Benefits] Who is the beneficiary of this project? It is obvious that all harm and risk remains in the community where the project is proposeed.

There is no legitimate reason to allow this size expansion when there are other scale levels of dairy production in the region. Overwhelm is never a good strategy. Profit for known (and possibly not known) actors make the case for short term decisions, but the long term degradation of the region will not be compensated for when the profits have been removed from the region.

Theresa Harsma **Letter 517**

I am opposed to the huge West Dairy expansion in Steven's county in MN. Riverview has a history of waste spills and the resulting environmental damage. A full environmental impact study must be completed before this is approved. These corporate CAFO's pollute waterways, groundwater, and wells. Small and medium size farms go out of business. Small towns and their economies suffer.

Merrilee Stahler **Letter518**

I am a land owner in Syness township where the proposed expansion of Riverview Dairy is to take place. My concerns include excessive stress and possible near depletion of the Pomme de Terre watershed, the volume of liquid manure and the magnitude of land required to offload it as well as the impact this expansion will have on neighboring land owners whether they are farming or renting their property.

The impact on wildlife and the wetlands that define this area would be disastrous. Both of these naturally occurring environmental factors have already been diminished over the years due to farming practices. Not that many years ago this township was rich in a natural habitat that fostered the continued migration of huge numbers of waterfowl as well as protective habitat for deer and other land animals. Today the elimination of this natural habitat has created major problems for wildlife including changes in migration patterns. The opportunity and desire to hunt for food which is a prominent cultural practice in this part of the country that has been handed down through generations is already threatened by farming methods. Riverview expansion would put additional stresses on this fragile connection between people and their environment.

As a land owner I also anticipate the negative impact this expansion would have on the land value of property in the township. A return to the land held by many young people would be discouraged by neighboring fields of manure and the constant threat that one day their wells would run dry and they would be unable to water their own livestock and themselves.

Heather Nord **Letter 519**

... I grew up on the Pomme de Terre river bottom, south of Morris. My father taught Sociology and my grandfather worked for US Fish & Wildlife, so I understand water quality issues. And as you well know, this is not just a Morris area issue. Large and small farmers along the Pomme de Terre – PDT river valley have moved fence lines away from the river, but decades later, there are still issues with high levels of bacteria in the PDT. So the problems are more complex than just moving fence lines. From what I understand, field tiles are buried 18" under topsoil, drain into ditches and then directly into river systems. Toxic manure pit slurry (also from other animal and bird facilities) is sprayed on fields or injected 8 inches under the topsoil. Current manure handling should be re-considered in all your decisions, statewide. My point, large factory facilities create heavier impact on water quality and wildlife; profits should NOT be the only consideration. What controls will you put on these open sewer lines to prevent it ending up in ground water or in the Mississippi River ? Sincerely, Heather Nord

Roger Hippe **Letter 520**

This is getting way out of hand. Put a stop to this nonsense! There is absolutely no need for this excess.

Stef Kirschbaum **Letter 521**

I wholeheartedly oppose this facility. It is not good for the animals, for the land, for the other small farms across the state. I do not live near here, but I feel for any neighbors near the current facility of such massive size.

Mechelle Sazama **Letter 522**

I vote no on this expansion. As a small farmer myself I feel strongly that mega farms do more harm than good.

Rebecca Heinz **Letter 523**

As a dairy farmer in Minnesota and a farmer advocate please stop Riverview and affilates from further expansion. The expansion is creating a monopoly in the dairy industry pushing many family farms out of business due to the high volume of milk they flood the market with. Competition in the industry is good but not at the rate at which Riverview is accelerating. Riverview is not considering the impact they have on Minnesota's dairy industry and they are not helping local economies by what they are doing. As a small farm family we buy local, sell local, hire local, and support local.

Riverview fills all of their needs "in house" and finds the cheapest suppliers not necessarily supporting local communities or even Minnesota. Please stop Riverview from further expansion in Minnesota or there will be a monopoly and more unforseen consequences to Minnesota's dairy industry. Thank you for your consideration.

Zachariah Grein **Letter 524**

Large dairy farms need to be treated like industrial factories not farms. Furthermore the dairy herd should be spread over many owners and many locations to minimize the liability of food security and environmental impact.

Thank You

Zachariah Grein

Mark Brakke **Letter 525**

Simply based on the huge size of this project and its negative impact on smaller dairy operations I strongly object to this project being approved. We need to keep more Minnesotans active in our farm community. We do not want to turn over all food production to large businesses.

The size of this proposed dairy operation is such that a detailed environmental assessment is essential.

Ben Lilliston, Institute for Agriculture and Trade Policy **Letter 526**

The Institute for Agriculture and Trade Policy thanks the Minnesota Pollution Control Agency for the opportunity to submit the attached comment on the proposed West Dairy Expansion. IATP believes that the proposed project should undergo a full Environmental Impact Statement (EIS). The expansion would make the dairy the largest in the state, by far. It is critical that we fully understand how the proposed project effects the environment, climate change, and the state's dairy farmers.

Baldomero Penaloza **Letter 527**

My name is Baldomero Penaloza. I am writing to express my support for the proposed expansion at West River Dairy. I have lived in Stevens County for five years, and my family and I live near one of

Riverview's farms. As a neighbor, I have seen how Riverview takes care of the roads and the environment. They keep the roads clean, especially during the harvest season. In the summer, they also work to dust on gravel roads controlled. Riverview is a responsible business and runs good operations. They have been good neighbors to me and a positive presence in the community. I am confident Riverview will continue to operate the West River Dairy expansion as they do with their current farms.

I support this project and encourage its approval.

Thank you!

Josh Betcher **Letter 528**

I support this project because Minnesota needs farms of all sizes. The existing laws have more than enough protections to ensure that the impact of the density of this proposed operation is a non relevant detail. This organization has shown the history and responsibility to properly manage all of the infrastructure to keep this size of operation conforming to all requirements and regulations.

Juan Mendoza **Letter 529**

My name is Juan Mendoza. I am writing to support the proposed expansion at West River Dairy. I am a certified animal waste technician with over ten years of experience, including helping Riverview apply manure on fields around Stevens County. Riverview takes manure application very seriously. They use modern equipment, including technology that allows them to remotely monitor application equipment. They also conduct regular equipment inspections to make sure it's working properly and there aren't issues in the field. Riverview also prioritizes safety. These can be dangerous and stressful situations, but Riverview does the right thing to protect people and the fields. I also want to say that manure application has a lot of rules in Minnesota. We have to follow application rates, setbacks, nutrient management plans, and wait for the right time and conditions to apply. I know Riverview does this responsibly and they are always looking for ways to improve.

Thank you and all have a great day

Greg Shirley **Letter 530**

We don't need more mega dairy farms. They hurt our rural communities. They don't buy local, they make it harder for small farmers to compete and they damage the environment. Where does all that methane and manure end up? Plus they use massive amounts fertilizer and other chemicals to grow the feed for these cattle.

We need to have smaller farms using regenerative ag to get our farm ecology back in balance. This expansion will cause massive amounts of damage instead.

Kurt Schulz **Letter 531**

Rural Minnesota has been ravaged enough by industrial scale agriculture, especially dairy. It has driven out small family farms, is an environmental risk, a biological threat and is responsible for the depopulation of rural towns , schools and hospitals.

Enough. This should be a resounding NO !

Sally Summer **Letter 532**

MPCA

Riverview LLP is proposing to expand in Steven's county. (West River Dairy Expansion) I am a land owner 15 miles away from this CAFO.

It is important to study the impact of this expansion and requires an EIS.

We who own land know that pollution from these CAFO are impacting our ground water, our land health ,our communities. The Pomme de Terre River watershed is within25 miles from its confluence with the Mn River for example. Plus the Minnesota Department of Natural Resources does not have a complete map of Steven's County groundwater resources and aquifers.

Accountability is the job of MPCA. Do not allow this expansion based on unknowns.

EIS needs to be completed before expansion.

Sincerely

Sally Summer

Adam Zeltwanger **Letter 533**

I am in favor of West River Dairy expansion.

Riverview follows the state rules on Manure management.

Soil sampling required before manure application

Nutrient Management Plans reviewed at the state level

Manure managed at agronomic rates

Stewardship practices that protect soil and water

Long-term soil health improvements from manure use

Thanks,

Adam Zeltwanger

Scott Ruiter **Letter 534**

My name is Scott Ruiter and I live and farm in Chippewa County Minnesota. I also live two miles from Riverviews Louriston Dairy site. My families experience with them has been nothing but positive.

We raise corn, edible beans, sugar beets and alfalfa on our farm. Riverview has given our farm many increased opportunities in working with them on forages and manure for our crop health. All manure is applied within state guidelines and in a safe manner. Our partnership with Riverview supports the long-term sustainability of our family farm. I support the West River expansion.

Mason Metzger **Letter 535**

I am in full support of the expansion!

I live one mile west of the original Riverview site, and 6 miles from the new expansion. I feel if anyone would have a reason to complain about smell, water drawdown, to much traffic or whatever excuse people might have, it would be me. Riverview has been nothing but great for my family and my small business!

I have watch Riverview grow since I was a kid, I have watched their customer relations get better with time. I have watched them use natural resources in a positive way as to not affect the environment

around these sites. I have watch them keep a community, which was slowly shrinking, stabilize it, to now have growth in a small town, where all other rural towns are dying. Not here!

To not let this project go through would be a major blow to this small town, no matter what other people might think. From my experience when people have negative things to say, it is usually because of lack of information.

I feel as though me being this close to Riverview my whole life gives my opinion more weight than someone that lives far away from here, with know actual interaction with Riverview.

Again I am in full support of this project!

Thank you!

-Mason

Lyle Grimm **Letter 536**

I am writing in support of the proposed West River Dairy expansion. As an employee at Riverview for the past 19 years, I have seen firsthand the importance of strong, responsible agricultural operations in sustaining rural communities. I was raised on a dairy farm, and although my family is no longer milking cows, I remain deeply connected to the industry. I am grateful to be part of a farm that prioritizes animal care, environmental stewardship, and long-term sustainability.

West River Dairy represents the kind of operation that helps keep rural economies alive. It provides stable jobs, supports local businesses, and contributes to the vitality of small communities like ours. Just as importantly, it plays a role in producing safe, high-quality dairy and beef products for people who rely on farmers to feed them. Many people in towns and cities do not have the ability to grow their own food, and operations like this ensure a reliable food supply while maintaining responsible environmental practices. In addition, manure from dairy operations provides a valuable source of organic nutrients for crops, helping improve soil health.

I live approximately one-half mile from the Riverview dairy farm and about seven miles from West River Dairy. In my experience, I only notice manure odors a few times per year, typically during application periods, which is expected in a rural area where livestock and crop production are part of everyday life.

I am also thankful for the long-term working relationship with the Minnesota Pollution Control Agency. Through this partnership, we continue to uphold regulations and implement practices that protect and enhance the environment and improve soil health. This collaboration helps ensure that agriculture can remain both productive and responsible for future generations.

I appreciate the opportunity to share my perspective and strongly support the continued growth of West River Dairy.

Raymond Walters **Letter 537**

Great to see western MN expansions that add jobs and value for this area.

Rhonda Wellnitz **Letter 538**

Hi i would like to say that i am in support of the expansion. We have worked with the company for many years. They are great people and very supportive of the community and the people that work for them!

Kaleb Pugsley **Letter 539**

It is clear in the EAW, that the project uses modern systems and standard environmental safeguards. Larger operations manage manure and water more effectively because they can invest in better infrastructure. This expansion benefits local communities, agriculture sustainability and consumers need for more dairy. Based on the information provided, I support continuing through the regular permitting process.

Javier Torillo **Letter 540**

My name is Javier Torillo, and I worked at West River approximately three years ago. I am writing to express my support for the expansion of this company.

In my experience, West River is an excellent organization that provides many employment opportunities and promotes cultural learning. It also encourages important values such as water conservation, animal welfare—especially the care of dairy cows—and the protection of the natural environment.

During my time there, I observed a positive and respectful work environment. For these reasons, I would like to continue supporting the growth of the dairy industry and the development of agriculture in this area.

I fully support the proposed expansion.

Thank you for your time and consideration.

Sincerely,

Javier Torillo

Sergio Vazquez **Letter 541**

I am writing in support of the proposed expansion of West River Dairy. As an employee, I have first-hand experience with the daily operations and environmental practices implemented at the facility, and I believe the project reflects a strong commitment to responsible and sustainable agriculture. I had beed working 21 year with Riverview

Through my work, I actively participate in programs designed to ensure the most efficient use of water. We closely monitor water consumption on a daily basis, including tracking usage per cow, and continuously look for ways to improve efficiency. The water used for the expansion will come from a previously vetted and permitted source, and the total appropriation has already been proposed to be reduced significantly. Additionally, the construction of water storage basins will serve as both a contingency and a climate-resiliency measure, further strengthening responsible water management.

Environmental stewardship is a core part of our operations. Employees are trained and continuously educated on best practices, including preventing manure spills and protecting surrounding land and water resources. We have systems in place to ensure manure is properly managed, not only onsite but also beneficially reused as an organic fertilizer for surrounding farmland. This reduces reliance on synthetic fertilizers and helps improve soil health. We also recycle manure solids for use as comfortable bedding for the cows, demonstrating a full-cycle approach to resource management.

Animal care is another top priority. The cows are treated with respect and provided with excellent living conditions, including proper ventilation systems that keep them cooler in the summer—often up to 10 degrees lower—and protected during winter from extreme cold and freezing temperatures. Healthy animals are essential, as they are the foundation of our work and livelihood.

I can also personally speak to the quality of life near the dairy. I lived for four years less than a mile from the facility, where my children grew up. Odors were rare and only noticeable on limited occasions, and beyond one to two miles, it is nearly impossible to detect any smell. The lagoons are properly covered, and fly control measures are effective, maintaining a clean and controlled environment.

West River Dairy also values its employees and community. The company treats its workforce with respect, fosters strong relationships with vendors, and actively seeks to collaborate with local businesses and individuals. There is an ongoing effort to involve the local community and provide opportunities for those interested in the dairy industry, especially local residents.

The operation is supported by trained professionals in every area, including dedicated teams that monitor water use and ensure full compliance with all permitting requirements. Every regulation is followed carefully, and decisions are guided by data, science, and a commitment to continuous improvement.

Based on my experience, I strongly support this expansion. It represents not only economic growth, but also a responsible and forward-thinking approach to agriculture that prioritizes environmental protection, animal welfare, and community engagement.

Sincerely,

Sergio Vazquez

Sandra Simonson **Letter 542**

In order for Minnesota to have strong rural communities, we need to preserve the beneficial economic impact of small and medium sized family farms. The approval of such an extreme large-scale operation such as the West River Dairy expansion only serves a single corporate interest not the economic and environmental well-being of rural communities.

Environmental protection needs to be a top concern, especially for an operation that would be the largest scale operation in Minnesota if approved. The requirement of an EIS is the responsible action needed to be taken by the MPCA and to not do so would be an extreme disservice to Minnesota residents. All of the previous operations previously determined to need an EIS were significantly smaller than West River's proposed operation.

The protection of water is a key concern in Minnesota! A corporate interest with a poor environmental record should not be allowed to pollute such an important resource. It is gravely irresponsible to other water users and residents of the area to move forward with this permit process without a full understanding of the potential impacts, especially in a sensitive watershed.

I submit these comments as a life-long resident of Minnesota who grew up on a farm. Since an ecology course taken in 1982, I have understood the importance of water as a resource. The two well renown ecology professors who taught the course implored us to be diligent about the protection of Minnesota's water. These professors correctly predicted the future attempted misuse of Minnesota's valuable resource - water.

Matt Wellnitz **Letter 543**

I am writing this letter in support of the West River Dairy Expansion. Having worked on the processing side of the dairy industry for over 20 years, I have had the opportunity to observe a wide range of operations, and it has truly been a pleasure to see how well Riverview manages and maintains its large-scale facilities.

From my experience, it is clear that the reason Riverview continues to grow and succeed is rooted in its commitment to doing things the right way. They consistently meet—and often exceed—all regulatory requirements, demonstrating a strong dedication to compliance, environmental stewardship, and animal care. Their success is not the result of cutting corners, but rather of maintaining high standards across every aspect of their operations.

In addition to their operational excellence, Riverview is also a strong and active supporter of the communities in which they operate. Their investment goes beyond their facilities, as they contribute to local economies, support community initiatives, and build meaningful relationships with those around them.

Based on my professional experience and firsthand observations, I fully support the West River Dairy Expansion and believe it will continue to reflect the high standards and positive community impact that Riverview is known for.

Esteban Marino Hernandez Lopez **Letter 544**

As a employee, I would like to give my support for the expansion of West River Dairy, it is fundamental for my self and for many of us is we have the opportunity to get a permit for this expansion. I truly believe that these will continue helping to us like employees and also like the community, this means a bigger source of employment and many other opportunities. With the pass of years Riverview has generated a lot experience in all the practices that the site applies day to day. I really believe that Riverview will not going to create a problem that affected to the community, neighbors or his own employees. Also I would like to mentioned at some point not just I'm part of this like Riverview, also we are part of these community.

Justin Steiner **Letter 545**

I personally know, and have worked with Riverview, and they operate with a high level of integrity and attention to detailand care a lot about the environment. Their facilities are second to none when it comes to cleanliness. They operate at a very professional level. I fully support the expansion of West River dairy because this group has proven to go above and beyond in many ways and so I have no problem with this expansion.

Thank you for your consideration in this matter!

Perry Aasness, Midwest Council on Agriculture **Letter 546**

Dear Commissioner Kessler and MPCA Staff,

On behalf of the Midwest Council on Agriculture, we respectfully submit this letter in support of Riverview LLP’s proposed dairy expansion at West River Dairy near Morris, Minnesota.

The Midwest Council on Agriculture represents agricultural producers, agribusinesses, ag lenders and commodity groups across the region who are committed to responsible stewardship of natural resources, strong rural economies, and a safe, reliable food supply. From our perspective, modern livestock producers like Riverview exemplify how environmental protection and agricultural growth can and do advance together.

Today's dairy producers operate in a vastly different landscape than previous generations. Investments in advanced nutrient management, manure handling technologies, precision feeding, and data monitoring allow modern dairies to reduce environmental impacts while improving efficiency. Riverview

has consistently demonstrated a commitment to operating within rigorous environmental standards and regulatory oversight, reflecting the broader evolution of the livestock sector toward sustainability, transparency, and continuous improvement.

Dairy expansions that undergo thorough environmental review, as this project has, reflect confidence in both science-based regulation and the ability of modern producers to meet or exceed those standards. When well-designed and properly regulated, dairy facilities protect water quality, improve soil health through responsible nutrient recycling, and contribute to long-term environmental outcomes.

Equally important is Riverview's long-standing approach to working closely with local communities and neighboring farmers. Large livestock operations do not exist in isolation; they are integrated into local economies and landscapes. Riverview's model emphasizes collaboration by creating opportunities for neighboring farmers through manure application partnerships, supporting local service providers, and contributing to employment and economic stability in Stevens County and the surrounding region.

Successful agricultural operations depend on trust, communication, and accountability. Riverview's engagement with neighbors, local leaders, and community stakeholders reflects an understanding that strong relationships are essential to long-term success. These partnerships help ensure that growth in agriculture also means growth in shared prosperity.

Finally, the expansion of responsible dairy operations is critical to meeting growing demand for dairy products—both domestically and globally. Minnesota plays a key role in supplying high-quality, safe, and nutritious dairy foods, and continued investment in the state's dairy sector helps ensure that production remains close to the consumers and communities it serves.

Supporting sustainable growth in dairy production also helps maintain Minnesota's leadership in agriculture, preserves valuable farming infrastructure, and provides opportunities for future generations to remain engaged in agriculture rather than seeing production shift elsewhere.

For these reasons, the Midwest Council on Agriculture supports Riverview LLP's proposed dairy expansion and respectfully encourages the Minnesota Pollution Control Agency to consider the demonstrated environmental safeguards, community engagement, and economic benefits associated with this project.

We appreciate the MPCA's commitment to a robust public process and science-based decision-making and thank you for the opportunity to provide comment.

Sincerely,

Perry Aasness, President

Midwest Council on Agriculture

Mark Tuls **Letter 547**

Dear Mr. Peterson,

My name is Mark Tuls, and I have over 20 years of experience in the dairy industry, including more than nine years as a proud employee of Riverview. I am writing in strong support of Riverview's proposed West River Dairy expansion in Stevens County.

Riverview has given me the opportunity to continue my journey as a fourth-generation dairy farmer, honoring what my family came to America to do — help feed millions of people. This work is not just a career for me; it is a legacy and a responsibility that Riverview has empowered me to carry forward.

Through my two decades of experience in the dairy industry, I understand the importance of a strong and stable livestock sector to Minnesota's rural economy. Operations like Riverview generate consistent economic activity, support local jobs, and drive investment that allows surrounding businesses and communities to thrive.

The proposed West River Dairy expansion represents a meaningful economic benefit to the region. It will create demand for local vendors, support construction and long-term employment, and contribute to the continued vitality of rural communities that depend on agriculture.

From my direct experience, Riverview is a professional and responsible operation that truly puts employees first. The company offers very competitive wages, invests heavily in its people, and maintains its facilities with a level of care that exceeds how many people maintain their own homes.

Animal care is a top priority, and Riverview's standards consistently exceed industry expectations.

Projects like this are essential to maintaining a competitive and sustainable agricultural economy in Minnesota. Continued investment ensures that local families can remain employed close to home and that agriculture remains a strong foundation of our state's economy.

Given the rigor and sufficiency of Minnesota's existing environmental review process, no Environmental Impact Statement is needed for this project. I respectfully encourage your support and approval of the West River Dairy expansion.

Thank you for your time and consideration.

Sincerely,

Mark Tuls

Rachel Zeltwanger **Letter 548**

I fully support West River Dairy expansion. I lived in Stevens County for 50+ years and around Riverview sites my entire life. The livestock facilities are always kept clean and held to the highest environmental standards.

Again, I am in support of West River Dairy expansion

Rachel Zeltwanger

Lafe Grimm **Letter 549**

ATTN: Charles Peterson

My name is Lafe Grimm and my wife and I have a family farm in neighboring Horton township, Stevens County. I am writing in support of the proposed **West River Dairy Expansion**.

Based on my experience and observations, Riverview Dairy operates with professionalism, integrity, and environmental responsibility. Their facilities are well-maintained, clean, and organized, and their teams are committed to doing things the right way.

I am also a cattle farmer and understand that manure management and water use are highly regulated in Minnesota. Riverview strives to follow these regulations, including nutrient management planning, soil testing, proper application rates, and timing based on field conditions. From what I have seen, their mindset is to meet and exceed these standards to ensure responsible stewardship. It is very apparent that they run their business with a long-term mind set and don’t take short cuts.

The use of manure as a nutrient source has clear benefits for local farms, including improved soil health, increased organic matter and reduced erosion. This supports longterm agricultural sustainability.

Riverview has also been a strong community partner, supporting farmers, creating jobs, maintaining roads, and investing in schools and local programs. I have found them to be excellent neighbors. Their positive impact to our local farm economy is huge and one that our local farm families desperately need.

I understand that this project is undergoing environmental review through the state's established process — one of the most rigorous in the region— and provides adequate oversight for this project. Based on the available data, existing regulations, and Riverview's proven track record, I am confident this project can continue to operate responsibly. I believe the current review process is sufficient and that additional regulatory burdens are unnecessary.

In closing, I respectfully encourage the appropriate agencies to approve the West River Dairy Expansion. This project supports local agriculture, strengthens rural communities, and reflects a responsible approach to environmental stewardship. I also believe that an EIS is not necessary.

Sincerely,

Lafe Grimm

Juan Manuel Palomo Posada **Letter 550**

I am in favor of the expansion of the West River dairy. As an employee at Riverview who has been working for 8 years in the dairy operations, the application of manure is an activity that is carried out following the manure management standards required always keeping in mind that work with integrity, responsibility, respect, and safety improves the conditions of our community. I support continuing through the regular permitting process. Thank you.

Michael Steffl Steffl Drilling & Pump Inc **Letter 551**

My name is Michael J Steffl. I am the owner/operator and an employee of Steffl Drilling & Pump Inc. We provide what nothing living can survive without WATER. We serve multiple agricultural operations in Minnesota, North Dakota, South Dakota, Iowa, and Wisconsin. I am writing in support of Riverview's proposed West River Dairy expansion in Stevens County.

We need operations like Riverview's consistent economic activity that supports local jobs and allows businesses like ours to grow and reinvest in our communities.

This proposed expansion represents a meaningful economic benefit to the region. Its supports the long-term employment and vitality of rural communities.

From our direct experience, Riverview is a professional and reliable partner that contributes positively to the communities where it operates and beyond.

Projects like this are essential to maintaining a competitive and sustainable rural economy. Continued investment in agriculture ensures that local businesses can continue to provide jobs, services, and economic stability in rural Minnesota and beyond.

No EIS is needed as the state environmental review process is rigorous and very sufficient. I respectfully encourage your support and approval of this important project

Sincerely,

Michael J Steffl

Ty Feuchtenberger **Letter 552**

Dear Mr. Peterson,

My name is Ty Feuchtenberger, and I am a local farmer, business owner, and resident of Stevens County. I am writing to express my support for the proposed West River Dairy Expansion.

Through my experience and familiarity with agricultural operations in this area, I have observed Riverview Dairy to be a professional and well-managed operation with a strong commitment to environmental responsibility. Their facilities are consistently orderly and well maintained, and their management approach reflects an emphasis on doing things properly and transparently.

Manure management and water usage are among the most highly regulated aspects of agriculture in Minnesota. Riverview has demonstrated a clear understanding of these requirements and works within established guidelines through detailed nutrient management plans, routine soil testing, proper application rates, and careful consideration of timing and field conditions. From what I have seen, their approach goes beyond simple compliance and reflects a genuine focus on responsible stewardship.

Utilizing manure as a fertilizer source provides important benefits to local farms, including improved soil structure, increased organic matter, and reduced erosion. These practices contribute to long-term soil health and support the sustainability of agriculture in our region.

Riverview has also played an important role in the local community by supporting neighboring farmers, providing employment opportunities, helping maintain infrastructure, and contributing to schools and community initiatives. Their ongoing communication with neighbors and officials demonstrates a sincere desire to operate as a responsible and respectful neighbor.

I understand the proposed expansion is currently undergoing environmental review through Minnesota's established regulatory process, which provides thorough oversight. Based on Riverview's operational history, available information, and the protections already in place, I am confident this project can move forward responsibly. I believe the existing review process is sufficient and that an Environmental Impact Statement is unnecessary.

Thank you for considering my comments. I respectfully urge the agency to approve the West River Dairy Expansion, which supports local agriculture, strengthens rural communities, and reflects sound environmental stewardship.

Sincerely,

Ty Feuchtenberger

Christe Singleton **Letter 553**

It is vital that the Riverview Dairy be REQUIRED to submit an environmental impact statement. It is nearly twice as big as any current operation in the state, and its environmental harm would be enormous.

Riverview would pump up to 226 million gallons/year from an off-site well, nearly as much as the entire City of Morris (which is permitted for 300 million gallons/year for 5,000+ residents). This is a massive water use project.

The facility would generate about 202.7 million gallons of liquid manure and wastewater annually, plus 26,400 tons of solid manure. This is a huge waste output.

There are unknown groundwater impacts: the DNR hasn't begun the hydrologic survey or completed the County Geologic Atlas for Stevens County, so aquifers and groundwater resources aren't mapped, making it risky to permit large withdrawals now.

Sensitive, already impaired waters: the expansion sits in the Pomme de Terre watershed, designated sensitive; the nearest waters-the Pomme de Terre River and a nearby unnamed creek are already listed as impaired. The addition to the existing farm would likely worsen these impairments.

Advancing permits without a full understanding of groundwater and water-quality risks is irresponsible. It is critical that the MPCA require a FULL Environmental Impact Statement.

Thank you,

Christe Singleton

Guillermo Cruz Arroyo — Letter 554

I really want this project to start because of the greatness it can bring to the community.

Mary Arroyo — Letter 555

I want this project to open up because it will bring opportunities to the community.

Megan Wulf — Letter 556

ATTN: Charles Peterson

My name is Megan Wulf, and I am a local farmer in Steven's County. I am writing in support of the proposed West River Dairy Expansion.

Based on my experience and observations, Riverview Dairy operates with professionalism, integrity, and environmental responsibility. Their facilities are well-maintained, clean, and organized, and their teams are committed to doing things the right way.

As someone familiar with agriculture in this region, I recognize that manure management and water use are highly regulated in Minnesota. Riverview strives to follow these regulations, including nutrient management planning, soil testing, proper application rates, and timing based on field conditions. From what I have seen, their mindset is to meet and exceed these standards to ensure responsible stewardship.

The use of manure as a nutrient source has clear benefits for local farms, including improved soil health, increased organic matter and reduced erosion. This supports long-term agricultural sustainability.

Riverview has also been a strong community partner, supporting farmers, creating jobs, maintaining roads, and investing in schools and local programs. Their communication with neighbors and officials reflects their commitment to being a good neighbor.

I understand that this project is undergoing environmental review through the state's established process — one of the most rigorous in the region— and provides adequate oversight for this project. Based on the available data, existing regulations, and Riverview's proven track record, I am confident this project can continue to operate responsibly. I believe the current review process is sufficient and that additional regulatory burdens are unnecessary.

In closing, I respectfully encourage the appropriate agencies to approve the West River Dairy Expansion. This project supports local agriculture, strengthens rural communities, and reflects a responsible approach to environmental stewardship. I also believe that an EIS is not necessary.

Sincerely,

Megan Wulf

Scott Hennen **Letter 557**

I support the expansion of West River Dairy. Through out my years of farming in synnes township I have seen what it was before West River Dairy was there to what it is today as it has evolved. They have brought value added market options to our farming region to which we would not have otherwise. As a neighbor to Riverview I have worked with them through all the tasks associated with the dairy from selling silage, working on the silage harvest crews, and receiving fertilizer from the dairy. In my pesonal experiences with Riverview, safety is of their top priority whether it be personal or environmental. As a neighbor and a farmer please support Riverview West River Dairy expansion!!

Rigoberto Cruz **Letter 558**

I have worked for nearly 11 years across Riverview's various systems and operations, and I have observed the benefits that new projects—or expansions of existing ones—bring to the communities.

I believe in Riverview's deep commitment to doing things the right way; I am in favor of the expansion of West River Dairy.

Max Feuchtenberger **Letter 559**

ATTN: Charles Peterson

My name is Max Feuchtenberger, and I am an employee of Riverview LLP, past local business owner and involved in other agricultural operations in Stevens County, Minnesota. I am writing in support of Riverviews proposed West River Dairy expansion in Stevens County.

Through our work in the agricultural sector, we depend on a strong and stable livestock industry. Operations like Riverview’s create consistent economic activity that supports local jobs, drives investment, and allows businesses like ours to grow and reinvest in our communities.

The proposed expansion represents a meaningful economic benefit to the region. It will generate demand for local vendors, support both construction and long-term employment, and contribute to the vitality of rural communities that rely on agriculture.

From my direct experience as an employee and vender, Riverview is a professional and reliable partner that contributes positively to the communities where it operates. Their presence strengthens the local economy and supports a broad network of agricultural and service-related businesses.

Projects like this are essential to maintaining a competitive and sustainable rural economy in Minnesota. Continued investment in agriculture ensures that local businesses can continue to provide jobs, services, and economic stability close to home.

No EIS is needed as the state environmental review process is rigorous and very sufficient. I respectfully encourage your support and approval of this important project.

Sincerely,

Max Feuchtenberger

Fredy Flores Avila **Letter 560**

My name is Fredy Flores Avila, and I am writing to express my support for the proposed West River Dairy Expansion in Stevens County.

I have worked with Riverview for over 15 years, and my support for this project comes from direct, firsthand experience. I have seen how operations like this function on a daily basis, and I understand the level of care, structure, and oversight involved.

This expansion represents a meaningful opportunity for our local economy. Many families depend on agricultural operations like this for stable employment. It is not only a source of jobs for current workers, but also for neighbors and for the children of local families, who return each year to work. These opportunities help young people gain work experience and support themselves while staying connected to their community.

Riverview is not just a job. It is a way of life for many families in this area. It provides stability, routine, and long-term opportunities that are essential in rural communities where economic options can be limited.

Based on my experience, the animals are treated with dignity, respect, and compassion. They are kept in well-managed, protected, and regulated environments, with consistent attention to their health and well-being. This is something I have personally witnessed over many years.

I also understand that environmental concerns are part of this process. However, modern agricultural operations like this operate under strict regulations and oversight. Expanding an existing facility allows for better use of established infrastructure and management systems, which can be more responsible than building new operations elsewhere.

I encourage decision-makers to carefully consider both the economic importance of this project and the realities of how these operations are managed. Based on my experience, I support moving this project forward.

Thank you for the opportunity to provide input.

Sincerely,

Fredy Flores Avila

Craigan Wulf **Letter 561**

As a neighbor of a Riverview location, I can testify the quality in standards and practice used in the daily operations and all year long is top notch. The areas are all kept clean and all runoff is contained. The odor is so minimal its hardly noticeable most days.

As a farmer working along side Riverview, the benefits of us working together are so important. To be able to help eachother as they have needs of crops for feed production and land for manure application. We have countless opportunities for selling crop, adding Alfalfa crop to our rotation, and options for helping in harvest to offset equipment costs.

Personally I would have no concerns with an expansion for Westriver Dairy and I fully support the proposal.

Thank you,

Craigan Wulf

Gail Hockert **Lettte 562**

I am opposed to West River Dairy Expansion. I am very concerned about the ramifications to the ground water in our area and hope it is not allowed to expand.

Thank you,

Gail Hockert

Scott Wulf **Letter 563**

As a neighbor of West River Dariy and a home owner by the well (400' from my front door)that is to provide the water for the sight expansion I would like to share a few comments.

-In resent years I've been involved in the instalation of Riverviews manure application infrastructure, there was much planning on how to keep the manure from reaching any streams/rivers if they would happen to have a spill.

-The location of the well that they plan to use is in an area where the aquifer is continously being replenished.

-With the integrity I've seen with the people Riverview, if there use of water would affect my personal use of water they would welcome a call and be willing to come up with a solution to fix any issue that might arise.(If you look at Riverviews history in Arizona, you will find they are one of the leaders in water conservation in the state. Also there willingness to help ther neighbors with water.)

I would have no concern with Riverviews plan to expand there dairy operations. I would also echo the neighbors that commented on all the benefits of having Riverview in our local economy.

Thanks MPCA for giving us a opportunity to share our comments with you.

Sincerely,

Scott A. Wulf

Conrad Spangler **Letter 564**

My name is Conrad Spangler and I have been working with Riverview for the last 14 years. My entire life has been spent in the dairy industry. I grew up on a dairy farm, studied dairy science, practiced dairy medicine, and have been active in the dairy community for my entire life. I am writing in support of Riverview's proposed West River Dairy expansion in Stevens County.

Riverview has an unparalleled culture of caring for people, communities, cattle, and the environment. The economic activity created by their dairies supports a variety of vendors, both locally and nationally, local businesses such as grocery stores, hardware stores, accountants, lawyers, and medical professionals. Additionally, all of this economic activity brings benefits and students to the local schools.

Riverview has consistently been a good steward of the environment.

• Every year they contract a pest company to ensure that mice and rodents are not present around their facilities.

• They actively incorporate proven methods to decrease fly populations.

• They cover lagoons to reduce greenhouse gases and odors from manure.

• They closely monitor water usage to ensure responsible use of resources.

Riverview cattle facilities undergo comprehensive audits twice per year to evaluate all aspects of dairy management. Routinely the auditors comment on the cleanliness of the facilities, the high level of management observed, and the excellent culture that Riverview and its employees have created. I have no doubt that the proposed expansion will be managed at a similarly high level as Riverview has done in the past.

Projects like this are essential to maintaining a competitive and sustainable rural economy in Minnesota. Continued investment in agriculture ensures that local businesses can continue to provide jobs, services, and economic stability close to home.

No EIS is needed as the state environmental review process is rigorous and very sufficient. I respectfully encourage your support and approval of this important project.

Sincerely,

Conrad Spangler

Matt Komro, Komro Sales & Service Inc. **Letter 565**

ATTN: Charles Peterson

My name is Matt Komro, and I am the Owner and President of Komro Sales & Service Inc. , a contractor, Ag. design, and service company, serving agricultural operations in Minnesota like Riverview. I am writing in support of their proposed West River Dairy expansion in Stevens County.

Through our work in the agricultural sector, we depend on a strong and stable livestock industry. Operations like Riverview's create consistent economic activity that supports local jobs, drives investment, and allows businesses like ours to grow and reinvest in our communities.

The proposed expansion represents a meaningful economic benefit to the region. It will generate demand for local vendors, support both construction and long-term employment, and contribute to the vitality of rural communities that rely on agriculture.

From our direct experience, Riverview is a professional and reliable partner that contributes positively to the communities where it operates. Their presence strengthens the local economy and supports a broad network of agricultural and service-related businesses.

Projects like this are essential to maintaining a competitive and sustainable rural economy in Minnesota. Continued investment in agriculture ensures that local businesses can continue to provide jobs, services, and economic stability close to home.

No EIS is needed as the state environmental review process is rigorous and very sufficient. I respectfully encourage your support and approval of this important project.

Sincerely,

Matt Komro

Lucas Koehl **Letter 566**

ATTN: Charles Peterson

My name is Lucas Koehl, and I am a neighbor, local resident and farmer in Darnen Township in Stevens County. Our farm and my family's house is located directly between Riverview's West River Dairy and

Riverview Dairy and less than 1 mile from the Pomme de Terre River. I am writing in support of the proposed **West River Dairy Expansion.**

Based on my experience and observations, Riverview Dairy operates with professionalism, integrity, and environmental responsibility. Their facilities are well-maintained, clean, and organized, and their teams are committed to doing things the right way.

As a farmer that utilizes manure on our own farm and works with Riverview to responsibly field apply their manure, I recognize that manure management and water use are highly regulated in Minnesota. Riverview strives to follow these regulations, including nutrient management planning, soil testing, proper application rates, and timing based on field conditions. From what I have seen, their mindset is to meet and exceed these standards to ensure responsible stewardship.

Based on my experience permitting wells on our own farm, I have complete confidence that the well permitting process in Minnesota protects our water resources. I have also had my own residential well water tested in the last few years, and the nitrate levels - (.03 mg/L) are far below MPCA's safe drinking water standard of 10 mg/L. Riverview's dairies have been operating in the neighborhood for 20 -30 years and there has been livestock production here for generations.

The use of manure as a nutrient source has clear benefits for local farms, including improved soil health, increased organic matter and reduced erosion. Farmers today put a tremendous value on manure as a resource, utilizing it at agronomically sound rates, displacing commercial fertilizer that they would otherwise purchase to produce their crops. This supports long-term agricultural sustainability.

Riverview has also been a strong community partner, supporting farmers (my family operates a business harvesting feed and field applying manure for Riverview), creating jobs, (I am a former employee) maintaining roads, (like the one in front of my house) and investing in schools and local programs. Their communication with neighbors and officials reflects their commitment to being a good neighbor.

I understand that this project is undergoing environmental review through the state's established process — one of the most rigorous in the region— and provides adequate oversight for this project. Based on the available data, existing regulations, and Riverview's proven track record, I am confident this project can continue to operate responsibly. I believe the current review process is sufficient and that additional regulatory burdens are unnecessary.

I feel like there have been many comments on this project from those who do not understand modern agricultural practices and lack appreciation for the permitting process that is in place. Many that are in agriculture today (including Riverview) have earned to be where they are through responsible stewardship of our natural resources.

In closing, I respectfully encourage the appropriate agencies to approve the West River Dairy Expansion. This project supports local agriculture, strengthens rural communities, and reflects a responsible approach to environmental stewardship. I also believe that an EIS is not necessary.

Thank you for the opportunity to comment on this important project.

Sincerely,

Lucas Koehl

Felix Camacho **Letter 567**

Riverview made me a better person, and I appreciate the opportunity to learn from this country. I love my job!

Carlos Portillo **Letter 568**

Riverview is an excellent company in which it provides a culture of opportunities in which it takes care of the well-being of each person in the same way it is treated with great respect and a strong ethics in the care of cows I am very happy to be part of this great company

Maggie Knobloch **Letter 569**

My name is Maggie Knobloch, and I am writing to express my support for the proposed West River Dairy Expansion.

I have been connected to Riverview for all of my life. My father as well as several of my family members have been involved in our company for quite some time now. I have been working at Riverview for approximately two years. During that time, I have had the opportunity to work across multiple areas of the company, including dairy operations, livestock, and other segments of the business.

Through this hands-on experience, I have developed a deep appreciation for the culture at Riverview. Our people are committed, supportive, and take pride in their work getting to produce food for Americans. Riverview is also 75% employee-owned, which reflects their strong commitment to investing in its people and creating meaningful opportunities for growth.

From an operational and environmental standpoint, I have personally observed Riverview's practices across many of its sites. Our company maintains high standards in how it treats its cattle. Cleanliness, care for animals, and attention to detail are consistently emphasized.

Riverview also demonstrates a responsible and sustainable approach to manure management. We partner with local growers, creating a cycle where crops are grown, fed to cattle, and nutrients are returned to the land through manure application. This system supports both agricultural productivity and environmental stewardship. Additionally, our company operates in compliance with all applicable regulations and is attentive to its impact on neighbors, roads, and surrounding communities.

Based on my experience, I believe Riverview operates responsibly and with a strong commitment to environmental care and compliance.

For these reasons, I fully and respectfully support the approval of the West River Dairy Expansion. I also believe that the current Environmental Assessment Worksheet process has been thorough and sufficient with all of the research, and that an Environmental Impact Statement is not at all necessary.

Thank you for the opportunity to provide comment.

Sincerely,

Maggie Knobloch

Ashdon Hacker **Letter 570**

I am writing in support of the proposed West River Dairy expansion. As a college student, I have had the opportunity to work at Riverview during my summers, and I am incredibly grateful for the experiences and support the company has provided me throughout my college journey.

I grew up living next to the dairy, and throughout that time, I rarely noticed any impact from it in my day-to-day life. Instead, I have seen firsthand how much it contributes to the community and how positive of an influence it has been. Riverview has also been very good to my family, providing opportunities and support that we truly appreciate.

Riverview has given me more than just a summer job—it has allowed me to return home, stay connected to my community, and continue building valuable skills while pursuing my education. The flexibility and opportunities provided have made a meaningful difference in helping me balance work and school.

One of the most impactful parts of my experience has been the relationships I have built. The people I work with are supportive, hardworking, and genuinely care about one another. These connections have made my time at Riverview not only enjoyable but also personally rewarding, and they are a big reason I look forward to returning each summer.

I am thankful for everything Riverview has provided me and strongly support the continued growth of West River Dairy. It is an organization that supports both its employees and the communities it serves.

Halle Grimm **Letter 571**

My name is Halle Grimm, and I am writing to express my support for the proposed West River Dairy Expansion.

Riverview was my first job at 14, where I worked in a front desk position. That experience opened up many opportunities for me and helped me grow both personally and professionally.

Riverview has continued to support me as I prepare to go off to college this fall through their scholarship program, which benefits around 55 high school seniors with $3,000 that I plan to use towards my academics.. This commitment to supporting young people and investing in the future of the community is something I have personally experienced and value deeply.

From my experience, Riverview operates in compliance with all regulations and is thoughtful in how it manages environmental responsibilities, including considerations related to land, roads, and the surrounding community. I believe Riverview is responsible and committed to environmental care, and I trust that this expansion will be handled with the same level of attention and integrity.

For these reasons, I respectfully support the approval of the West River Dairy Expansion. Thank you for the opportunity to provide comment

Thank you,

Halle

Jonathan Tomic **Letter 572**

Had the opportunity to tour a bunch of their facilities, was blown away by how clean, creative, and environmentally conscious they were! They don't let a thing go to waste and are very committed to providing a sustainable future for generations to come! I fully support the expansion of the West River dairy!

Alejandro Díaz Flores **Letter 573**

Buenas tardes, tengo 5 años trabajando para Riverview y es una empresa de compromiso, grandes valores y oportunidades.

Es una empresa que trabaja con mucha seguridad, responsabilidad y mucho compromise Yo estoy a favor de la expansion

Translation:

Good afternoon. I've been working at Riverview for five years, and it's a company that's committed to its values and offers great opportunities.

It is a company that operates with a strong sense of security, responsibility, and commitment I am in favor of the expansion

Hunter Massner **Letter 574**

My name is Hunter Massner. I am a resident of Stevens County and am writing this in **support** of the West River Dairy expansion. I also believe the current review process is sufficient and that additional regulatory burdens are unnecessary.

I am a local business owner and expanding the West River Dairy would be a benefit to my business and almost all of the local business owners. As a home appliance and heating and cooling business, Riverview is a large part of our sales. An expansion means more laborers, more job opportunities, and increased cash flow in our community. The expansion would mean opportunities for business directly related to Riverview and others that are not connected at all.

An expansion to the West River Dairy would increase the amount of local revenue. This expansion positively affects much more than Riverview and the local farmers. Each employee and contractor of West River has a need to purchase things to live, therefore increasing local business profits. Everyone needs to buy groceries. Everyone needs appliances. Everyone needs a car, gas, clothes, water, electricity, a home, furniture, appliances, and tools.The list goes on and on. Most importantly services from the repair man, the carpenter, the electrician, and many other businesses that rely on Riverview for a large portion of their business.

In conclusion, the West River Dairy expansion would be great for the local business and the residents of Stevens County. **We fully support** the expansion of West River Dairy.

Thank you,

Hunter Massner

Mary Margaret Lawler **Letter 575**

The way we treat our animals is a reflection of who we are as human beings. There is no possible way to humanely treat 18,000 cows. This is wrong. According to the Animal Humane Society, one of the rights of animals is the freedom to express normal behavior. You will be violating this right if you allow this expansion. Please do not allow this expansion.

Janice Nelson **Letter 576**

I am very, very concerned about this proposed immense dairy that is being proposed to be located near Morris, Mn. The damage to the environment, including wildlife and waterfowl areas would be extreme and irreversible! The amount of water required would affect the water table in the area and the effects on the Pomme de Terre water shed must be very carefully considered. Environmental effects must be very thoroughly checked and considered!! Also, the effect on small to midsized dairy farms would be unfair and damaging! Please be careful of irreversible outcomes of this decision! Thanks for your consideration. Jan Nelson

Brandon Thesing **Letter 577**

Good morning, my name is Brandon Thesing, and I serve as a Corporate Account Manager for Select Sires Member Cooperative, working directly with Riverview. As an organization and myself we fully support Riverview Dairy's proposal to develop and permit this new facility. Riverview has built a strong reputation for progressive dairy management, with a clear focus on doing things the right way—taking great care of their animals, growing responsibly, and always looking for ways to improve. Their team puts a lot of emphasis on cow comfort, health, and performance, using good data, strong facilities, and well-trained people who understand that animal care is at the core of everything they do. This project is not just about growth, but about continuing to move the industry forward in a responsible and sustainable way.

Brett Petersen **Letter 578**

My name is Brett Petersen, and I am a Neighbor and farmer of Riverview in Louriston Twp, Chippewa County MN. I am writing in support of the proposed West River Dairy Expansion.

For many years my family has worked with Riverview dairy, Riverview Dairy operates with professionalism, integrity and environmental responsibility. All their dairies are clean, organized and are committed to doing things the right way every time.

As someone that lives and breathes agriculture every day in Minnesota, I recognize the importance of water management and manure management in Minnesota. Riverview has always strived to exceed the states regulations and go above and beyond with all operations. This is accomplished by nutrient management planning, soil testing and proper application rates. I would not work with a company if I did not believe they were not the best at these items in the state of Minnesota.

The use of manure as a fertilizer source has had huge benefits to my farming operation and local operators. This is seen through soil health, crop health and supports long term agricultural sustainability.

Riverview has also been a strong community partner supporting local farmers, creating local jobs, investing in schools and local programs. I know personally Riverview has donated multiple times to local groups and organizations in the Kerkhoven and Murdock areas.

I understand that this project is undergoing environmental review through the state's established process one of the most rigorous in the region. Based on what I can see Riverview has exceeded all environmental standards the state has set for them to meet and believe that no additional regulatory burdens are necessary on Minnesota businesses.

I respectfully encourage the appropriate agencies to approve the West River Dairy Expansion. This project supports local agriculture, strengthens rural communities and reflects responsible approach to environmental stewardship. I believe that an EIS is not necessary.

Sincerely,

Brett Petersen

Dustin Hollermann **Letter 579**

ATTN: Charles Peterson

My name is Dustin Hollermann, and I am writing in support of the proposed West River Dairy Expansion. I have worked at Riverview for nine years in Dairy Genetics and Reproduction, and prior to that spent four years as a vendor working with the company. With over 25 years in the dairy industry, I have seen a lot of operations — and Riverview stands apart.

Riverview is simply the best in the world when it comes to animal husbandry. The care, attention, and standards applied to their cattle are unmatched in my experience. But what truly sets Riverview apart is the opportunity it creates for its people. It is a place where employees can build real careers and grow in ways that are hard to find anywhere else.

I also live very close to one of Riverview's existing sites, and I can say from personal experience that odor, traffic, and noise are a complete non-issue — barely noticeable. The concerns some raise simply do not reflect the reality of living near one of their operations.

I have four kids, and projects like this expansion give me confidence that they will have the opportunity to be part of this incredible organization someday. For that reason and many others, I fully support the West River Dairy Expansion.

Thank you for the opportunity to provide comment.

Sincerely,

Dustin Hollermann

Dawn Kisgen **Letter 580**

I support the expansion at West River Dairy.

Catherine Anderson **Letter 581**

To Whom It May Concern:

I just read an article regarding a proposed major increase in size of a dairy farm operation near Morris. It is my opinion that this should be adamantly opposed due to environmental concerns, especially excess water consumption and contamination. Aren't all humans dependent on clean water for our very survival and, therefore, shouldn't we be good stewards of its balanced care?

Sincerely,

Catherine Anderson

Ali Bouta **Letter 582**

ATTN: Charles Peterson

My name is Ali Bouta and I am a local resident, farm owner/operator and local community agricultural loan officer in both Kerkhoven and Dublin Townships of Swift County. I am writing in support of the proposed **West River Dairy Expansion**.

Based on my experience and observations, Riverview Dairy operates with professionalism, integrity, and environmental responsibility. Their facilities are well-maintained, clean, and organized, and their teams are committed to doing things the right way.

As someone familiar with agriculture in this region, I recognize that manure management and water use are highly regulated in Minnesota. Riverview strives to follow these regulations, including nutrient management planning, soil testing, proper application rates, and timing based on field conditions. From what I have seen, their mindset is to meet and exceed these standards to ensure responsible stewardship.

The use of manure as a nutrient source has clear benefits for local farms, including improved soil health, increased organic matter and reduced erosion. This supports long-term agricultural sustainability.

Riverview has also been a strong community partner, supporting farmers, creating jobs, maintaining roads, and investing in schools and local programs. Their communication with neighbors and officials reflects their commitment to being a good neighbor.

I understand that this project is undergoing environmental review through the state's established process — one of the most rigorous in the region— and provides adequate oversight for this project. Based on the available data, existing regulations, and Riverview's proven track record, I am confident this project can continue to operate responsibly. I believe the current review process is sufficient and that additional regulatory burdens are unnecessary.

In closing, I respectfully encourage the appropriate agencies to approve the West River Dairy Expansion. This project supports local agriculture, strengthens rural communities, and reflects a responsible approach to environmental stewardship. I also believe that an EIS is not necessary.

Sincerely,

Ali Bouta

Bravera Bank - Ag Banking Officer/Dairy Farmer

Kyle Clark — Letter 583

ATTN: Charles Peterson

My name is Kyle Clark, and I am a lifelong resident of Swift County in addition to owner/operator of Clark Family Farm Partnership in Dublin Township of Swift County. I am writing in support of the proposed **West River Dairy Expansion**.

Based on my experience and observations, Riverview Dairy operates with professionalism, integrity, and environmental responsibility. Their facilities are well-maintained, clean, and organized, and their teams are committed to doing things the right way.

As someone familiar with agriculture in this region, I recognize that manure management and water use are highly regulated in Minnesota. Riverview strives to follow these regulations, including nutrient management planning, soil testing, proper application rates, and timing based on field conditions. From what I have seen, their mindset is to meet and exceed these standards to ensure responsible stewardship.

The use of manure as a nutrient source has clear benefits for local farms, including improved soil health, increased organic matter and reduced erosion. This supports long-term agricultural sustainability.

Riverview has also been a strong community partner, supporting farmers, creating jobs, maintaining roads, and investing in schools and local programs. Their communication with neighbors and officials reflects their commitment to being a good neighbor.

I understand that this project is undergoing environmental review through the state's established process — one of the most rigorous in the region— and provides adequate oversight for this project. Based on the available data, existing regulations, and Riverview's proven track record, I am confident this project can continue to operate responsibly. I believe the current review process is sufficient and that additional regulatory burdens are unnecessary.

In closing, I respectfully encourage the appropriate agencies to approve the West River Dairy Expansion. This project supports local agriculture, strengthens rural communities, and reflects a responsible approach to environmental stewardship. I also believe that an EIS is not necessary.

Sincerely, Kyle Clark

Justin Cronen **Letter 584**

c/o Charles Peterson

I am writing to provide my support for the proposed West River Dairy Expansion outlined in the draft Environmental Assessment Worksheet (EAW) currently under public review.

Riverview, LLP has demonstrated a long-standing commitment to responsible agricultural development, regulatory compliance, and environmental stewardship. Their facilities are known for incorporating modern technologies aimed at protecting water quality, managing manure responsibly, and supporting sustainable production practices. Based on Riverview's operational track record and their adherence to state and federal oversight, I am confident that the proposed expansion can be implemented responsibly and with appropriate environmental safeguards.

The expansion also represents significant economic value for rural Stevens County and the surrounding region. Large-scale dairy operations like West River Dairy contribute to local employment, increase demand for local goods and services, and help support the long-term vitality of rural communities. Riverview has historically been a strong partner to the communities in which they operate, and this project is a continuation of that commitment.

For these reasons, I support Riverview LLP's proposed West River Dairy expansion and believe the project merits favorable consideration as it advances through the environmental review and permitting processes. Thank you for the opportunity to comment.

Sincerely,

Justin Cronen

Emily Ann Raeker **Letter 585**

Please do an EIS before hand. There is a lot at stake here.

Im not as elegantly voiced as some individuals but please hear my voice as well.

We live nearby and are concerned about many things involved woth this project.

The amount of water they want to take is almost as much as the city of Morris! That's frightening, especially for people that live off wells around this area. Not to mention the wildlife in the area.

There is also too much land they want to destroy that is a habitat for many water fowl in the area. That would be devastating.

The smell would also be terrible.

I dont trust that they would abide by everything they are saying they would.. in other locations of theirs they have already over pumped and polluted the land.

It also won't supply that many more jobs at all.

My main concern is the auquafir, the pollution and the loss of habitat.

Please enforce a thorough investigation. I know this won't stop it yet but we need to start somewhere.

Thank you

Jeff Kisgen **Letter 586**

I support the West River Dairy expansion!

Charles Steffl, Step Saver Inc **Letter 587**

ATTN: Charles Peterson

My name is Charles Steffl, and I am the owner/operator/employee of Step Saver Inc, a Water Softener Salt delivery service serving agricultural operations in Minnesota like Riverview. I am writing in support of their proposed West River Dairy expansion in Stevens County.

Through our work in the agricultural sector, we depend on a strong and stable livestock industry. Operations like Riverview's create consistent economic activity that supports local jobs, drives investment, and allows businesses like ours to grow and reinvest in our communities.

The proposed expansion represents a meaningful economic benefit to the region. It will generate demand for local vendors, support both construction and long-term employment, and contribute to the vitality of rural communities that rely on agriculture.

From our direct experience, Riverview is a professional and reliable partner that contributes positively to the communities where it operates. Their presence strengthens the local economy and supports a broad network of agricultural and service-related businesses.

Projects like this are essential to maintaining a competitive and sustainable rural economy in Minnesota. Continued investment in agriculture ensures that local businesses can continue to provide jobs, services, and economic stability close to home.

No EIS is needed as the state environmental review process is rigorous and very sufficient. I respectfully encourage your support and approval of this important project.

Sincerely,

Charles Steffl. President Step Saver Inc.

Debra Hacker **Letter 588**

ATTN: Charles Peterson

We are Charles and Debra Hacker. We are residents of Stevens County. We are writing in support of the proposed West River Dairy Expansion.

Based on our experience and observations, Riverview operates with professionalism, integrity, and environmental responsibility. Their facilities are well-maintained, clean, and organized, and they are committed to doing things the appropriate way.

As Seniors born and raised in Stevens County, we are well aware of all the regulations that have occurred over time when it comes to manure management and water which are highly regulated in Minnesota. Riverview strives to follow these regulations, including nutrient management planning, soil testing, proper application rates, and timing based on field conditions. From what we have seen first hand, their mindset is to meet and exceed these standards to ensure responsible stewardship.

The use of manure as a nutrient source has clear benefits for local farms, including improved soil health, increased organic matter and reduced erosion. This supports long-term agricultural sustainability.

Riverview has also been a strong community partner, supporting farmers, creating jobs, maintaining roads, and investing in schools and local programs. Their communication with the community reflects their commitment to being a good neighbor.

We understand that this project is undergoing environmental review through the state's established process — one of the most rigorous in our area — and provides adequate oversight for this project. Based on the available data, existing regulations, and Riverview's proven track record, we are confident this project can continue to operate responsibly. We believe the current review process is sufficient and that additional regulatory burdens are unnecessary.

In closing, we respectfully encourage the appropriate agencies to approve the West River Dairy Expansion. This project supports local agriculture, strengthens rural communities, and reflects a responsible approach to environmental stewardship. We also believe that an EIS is not necessary.

Sincerely, Charles and Debra Hacker

Dave Lemke **Letter 589**

Having been a small family dairy farmer and still helping daily on family dairies I am strongly against the expansion of the large dairy Cafos. Water usage and manure application problems are without a doubt some of the more troubling aspects of these operations. Also there is currently an oversupply of milk that is driving prices down to all dairy farmers. Who in their right mind wants to create more milk and lower prices on their own product. We have already decimated the small farming communities in Minnesota. We here complaints about how far a veterinarian or machinery dealer or dairy parts facility are from these large dairies. More expansion of dairy will only cause more destruction to Minnesota and its people.

Karie Kirschbaum **Letter 590**

ATTN: Charles Peterson

My name is Karie Kirschbaum. I previously served as Mayor of Gary, Minnesota, and as Chair of the Norman County Economic Development Authority. I currently serve as National Sales and Procurement Director for a grain mill based in Northwest Minnesota, working closely with agricultural operations across the region, including Riverview.

I am writing in strong support of Riverview Dairy’s proposed West River Dairy expansion in Stevens County.

Riverview established its presence in Waukon Township, Norman County, in 2021. Since that time, it has proven to be a significant and positive economic force in our region. From the outset, Riverview committed to operating as a responsible and community-minded partner, and they have consistently delivered on that commitment. Their presence has contributed to local economic growth, supported housing development, strengthened school enrollment, and created opportunities for a wide range of agricultural and service-based businesses.

In my current role within the agricultural sector, I see firsthand the importance of a strong and stable livestock industry. Operations like Riverview provide dependable economic activity that supports local jobs, drives continued investment, and enables businesses like ours to grow and reinvest in rural communities.

The proposed expansion represents a meaningful opportunity for continued regional growth. It will create demand for local vendors, support both construction and long-term employment, and contribute

to the overall vitality of rural Minnesota. Projects like this are critical to maintaining a competitive and sustainable agricultural economy and ensuring that communities across our state remain strong and viable.

Minnesota's environmental review process is thorough and rigorous. Based on that, I do not believe an Environmental Impact Statement is necessary for this project.

I respectfully encourage your support and approval of Riverview Dairy's expansion.

Sincerely, Karie Kirschbaum

Brooke Gordon **Letter 591**

ATTN: Charles Peterson

My name is Brooke Gordon, and I am a local resident in Dublin Township, Murdock, MN. I am writing in support of the proposed West River Dairy Expansion.

Based on my experience and observations, Riverview Dairy operates with professionalism, integrity, and environmental responsibility. Their facilities are well-maintained, clean, and organized, and their teams are committed to doing things the right way.

As someone familiar with agriculture in this region, I recognize that manure management and water use are highly regulated in Minnesota. Riverview strives to follow these regulations, including nutrient management planning, soil testing, proper application rates, and timing based on field conditions. From what I have seen, their mindset is to meet and exceed these standards to ensure responsible stewardship.

The use of manure as a nutrient source has clear benefits for local farms, including improved soil health, increased organic matter and reduced erosion. This supports long-term agricultural sustainability.

Riverview has also been a strong community partner, supporting farmers, creating jobs, maintaining roads, and investing in schools and local programs. Their communication with neighbors and officials reflects their commitment to being a good neighbor.

I understand that this project is undergoing environmental review through the state's established process — one of the most rigorous in the region— and provides adequate oversight for this project.

Based on the available data, existing regulations, and Riverview's proven track record, I am confident this project can continue to operate responsibly. I believe the current review process is sufficient and that additional regulatory burdens are unnecessary.

In closing, I respectfully encourage the appropriate agencies to approve the West River Dairy Expansion. This project supports local agriculture, strengthens rural communities, and reflects a responsible approach to environmental stewardship. I also believe that an EIS is not necessary.

Sincerely,

Brooke Gordon

Michael J. Yost **Letter 592**

ATTN: Charles Peterson

My name is Michael J. Yost and I am a farmer from Murdock, MN in Dublin Township, Swift County. I am writing in support of the proposed West River Dairy Expansion. For over 25 years our farm has been

involved with Riverview Dairy, and we could not have asked for a better partner in our community. Based on our first-hand experience, Riverview Dairy operates with professionalism, integrity and environmental responsibility. Simply put, they are the definition of what you look for in a business that you want to have in your community and your state, they do things the right way.

Manure management and water usage are highly regulated in Minnesota and I recognize the importance of having high standards when it comes to practices that impact our environment. Through rigorous nutrient management planning, soil testing and ensuring that proper application rates are followed, Riverview not only meets these standards to ensure responsible stewardship but often exceeds them.

The use of manure as a nutrient source has significant benefits for all farms. On our farm, by having access to manure, we have been able to dramatically reduce commercial fertilizer usage. Our fields have also seen improved soil health, an increase in organic matter and a reduction in erosion and runoff. The result is a win-win for both farmers and the environment.

Riverview's track record speaks for itself. They support farmers, create jobs, maintain roads, and invest in schools and local programs. Their open communication and transparency with local farmers, businesses and officials reflect Riverview's commitment to being a good neighbor.

I understand that this project is undergoing environmental review through the state's established process – one of the most rigorous in the region – and provides adequate oversight for this project. Based on available data, existing regulations, and Riverview's proven track record, I am confident this project can continue to operate responsibly. I believe the current review process is sufficient and that additional regulatory steps, such as a requirement for an environmental impact statement (EIS), are unnecessary.

In closing, I respectfully encourage the appropriate agencies to approve the West River Dairy Expansion. This project supports local agriculture, strengthens rural communities, and reflects a responsible approach to environmental stewardship.

Sincerely,

Michael J. Yost

Yost Farm Inc.

Chris Dauer **Letter 593**

Attn: Charles Peterson

My name is Chris Dauer, I am the owner of Dairyland Supply in Sauk Centre, MN and Courtland Waste Handling Inc. in Courtland, MN. We offer a wide range of agricultural equipment that services customers in and out of the State of Minnesota, including Riverview. I am writing in support of Riverview and their proposed West River Dairy expansion in Stevens County.

Through our work in the agricultural sector, we depend on a strong and stable livestock industry. Operations like Riverview's create consistent economic activity that supports local jobs, drives investment, and allows businesses like ours to grow and reinvest in our communities.

The proposed expansion represents a meaningful economic benefit to the region. It will generate demand for local vendors, support both construction and long-term employment, and contribute to the vitality of rural communities that rely on agriculture.

From our direct experience, Riverview is a professional and reliable partner that contributes positively to the communities where it operates. Their presence strengthens the local economy and supports a broad network of agricultural and service-related businesses.

Projects like this are essential to maintaining a competitive and sustainable rural economy in Minnesota. Continued investment in agriculture ensures that local businesses can continue to provide jobs, services, and economic stability close to home.

In closing, Riverview has been a valued client and nothing short of incredible to partner with. This business not only talks the talk but walks the walk. Riverview genuinely cares about their employees and vendors they conduct business with. They are stewards of the land and are of the most professional companies I have ever had the pleasure of doing business with.

No EIS is needed as the state environmental review process is rigorous and very sufficient. I respectfully encourage your support and approval of this important project.

Sincerely,

Chris Dauer

Sharon Vipond **Letter 594**

Being a land owner, I am concerned for the safety of our environment which includes care the air, our water, the soil. This expansion of 11,000 dairy cows needs to have an EIS completed and evaluated before any permit can be granted. The people need to know if it would compromise our air quality, the negative effects on acquafirs and the condition of water that would be released onto the land, ditches and lakes. Besides bigger isn't necessarily better for anyone including the dairy cows.

Many Mn small dairy farmers have had to sell their cows which is sad and unfair because of the monopoly on the price of milk sold by the huge dairy operators. Please prevent this exspansion from happening. The state benefits when we have smaller farms and businesses.

Thank you

Bo Massner, McGinnis Appliance Heating & Cooling **Letter 595**

ATTN: Charles Peterson

My name is Bo Massner, and I am the owner of McGinnis Appliance Heating and Cooling. We are an appliance and HVAC small business serving agricultural operations across Minnesota like Riverview. I am writing in FULL SUPPORT of their proposed West River Dairy expansion in Stevens County.

Our company has been around for over 50+ years. When the first dairy started in Stevens county we were there from the beginning helping with the design of heating and cooling systems in the apartments and housing, appliances for kitchens and laundry all around the dairy to chiller systems that cool the milk and heat in the required buildings and around the works areas for the cows. From my personal experience first hand on the dairies, Riverview has been a very supportive customer of ours. Every time I get to go work out in the barns, I am amazed at how well the cows and facilities are taken care of. The cows are always happy and curious when I walk by their spacious areas. To me everyone should take a tour to see how amazing this operation truly is. We are very lucky to have them be a part of our community.

Through our work in the agricultural sector, we depend on a strong and stable livestock industry. Operations like Riverview's create a strong and consistent economic activity that supports local jobs,

drives investment, and allows businesses like ours to grow and reinvest in our communities. It allows our small business to donate and give back to local groups that also help the Stevens county community thrive.

The proposed expansion represents a meaningful economic benefit to the region. It will generate more demand for local business like ours, support both construction and long-term employment, and contribute to the vitality of rural communities that rely on agriculture.

From our direct experience, Riverview is a very professional and reliable partner that contributes positively to the communities where it operates. Their presence greatly strengthens the local economy and supports a broad network of agricultural and service-related businesses.

Projects like this are essential to maintaining a competitive and sustainable rural economy in Minnesota. Continued investment in agriculture ensures that local businesses can continue to provide jobs, services, and economic stability close to Home.

No EIS is needed as the state environmental review process is rigorous and very sufficient. I respectfully encourage your support and APPROVAL of this important project.

Sincerely,

Bo Massner (Owner/McGinnis Appliance Heating & Cooling)

Bryce E. Gibbs, Pinion **Letter 596**

Dear Mr. Peterson:

My name is Bryce Gibbs, and I am a principal at Pinion, LLC a consulting and accounting firm that serves agricultural operations across the United States, including Riverview. I am writing to express my support for Riverview's proposed West River Dairy expansion in Stevens County.

Through our work in the agricultural sector, we depend on a strong and stable livestock industry. Operations like Riverview's generate consistent economic activity that supports local jobs, drives investment, and helps rural communities thrive.

In my view, the proposed expansion would provide economic benefits to the region by increasing demand for local vendors, supporting construction activity, and contributing to long-term employment.

Based on our experience working with Riverview, they have been a professional and reliable partner, and have a constructive presence in the communities where they operate. Their investments support a broad network of agricultural and service-related businesses.

Based on my understanding of the project and Minnesota's environmental review framework, it is my understanding that an environmental impact statement (EIS) may not be required. As you complete your review, I respectfully encourage the Agency to consider the project's economic benefits alongside its proposed environmental safeguards. Thank you for your time and consideration; please let me know if I can provide any additional information.

Respectfully,

Pinion, LLC

Bryce E. Gibbs, Principal

Joe Koehl **Letter 597**

I think it is a good thing for me and my operation it gives me some extra employment opportunity. It's another place in the area to market crops. It's another crop nutrient opportunity so you don't have to import so much commercial fertilizer this can help organic crop farms

Lowell and Pat Nelson **Letter 598**

ATTN: Charles Peterson

Our names are Lowell and Pat Nelson, and we are land owners in Stevens County, which we are currently renting out to local farmers. We support agricultural operations in Minnesota like Riverview. We are writing in support of their proposed West River Dairy expansion in Stevens County.

Through our work in the agricultural sector, we depend on a strong and stable livestock industry. Operations like Riverview's create consistent economic activity that supports local jobs, drives investment, and allows businesses to grow and reinvest in our communities.

The proposed expansion represents a meaningful economic benefit to the region. It will generate demand for local vendors, support both construction and long-term employment, and contribute to the vitality of rural communities that rely on agriculture. From our direct experience, Riverview is a professional and reliable partner that contributes positively to the communities where it operates. Their presence strengthens the local economy and supports a broad network of agricultural and service-related businesses.

Projects like this are essential to maintaining a competitive and sustainable rural economy in Minnesota. Continued investment in agriculture ensures that local businesses can continue to provide jobs, services, and economic stability close to home.

No EIS is needed as the state environmental review process is rigorous and very sufficient. We respectfully encourage your support and approval of this important project.

Sincerely,

Lowell and Pat Nelson

Tracee Skaurud **Letter 599**

My name is Tracee Skaurud. I am in favor of the West River Dairy Expansion. Our farm is next to a RiverView dairy. We live 1 1/2 miles from the dairy and I don't even notice that it is there. The operation is as clean as it gets. It's amazing actually. I grew up on a small dairy farm as a kid and it has changed so much. Technology is better, the way they apply manure is efficient and safe. Water has never been an issue at all. The way they treat there cows and there calves is with complete care and compassion. Like dad always said. A happy cow makes more milk.

From experiences on our farm, MN is one of the most highly regulated states for agriculture In The USA. I trusted MPCA did all there research when the dairy was built here and it has gone very well, and I would trust them again. You don't need an EIS.

Mark Stromswold **Letter 600**

Riverview is a good steward of the land and a respected owner of cattle.

The water usage stated is the 'no rain' amount that must be used for consumption if no rain occurs. Over 50% of water used during normal rain years comes from impervious runoff with on site storage. Just one example of forward thinking by a corporation.

Justin Gaukler **Letter 601**

Riverview is super beneficial to all local farmers. On our farm we haul about 300,000 bushel of corn to them every year for grinding. We also have the chop 800 acres of corn. We are very pleased with having them in our local area.

Travor Timm **Letter 602**

I stand with Riverview as they navigate the permitting process for the West River Dairy expansion. Im confident in their commitment to responsible stewardship, environmental compliance, and supporting Minnesotas agricultural community.

Mike Staples **Letter 603**

My name is Mike Staples, and I farm in Synnes and Baker. I am writing in support of the proposed West River Dairy Expansion.

Based on my experience and observations farming a mile away from West River Dairy for 16 years now with my cousin, Riverview Dairy operates with professionalism, integrity, and environmental responsibility. Their facilities are well-maintained, clean, and organized, and the odor is a minimum for the size of the operation.

As someone familiar with agriculture in this region, I recognize that manure management and water use are highly regulated in Minnesota. Riverview strives to follow these regulations, including nutrient management planning, soil testing, proper application rates, and timing based on field conditions. From what I have seen, their mindset is to meet and exceed these standards to ensure responsible stewardship.

The use of manure as a nutrient source has clear benefits for local farms, including improved soil health, increased organic matter and reduced erosion. This supports long-term agricultural sustainability. By adding another facility of this size will increase the need for more acres of silage and hay as well. I see this as a positive for local demand for corn. Obviously will increase the acres needed to put manure on as well. We get a little manure from West River Dairy already and we wish we could get more every year.

Riverview has also been a strong community partner, supporting farmers, creating jobs, maintaining roads, and investing in schools and local programs. Their communication with neighbors and officials reflects their commitment to being a good neighbor.

I understand that this project is undergoing environmental review through the state's established process — one of the most rigorous in the region— and provides adequate oversight for this project. Based on the available data, existing regulations, and Riverview's proven track record, I am confident this project can continue to operate responsibly. I believe the current review process is sufficient and that additional regulatory burdens are unnecessary.

In closing, I respectfully encourage the appropriate agencies to approve the West River Dairy Expansion. This project supports local agriculture, strengthens rural communities, and reflects a responsible approach to environmental stewardship. I also believe that an EIS is not necessary.

Sincerely,

Mike Staples

John Sertich, Nuss Truck & Equipment **Letter 604**

My name is John Sertich and I am the Regional Manager of Nuss Truck & Equipment who sells and services numerous agricultural operations in Minnesota like Riverview. I am writing in support of their proposed West River Dairy expansion in Stevens County.

Through our work in the agricultural sector, we depend on a strong and stable livestock industry. Operations like Riverview's create consistent economic activity that supports local jobs, drives investment, and allows businesses like ours to grow and reinvest in our communities.

The proposed expansion represents a meaningful economic benefit to the region. It will generate demand for local vendors, support both construction and long-term employment, and contribute to the vitality of rural communities that rely on agriculture.

From our direct experience, Riverview is a professional and reliable partner that contributes positively to the communities where it operates. Their presence strengthens the local economy and supports a broad network of agricultural and service-related businesses. Nuss Truck & Equipment has valued our relationship with Riverview (and it's related companies) since 2008. During that time we have also grown our footprint in the Western Minnesota agricultural sector along with numerous other construction and trucking companies. We have found that many of these communities and businesses were not being served at the same level as larger metropolitan areas. The growth of responsible businesses like Riverview has also facilitated growth in our employee base who live, serve, volunteer and support the many local businesses in the area.

Projects like this are essential to maintaining a competitive and sustainable rural economy in Minnesota. Continued investment in agriculture ensures that local businesses can continue to provide jobs, services, and economic stability close to home.

No EIS is needed as the state environmental review process is rigorous and very sufficient. I respectfully encourage your support and approval of this important project.

Sincerely,

John Sertich

Rita Bolluyt **Letter 605**

We are concerned about the increased amount of and area which will be used for manure application. Some of this land will be adjacent to and is tiled to drain to Page Lake--which would contaminate the lake.

Also, the manure application initially and for the first few days--greatly affects the air quality making breathing it unpleasant at best. This seems to be caused by the applicators which when turning at the ends of the fields, raise above the dirt and spread the liquid on top of the ground.

Adam Lichtsinn **Letter 606**

ATTN: Charles Peterson

My name is Adam Lichtsinn, and I am a farmer in Dollymount, Traverse County, MN. I am writing in support of the proposed West River Dairy Expansion.

Based on my experience and observations, Riverview Dairy operates with professionalism, integrity, and environmental responsibility. Their facilities are well-maintained, clean, and organized, and their teams are committed to doing things the right way.

As someone familiar with agriculture in this region, I recognize that manure management and water use are highly regulated in Minnesota. Riverview strives to follow these regulations, including nutrient management planning, soil testing, proper application rates, and timing based on field conditions. From what I have seen, their mindset is to meet and exceed these standards to ensure responsible stewardship.

The use of manure as a nutrient source has clear benefits for local farms, including improved soil health, increased organic matter and reduced erosion. This supports longterm agricultural sustainability.

Riverview has also been a strong community partner, supporting farmers, creating jobs, maintaining roads, and investing in schools and local programs. Their communication with neighbors and officials reflects their commitment to being a good neighbor.

I understand that this project is undergoing environmental review through the state's established process — one of the most rigorous in the region— and provides adequate oversight for this project. Based on the available data, existing regulations, and Riverview's proven track record, I am confident this project can continue to operate responsibly. I believe the current review process is sufficient and that additional regulatory burdens are unnecessary.

In closing, I respectfully encourage the appropriate agencies to approve the West River Dairy Expansion. This project supports local agriculture, strengthens rural communities, and reflects a responsible approach to environmental stewardship. I also believe that an EIS is not necessary.

Sincerely,

Adam Lichtsinn

Paul Tackes **Letter 607**

Minnesota is known for its quality of water. Though industrial pollution is less today than 60 years ago, agricultural and residential runoff has greatly contributed to the decline of water quality.

Recreating by canoe on smaller waters makes one realize how they have deteriorated over the years. Once clear waters are now a soupy, smelly mess by midsummer. While small scale dairy operations are suffering from unsustainably low milk prices it seems counterintuitive to promote large scale dairy operations. These operations force family dairy operations out of business causing declining vitality of small communities all over the farming communities. I digress.

The scale of the factory dairy farms produces so much concentrated waste in a small area that it is always a risk for loss of containment. Historically, small farms could manage the manure and use it on their land with far less risk of watershed or aquifer contamination. That cannot be said for these large scale operations. Concentrated turkey, hog and dairy operations are of great concern to me. I witnessed, living in Montana, how mining operations promised "foolproof" containment only for the taxpayer to pick up the mitigation costs after the company and its well golden parachuted executives were off the hook. How long will it be before I have to operate a costly decontamination system for my well, much less endure the smell and low quality waterways and lakes. I urge that this permit be denied.

Steve Molenaar **Letter 608**

I am concerned about the environmental effects of intensive land use by large farming operations. Rather than be served by a few giant dairies, I feel the public is better off with smaller operations spread throughout the state. The manure can be more widely distributed, resulting is a lessened environmental impact and as a side benefit, the industry will not be controlled by just a few providers.

James Radermacher **Letter 609**

ATTN: Charles Peterson

My name is James Radermacher. I am a resident of Kandiyohi County near Willmar, MN. I am writing in support of the proposed West River Dairy Expansion.

I have been working in the Ag Industry for most of my life. I have been a Certified Crop Advisor since October of 2007. I have also received my Technical Service Provider designation within the last couple of years.

It has been my experience working with crop and nutrient management planning in Minnesota that the regulations currently in place are sufficient to regulate water quality, and environmental impacts of livestock farms in rural Minnesota.

The manure that is produced from the Riverview Dairy facilities has been a valuable resource for the local farms who are located near their locations in my area. It not only provides local crops with valuable nutrients but adds a biological component to the soil producers cannot get with commercial fertilizer alone.

Riverview has become a very beneficial partner for local farms in my area. They provide an opportunity for local growers to participate in harvest operations that helps add an additional revenue source for their operations. They have also been very strong supporters of the local communities that are in the vicinity of their dairies.

From my experience with Riverview, I strongly support the expansion of the West River Dairy site. I have confidence they will follow all regulations and laws that pertain to Environmental Stewardship that will be part of the expansion.

Sincerely,

James Radermacher

Gates Blodgett **Letter 610**

I have worked with Riverview for over 10 years and consider them a key positive contributor to the Minnesota Agricultural sector. They are the gold standard in the dairy business with incredibly efficient, humane and smart operations that produce solid jobs and meaningful community involvement. The expansion of the West River site makes a lot of sense and I know they will be as careful with this project as any of the many dairies they have constructed in the recent past. Riverview's attention to detail, their community engagement, their respect for employees, their careful/humane treatment of cows and their stewardship of the land adjacent to their sites is something that should be honored and encouraged.

Darlene Donahue **Letter 611**

The water usage is a concern. If Morris grows or has dry years, the Dairy using potentially 75% of the water would create problems for the area. I believe the Dairy needs to scale back their size and not ne allowed to use more than 50% of the water. The size is also a concern regarding the land, and water in the area.

Randy Pothen **Letter 612**

My name is Randy Pothen and I farm in Swift County and have lived less than 1 mile from an existing Riverview site for 18 years. The reasons I support the permit for the West River Dairy expansion are as follows.

1. We've farmed for 48 years and I've never seen cleaner, better managed livestock facilities! 2. We have been able to market corn silage and alfalfa to the local dairy instead of shipping many of those acres of production overseas.

3. Alfalfa grown near the dairy sites is fantastic for our soils and gives us another crop for rotation.

4.Manure is applied by injection in the fall and has been a plus for our soil fertility in the area. We have all been reminded recently of the costs involved of shipping crop nutrients, especially nitrogen products, from areas like the Persian Gulf and the Strait of Hormuz.

5. I believe the West River Dairy expansion would be positive for the area and I strongly support the permit.

Sincerely

Randy Pothen

Christopher Spangler, Perspective 180 LLC — Letter 613

ATTN: Charles Peterson

My name is Christopher (Kit) Spangler, and I am the owner of Perspective 180 LLC, a consulting company that has provided consulting services to Riverview LLP. I am writing in support of Riverview's proposed West River Dairy expansion in Stevens County.

My work has been primarily in international business, working with dairies in China and Indonesia. I have had the opportunity to accompany international dairy companies to visit Riverview's operations in the upper Midwest. Riverview is seen internationally as a leader in how to build and operate large scale dairy operations in a responsible and environmentally responsible manner. Because of this reputation, they are frequently asked to host international dairy delegations. From my interactions with Riverview, how they operate their dairies reflects the company culture they have built over several decades. They stress being an asset to any community not only economically, but also socially and environmentally.

Prior to my work internationally, I also operated my own dairy farm for 28 years and worked as a consulting dairy nutritionist for 24 years. That experience allowed me to observe varying management styles of dairies in the upper Midwest. In my opinion, Riverview is without a doubt one of the cleanest operations I have seen, both here in the United States, as well as abroad. They would not operate a dairy without commitment and responsibility to their community.

Sincerely,

Christopher (Kit) Spangler

Perspective 180 LLC

Steven Wendling — Letter 614

We live within 2 1/2 miles of Riverview's Washington Dairy. I farm around this dairy and have nothing but positive views on Riverview. You will not find a cleaner, better managed dairy anywhere. Their manure management system is very well run. Some have worried about township roads including myself, but now we have some of the best township roads due to Riverview taking care of any roads

they use. That includes even completely rebuilding some dirt roads into nice gravel roads. I feel Riverview will be a benefit to any community. They have had lasting beneficial impacts on our community.

Kevin Lundberg **Letter 615**

ATTN: Charles Peterson

My name is Kevin Lundberg and I am a Farmer in Dublin Twp, Swift Co MN, I am writing in support of the proposed West River Dairy Expansion.

Based on my experience and observations, Riverview Dairy operates with professionalism, integrity, and environmental responsibility. Their facilities are well-maintained, clean, and organized, and their teams are committed to doing things the right way.

As someone familiar with agriculture in this region, I recognize that manure management and water use are highly regulated in Minnesota. Riverview strives to follow these regulations, including nutrient management planning, soil testing, proper application rates, and timing based on field conditions. From what I have seen, their mindset is to meet and exceed these standards to ensure responsible stewardship.

The use of manure as a nutrient source has clear benefits for local farms, including improved soil health, increased organic matter and reduced erosion. This supports longterm agricultural sustainability.

Riverview has also been a strong community partner, supporting farmers, creating jobs, maintaining roads, and investing in schools and local programs. Their communication with neighbors and officials reflects their commitment to being a good neighbor.

I understand that this project is undergoing environmental review through the state's established process — one of the most rigorous in the region— and provides adequate oversight for this project. Based on the available data, existing regulations, and Riverview's proven track record, I am confident this project can continue to operate responsibly. I believe the current review process is sufficient and that additional regulatory burdens are unnecessary.

In closing, I respectfully encourage the appropriate agencies to approve the West River Dairy Expansion. This project supports local agriculture, strengthens rural communities, and reflects a responsible approach to environmental stewardship. I also believe that an EIS is not necessary.

Sincerely,

Kevin Lundberg

Former Neighbor **Letter 616**

I am a former resident of Stevens County and neighbor to Riverview. I have many family members in the area and have plans to return to the community. I was also part of the contingency that was successful in requiring a full environmental impact review that shut down their planned expansion south of Chokio in Baker township 10+ years ago. You're Welcome Stevens County! The biggest issue then, as it is now, is water. The aquifer simply wasn't meant to sustain this density of animals.

Stevens County has enough cows. The market is saturated already with Milk. Has anyone taken a critical look into the finances of these megadairies. Milk prices are subsidized by the federal government and the market is saturated. The buildout on these large dairies is in the $50M-$100M range. These expansions are not financed with equity. Why? Because milk prices have never supported $50M-$100M

capital investments. They are financed with new investors and that is why they have to keep building them. Constant expansion to avoid the inevitable collapse when the bill comes due. All of this at the expense of our aquifer and the environment. Essentially a Ponzi scheme to eat up resources and drive out small business and keep milk prices compressed. Definitely not the free markets at work. I am sure that Riverview is a good steward in the community. I can't argue one way or another because I don't live there. If I ran the company I would make sure I invested heavily in making sure the labor and resources I were exploiting felt like they were valued. I saw a lot of comments from local businesses talking about the economic engine that Riverview is and how happy they were doing business with them. It is never good to have your customer base this consolidated. If I were a business and Riverview was my only customer, I am not going to be around long. Riverview will only be around as long as they can find new investors to keep the expansion ahead of the bill.

Karen Hettver **Letter 617**

We are a neighboring resident only a few miles to the West of the West River Dairy.

When they put that first dairy in, our well water started with black silt in the water. We ended up having to dig a brand new well. If they put that many more dairy cows in, that is going to take more water than it is already and more land to get rid of the manure, also we should worry about run off into our streams and lakes.

I am not in favor of the expansion.

Richard and Catherine Tate **Letter 618**

My wife and I are investors in Riverview Dairy for the past 20 plus years. Based on my observations they are professional, have a high level of integrity, and environmental responsibility. There facilities are well maintained, clean, and organized. They are committed to doing things the right way. including manure management. They are a strong community partner, supporting farmers, creating jobs, maintaining roads, and investing in schools and local programs. In closing, we respectfully encourage the appropriate agencies to approve the West River Dairy expansion.This project supports local agriculture, strengthens rural communities, and reflects a responsible approach to environmental stewardship.

Pat Ascheman **Letter 619**

ATTN: Charles Peterson

My name is Pat Ascheman. I am a farmer in Fairfield Township (Holloway), Minnesota, and I have worked with Riverview for many years. I am writing in strong support of the proposed West River Dairy Expansion.

From my long experience working alongside Riverview, I have nothing but respect for their integrity and the way they operate. Their facilities are well-maintained, clean, and organized, and their staff approach their work with professionalism and a clear commitment to doing things the right way.

I know manure management and water use are tightly regulated here in Minnesota. Riverview consistently follows those regulations — nutrient management planning, soil testing, proper application rates, and timing based on field conditions — and, in my experience, strives to meet or exceed those standards. They treat manure as a valuable nutrient source that improves soil health, increases organic matter, and helps reduce erosion, which supports long-term agricultural sustainability in our area.

Riverview is also a strong community partner. They support local farmers, create jobs, help maintain roads, and invest in schools and local programs. Their communication with neighbors and local officials reflects a genuine commitment to being a good neighbor.

I understand the project is under environmental review through Minnesota's established process, which provides robust oversight. Based on Riverview's proven track record, existing regulations, and the available data, I am confident this operation can continue to be managed responsibly. I believe the current review process is sufficient and that an Environmental Impact Statement (EIS) is not necessary.

For these reasons, I respectfully encourage the appropriate agencies to approve the West River Dairy Expansion.

Sincerely,

Pat Ascheman

Donita Ascheman **Letter 620**

ATTN: Charles Peterson

My name is Donita Ascheman. I am a farmer in Fairfield Township (Holloway), Minnesota, and have lived near several Riverview Dairy operations since they began. I have visited their properties many times and have observed their daily operations. Riverview should be commended for maintaining well-managed, controlled, and clean facilities. My husband and I have consistently done business with Riverview, and in every instance they have acted with professionalism and integrity.

As farmers in Minnesota—a state that depends heavily on agriculture—the ability to market corn to Riverview and to receive manure as a nutrient source is essential to our farm business. I support the West River Dairy expansion and believe Riverview has proven, and will continue, to comply with the rules and regulations set forth by the state of Minnesota.

Sincerely,

Donita Ascheman

Mario Alvarez **Letter 621**

Riverview is an excellent company that not only supports its people but also the entire community. It stands out for its commitment to local infrastructure, such as maintaining roads, and for the strong support it provides to farmers. Through its operations, it helps drive economic growth across the entire region.

Schurkey Swanke **Letter 622**

This MUST NOT BE ALLOWED.

That many animals will create an enormous burden on the local and area environment, perhaps the regional environment. They will contaminate air, water, and soil with an excess of waste.

At least as important is that a huge number of animals CANNOT be properly cared-for. This is going to be "cruelty on the hoof". They will use an excess of antibiotics to control disease that wouldn't happen if the critters had appropriate room to move around in, and weren't so concentrated.

John Franey **Letter 623**

Such a large expansion needs to be carefully considered. The environmental impact of a massive increase in the operation of Riverview dairy, while monetarily beneficial, would have potentially irreversible effects on the place we live, and needs to be carefully calculated and researched with a deep sense of stewardship rather than profit.

Mike Koehl **Letter 624**

ATTN: Charles Peterson

My name is Mike Koehl and I am a neighboring farmer in Horton township of Stevens County. I am writing in support of the proposed West River Dairy Expansion.

Based on my experience and observations, Riverview Dairy operates with professionalism, integrity, and environmental responsibility. Their facilities are well-maintained, clean, and organized, and their teams are committed to doing things the right way.

As someone familiar with agriculture in this region, I recognize that manure management and water use are highly regulated in Minnesota. Riverview strives to follow these regulations, including nutrient management planning, soil testing, proper application rates, and timing based on field conditions. From what I have seen, their mindset is to meet and exceed these standards to ensure responsible stewardship.

The use of manure as a nutrient source has clear benefits for local farms, including improved soil health, increased organic matter and reduced erosion. This supports longterm agricultural sustainability.

Riverview has also been a strong community partner, supporting farmers, creating jobs, maintaining roads, and investing in schools and local programs. Their communication with neighbors and officials reflects their commitment to being a good neighbor.

I understand that this project is undergoing environmental review through the state's established process — one of the most rigorous in the region— and provides adequate oversight for this project. Based on the available data, existing regulations, and Riverview's proven track record, I am confident this project can continue to operate responsibly. I believe the current review process is sufficient and that additional regulatory burdens are unnecessary.

In closing, I respectfully encourage the appropriate agencies to approve the West River Dairy Expansion. This project supports local agriculture, strengthens rural communities, and reflects a responsible approach to environmental stewardship. I also believe that an EIS is not necessary.

Sincerely,

Mike Koehl

David Kruize **Letter 625**

100% against this! How can you even consider this without a EIS study when there would end up having 26,397 animals in one site. Where is the common sense? The Pomme De Terre Water shed is nearby.

Trent Timm **Letter 626**

Dear Mr Peterson,

I am writing to express my strong support for Riverview Dairies and their proposed West River Dairy expansion.

Riverview Dairies has consistently demonstrated a commitment to operating clean, well-maintained. and professionally managed facilities. Their dairy operations are orderly, environmentally responsible, and reflective of high standards in animal care and site management. In my experience, their facilities are kept in excellent condition, and they take pride in maintaining their property in a way that positively represents modem agriculture.

Beyond their operational standards, Riverview Dairies provides meaningful benefits to the local community. They create jobs, support local businesses, contribute to the tax base, and strengthen the agricultural economy in the region. Their presence helps sustain rural communities and ensures continued economic vitality.

Based on their track record and the way they manage their existing facilities, I am confident that the West River Dairy expansion will be handled responsibly and with respect for environmental regulations and community standards.

Thank you for your time and consideration. I appreciate the opportunity to share my support for the West River Dairy Expansion.

Sincerely,

Trent Timm

Mark Billstrom **Letter 627**

ATTN: Charles Peterson

I am the president of Lester Building Systems, LLC, an engineered wood-frame building engineer and manufacturer based in Minnesota serving many market sectors, including agricultural operations in Minnesota, like Riverview, LLP. I am writing in support of Riverview's proposed West River Dairy expansion in Stevens County.

Through our work in the agricultural sector, we depend on a strong and stable livestock industry. Operations like Riverview's create consistent economic activity that supports local jobs, drives investment, and allows businesses like ours to grow and reinvest in our communities.

The proposed expansion represents a meaningful economic benefit to the region. It will generate demand for local vendors, support both construction and long-term employment, and contribute to the vitality of rural communities that rely on agriculture.

From our direct experience, Riverview is a professional and reliable partner that contributes positively to the communities where it operates. Their presence strengthens the local economy and supports a broad network of agricultural and service-related businesses.

I have had many opportunities to tour their dairy facilities and never cease to be impressed by the overall operation, the employees, and how well the animals are treated.

Projects like this are essential to maintaining a competitive and sustainable rural economy in Minnesota. Continued investment in agriculture ensures that local businesses can continue to provide jobs, services, and economic stability close to home.

No EIS is needed as the state environmental review process is rigorous and very sufficient. I respectfully encourage your support and approval of this important project.

Sincerely,

Mark Billstrom

Phillip Horsager **Letter 628**

My name is Phillip Horsager, and I am a neighbor, farmer, and business owner in Grace Township, Chippewa County. I am writing in support of the proposed West River Dairy Expansion.

Based on my experience and observations, Riverview Dairy operates with professionalism, integrity, and environmental responsibility. Their facilities are well- maintained, clean, and organized, and their teams are committed to doing things well and respectfully.

As someone familiar with agriculture in this region, I recognize that manure management and water use are highly regulated in Minnesota. All my experience indicates that Riverview strives to follow these regulations, including nutrient management planning, soil testing, proper application rates, and timing based on field conditions. From what I have seen, their mindset is to meet and exceed these standards to ensure responsible stewardship.

The use of manure as a nutrient source has clear benefits for local farms, including improved soil health, increased organic matter and reduced erosion. This supports long-term agricultural sustainability. Riverview has also been a strong community partner, supporting farmers, creating jobs, maintaining roads, and investing in schools and local programs. Their communication with neighbors and officials reflects their commitment to being a good neighbor.

I understand that this project is undergoing environmental review through the state's established process. Based on the available data, existing regulations, and Riverview's positive track record, I believe this project can continue to operate responsibly. I believe the current review process is sufficient and that additional regulatory burdens are unhelpful.

I respectfully encourage the appropriate agencies to approve the West River Dairy Expansion. This project supports local agriculture, strengthens rural communities, and reflects a responsible approach to environmental stewardship. I also believe that an EIS is ill-disposed to benefit the community, the environment, and the State.

Sincerely,

Phillip Horsager

Jeremy Bottelberghe, Redfield LLC **Letter 629**

ATTN: Charles Peterson

My name is Jeremy Bottelberghe, and I am the owner of Redfield LLC, a Concrete Contractor serving agricultural operations in Minnesota like Riverview. I am writing in support of their proposed West River Dairy expansion in Stevens County.

Through our work in the agricultural sector, we depend on a strong and stable livestock industry. Operations like Riverview’s create consistent economic activity that supports local jobs, drives investment, and allows businesses like ours to grow and reinvest in our communities.

The proposed expansion represents a meaningful economic benefit to the region. It will generate demand for local vendors, support both construction and long-term employment, and contribute to the vitality of rural communities that rely on agriculture.

From our direct experience, Riverview is a professional and reliable partner that contributes positively to the communities where it operates. Their presence strengthens the local economy and supports a broad network of agricultural and service-related businesses.

Projects like this are essential to maintaining a competitive and sustainable rural economy in Minnesota. Continued investment in agriculture ensures that local businesses can continue to provide jobs, services, and economic stability close to home.

No EIS is needed as the state environmental review process is rigorous and very sufficient. I respectfully encourage your support and approval of this important project.

Sincerely,

Jeremy Bottelberghe

President

Redfield, LLC

Jeff Karschnik **Letter 630**

ATTN: Charles Peterson

My name is Jeff Karschnik I am an alumni of University of Minnesota Morris and a partner of Riverview Dairy I am writing in support of their proposed West River Dairy expansion in Stevens County.

Operations like Riverview's create consistent economic activity that supports local jobs, drives investment, and allows businesses like ours to grow and reinvest in our communities. This community helps support the University of Minnesota Morris.

The proposed expansion represents a meaningful economic benefit to the region. It will generate demand for local vendors, support both construction and long-term employment, and contribute to the vitality of rural communities that rely on agriculture.

Riverview is a professional and reliable business that contributes positively to the communities where it operates. Their presence strengthens the local economy and supports a broad network of agricultural and service-related businesses.

Projects like this are essential to maintaining a competitive and sustainable rural economy in Minnesota. Continued investment in agriculture ensures that local businesses can continue to provide jobs, services, and economic stability close to home.

No EIS is needed as the state environmental review process is rigorous and very sufficient. I respectfully encourage your support and approval of this important project.

Sincerely,

Jeff Karschnik

Kurt Staples **Letter 631**

My name is Kurt Staples and my family has farmed here for over 100 years. I live 3 miles from West River Dairy, as does my son and his family. First let me address the 1000 lb gorilla, manure. Riverview has done everything in the past to apply the manure in a safe and responsible manner. If there was a issue, it was taken care of. Manure is not so much a waste product but a commodity, it is beneficial to the fields it is applied to and the farmers using it. Next Issue: Water. This is where I am not in support. I live 3 miles from West River and 3 miles from the next well site. Others in our area have seen issues with their wells in the past. Using more water is not an option. My question to those granting said permit is who is to be held responsible if our wells go dry? Is this in writing? And uphold-able in a court of law. For this reason I am not in support of the expansion.

Representative Dave Baker **Letter 632**

Thank you for allowing me to comment. Having worked with this company for a number of years and the level of professionalism and commitment to bring a positive impact on the community I strongly urge this to proceed. Great jobs coming and a wonderful employer!

Kathryn Buendgen **Letter 633**

I live in Stevens County and am concerned about the environmental impact of such a large dairy operation. How will this affect our ground water and the overall usage of water. Has an economic plan been put into place as this will certainly further put smaller herd dairy farmers under additional financial stress. Small farms are the back bone of our agricultural economy. Where will additional farm workers live as there is a shortage of housing in Morris. At this point, I am a big NO until questions can be addressed as to how this is going to affect our ground water and environment. This dairy operation is large enough.

Lucio Minces **Letter 634**

Completely oppose. It blatantly defies common sense that this will not produce unmanageable amounts of manure and in tandem water and soil contamination, and deleterious impact on infrastructure. It would not pass a serious investigation on the environmental and economic impact, so I hope the regulatory entities are serious in reviewing this

Renee Konz **Letter 635**

ATTN: Charles Peterson

As a locally elected school board member in Morris. I am writing to express my strong support for the proposed West River Dairy expansion. In my time with Riverview, I have consistently found the company to be transparent, approachable, and committed to the communities where it operates. When questions arise, Riverview engages in open dialogue and welcomes community members to tour its facilities. This good-faith engagement gives me confidence that Riverview will continue to be a responsible operator as the expansion moves forward.

Riverview's business model is built on collaboration. Hundreds of local farmers work directly with Riverview—growing crops to feed the dairy herd and receiving manure to improve the fertility of their fields. This strengthens individual farm operations and helps keep them viable. Dairy farms like Riverview's also benefit our rural economies. In out-state Minnesota, where economic development opportunities are limited, this kind of sustained, locally rooted investment is essential. Through its investments and employment, Riverview has strengthened our local tax base, helped stabilize enrollment, and generously supported our schools.

Riverview has responsibly managed natural resources in our community, and I am confident that the West River Dairy expansion would be no different. Riverview is passionate about providing opportunities for people, and that starts with a clean and safe environment. I do not believe an Environmental Impact Statement is necessary for the proposed project. I strongly encourage the MPCA and other regulatory agencies to grant Riverview its necessary permits without further delay.

Thank you,

Renee Konz, Morris Area School Board

Judith Derauf **Letter 636**

To the Minnesota Pollution Control Agency:

Enough is enough! Concentrated Animal Feeding Operations are bad for the environment, bad for rural economies, and bad for the animals raised under these conditions. As the state regulatory agency permitting and regulating these operations, you must do more to protect the people of Minnesota from this destructive industry. Is there no upper limit to the number of animals allowed on a CAFO site? Why are these operations getting bigger and bigger when the water and air quality in the areas near these operations is becoming more and more polluted? This is cause and effect and it doesn't take an expert to see that regulations are too slack or are not being enforced.

Regarding, the proposed West River Dairy Expansion I am asking you as an agency to demand a full Environmental Impact Statement for this project. I believe careful analysis needs to be done before issuing a permit for any Concentrated Animal Feeding Operation, but when the number of animals on an existing CAFO is going to be more than doubled a simple Environmental Assessment is not adequate.

Keith Doane **Letter 637**

The expansion is only going to benefits the pockets of its owner and investors. It will not benefit the real stakeholders- the environment and the farmers who need more opportunities in farm business.

Can we even hold Riverview LLP accountable in any case of environment damage in the future? If we cannot guarantee the accountability, then we must not let Riverview LLP have this opportunity to abuse the environment.

Please do not grant this permit to the Riverview, LLP.

Jesper Rosendahl **Letter 638**

I'm very much in favor of this requested expansion project. Riverview is a key driver of financial growth in the region creating many high-quality jobs. Furthermore Riverview is always keeping business ethics for its employees, partners and community to highest standards. Increased dairy production in the US are required to support increased demand for higher quality and healthier foods.

Adam Johnson **Letter 639**

Modern dairy farmers have not only proven that proper wastewater management is possible, but that it is beneficial to the surrounding community, watershed, and the farmers themselves.

Thiago Carvalho **Letter 640**

Disclaimer: I am not employed by Riverview, LLP but I am personally working with them in a separate project.

Having met several decision makers in the company, I know that Riverview puts high priority on the quality of their products and the impacts on its employees and communities. I have high confidence that Riverview is concerned with the societal, environmental, and economic impacts on the Morris community and will do everything in its power to achieve win-win solutions with residents and lawmakers. This expansion project is a great opportunity to provide jobs in a high-quality employer in the area and meet demand for food.

Nedd Knobloch **Letter 641**

ATTN: Charles Peterson

My name is Nedd Knobloch, and I am the owner/operator/employee of an agriculture company with agricultural operations like Riverview. I am writing in support of their proposed West River Dairy expansion in Stevens County.

Through our work in the agricultural sector, we depend on a strong and stable livestock industry. Operations like Riverview's create consistent economic activity that supports local jobs, drives investment, and allows businesses like ours to grow and reinvest in our communities.

The proposed expansion represents a meaningful economic benefit to the region. It will generate demand for local vendors, support both construction and long-term employment, and contribute to the vitality of rural communities that rely on agriculture.

From our direct experience, Riverview is a professional and reliable partner that contributes positively to the communities where it operates. Their presence strengthens the local economy and supports a broad network of agricultural and service-related businesses. I believe and support Riverview's core values and beliefs.

Projects like this are essential to maintaining a competitive and sustainable rural economy in Minnesota. Continued investment in agriculture ensures that local businesses can continue to provide jobs, services, and economic stability close to home. There are multiple examples of communities that lack economic engines like Riverview and the impacts are detrimental.

No EIS is needed as the state environmental review process is rigorous and very sufficient. I respectfully encourage your support and approval of this important project. Riverview's environmental stewardship is far and above than any other I have experienced. I would have no concern with the expansion.

Sincerely,

Nedd Knobloch

Seth Berg, Sentry **Letter 642**

ATTN: Charles Peterson

My name is Seth Berg, and I'm with Sentry. Our company does millwright work, roll-off container service, and crane work for ag operations, including Riverview.

I'm writing in support of their expansion at West River Dairy in Stevens County.

Work like this matters to businesses like ours. Projects like Riverview's keep guys working, keep equipment moving, and support a lot of local vendors and contractors. It's not just one operation—it has a ripple effect across the whole area.

From what we've seen working with Riverview, they run a solid operation and are good to work with. They know what they're doing and handle things professionally.

In my opinion, the current environmental review process is more than adequate, and I don't see a need for an additional EIS. I'd encourage you to approve the project.

Sincerely,

Seth Berg

Taya Hemphill **Letter 643**

Please assess properly what this will do to not only the land but also small businesses and Minnesota as a whole.

Brooke Reynolds **Letter 644**

I oppose having this giant CAFO in Minnesota. These sprawling industrial facilities jeopardize our natural resources, animal welfare and public health.

The environmental harm caused by these massive operations is especially troubling. At Riverview's proposed facility, vast quantities of manure would generate significant greenhouse gas emissions and likely seep into nearby waterways, posing a threat to our state's iconic lakes and rivers. This risk is reinforced by Riverview's history of manure spills in western Minnesota.

That pollution also threatens the health of Minnesotans. Manure runoff can contaminate drinking water with nitrates, which is especially dangerous for infants. It also releases phosphorus that can lead to algae blooms, making lakes unsafe for swimming. In 2015, a child was hospitalized and a dog died after exposure to toxic algae while swimming in an Alexandria lake. Tragedies like this are preventable by curbing agricultural runoff.

Marlowe Engler **Letter 645**

I support the West River Dairy

Nicole Wallace **Letter 646**

Please do not bring suffering that comes with this type of farm to people, animals, environment.

Just say no!

Travis Miller **Letter 647**

I am writing in support of Riverview's West River Dairy expansion. My family has known and worked with the Riverview group for many years and in a variety of different capacities, and we have consistently found them to be professional, responsible, and committed to excellence.

In 2018, Riverview constructed a 10,000-head dairy near Campbell, Minnesota (Campbell Dairy). Since that time, I have seen firsthand the positive economic impact they have brought to the surrounding area. They are a strong economic driver, providing meaningful employment opportunities for local residents and contributing to the overall strength and stability of the rural economy.

Beyond job creation, Riverview adds significant value to local agriculture. Their dairies create an additional, reliable end user for grain, giving farmers more market opportunities and stability. They also help improve the land by putting nutrients back into the soil, which supports healthier, more productive farmland over time.

Another aspect that stands out is how clean, organized, and well-maintained their sites are. Their facilities are operated with a high level of care and attention to detail, reflecting their respect for the land, the community, and the people they work with.

Riverview's team is made up of honest, hardworking, and passionate individuals who take pride in their work and remain mindful of their neighbors and the broader community. They operate with integrity and a clear commitment to doing things the right way.

I firmly believe that Riverview has made the land, roads, schools, and community stronger since establishing operations in our area. They are exactly the kind of neighbor and partner that rural communities benefit from, and I fully support their continued growth and expansion.

Erin Larson **Letter 648**

Dear Commissioner Kessler and MPCA Staff,

I am writing to express my support for the proposed expansion of West River Dairy near Morris, Minnesota. Having followed this process and reviewed the comments of neighbors, farmers, environmentalists, and agricultural organizations who know Riverview's operations firsthand, I am confident that this expansion represents not only a sound economic investment in our region, but a genuine step forward for environmental stewardship in Minnesota agriculture.

A common misconception is that expanding livestock operations is inherently at odds with environmental protection. The reality is exactly the opposite when the operator is as committed to best practices as Riverview has proven to be. Today's dairies operate in a vastly more regulated and technologically advanced environment than previous generations. Riverview employs precision nutrient management planning, rigorous soil testing, controlled manure application schedules tied to field conditions and seasonal timing, and data-driven monitoring systems that continuously verify environmental compliance.

One particularly compelling environmental benefit of this expansion is water stewardship. As noted by supporters familiar with Riverview's infrastructure, more than half of the water used during normal rainfall years comes from captured impervious surface runoff stored on-site. This kind of forward-thinking water management is exactly the approach we should be encouraging in Minnesota agriculture, and it sets a model for the entire industry.

Perhaps the most under-appreciated environmental benefit of these well-managed dairies is what happens to the manure. Far from being a pollutant, manure managed according to Minnesota's nutrient management standards becomes a valuable agricultural resource. Certified Crop Advisors and farmers in the region surrounding Riverview's existing facilities have documented real improvements in soil health, including increased organic matter, better soil structure, and reduced erosion. These may be outcomes that no commercial synthetic fertilizer can fully replicate.

This project is not proceeding without scrutiny. It is undergoing one of the most thorough environmental review processes available in state government. Multiple farmers, agronomists, and community members who have worked alongside Riverview for years have affirmed in their comments that the company's mindset is not merely to meet regulatory minimums but to exceed them. The MPCA's existing permitting and oversight framework, including nutrient management plan requirements, manure application restrictions, setbacks, and monitoring obligations, is specifically designed for farms like this one. Requiring an Environmental Impact Statement beyond the already comprehensive Environmental Assessment Worksheet process would be redundant given the available data and Riverview's well-documented compliance history.

Rural communities like Morris and Stevens County depend on operations like West River Dairy to sustain local economies, keep family farms viable through crop and harvest partnerships, and support the schools, businesses, and infrastructure that make rural life possible. But these economic benefits do not come at the expense of the environment - they are paired with it. Riverview's long-standing working relationship with the MPCA, its transparent engagement with neighboring landowners, and its

consistent investment in environmental improvements demonstrate that responsible growth and environmental protection reinforce each other.

Approving this expansion sends exactly the right signal: that Minnesota welcomes responsible agriculture and that operators who do things the right way will be able to grow and continue serving their communities.

I respectfully urge the Minnesota Pollution Control Agency to approve the West River Dairy Expansion. The environmental safeguards in place are rigorous. Riverview's track record is strong. The benefits to soil health, water stewardship, nutrient recycling, and the broader regional agricultural ecosystem are real and well-documented. This is the kind of project the permitting process was designed to review and approve and it deserves to move forward.

Sincerely,

Erin Larson

Emily Johnson **Letter 649**

It is vital that the Riverview Dairy be required to submit an environmental impact statement. It is nearly twice as big as any current operations in the state, and its environmental harm would be enormous. Here's what we know now.

• Massive water use: Riverview would pump up to 226 million gallons/year from an off-site well—nearly as much as the entire City of Morris (permitted for 300 million gallons/year for 5,000+ residents).

• Huge waste output: The facility would generate about 202.7 million gallons of liquid manure and wastewater annually, plus 26,400 tons of solid manure.

• Unknown groundwater impacts: The DNR hasn't begun the hydrologic survey or completed the County Geologic Atlas for Stevens County, so aquifers and groundwater resources aren't mapped—making it risky to permit large withdrawals now.

• Sensitive, already-impaired waters: The expansion sits in the Pomme de Terre watershed, designated sensitive; the nearest waters—the Pomme de Terre River and a nearby unnamed creek—are already listed as impaired. The project would likely worsen these impairments. Advancing permits without a full understanding of groundwater and water-quality risks is irresponsible. It is critical that the MPCA require a full Environmental Impact Statement.

Sarah Super **Letter 650**

I strongly oppose the West River Dairy Expansion.

Amanda Churchill **Letter 651**

Hello,

I am writing to express my deep concern about and strong opposition to this proposed dairy expansion. I oppose factory farms (CAFOs), as they jeopardize our natural resources, animal welfare and public health.

Countless dangers would come with this expansion, like polluting air and waterways, rural residents facing health risks in proximity to a factory farm, crowded conditions and spreading of zoonotic diseases, not to mention the greatly increased animal suffering.

This is unsafe for all of us. Please hear the voices of concerned Minnesotans, speaking for ourselves and for animals and the earth.

Thank you.

Claire Lienesch **Letter 652**

Hello,

I am very concerned about this proposed expansion due to the effects on the animals themselves and the neighbors' air and water quality. CAFO operations routinely disrupt the quality of life of the surrounding people due to the amount of waste a concentrated amount of animals produce, not to mention the accompanying issues like increased traffic by milk tanker trucks. I also highly doubt this many animals on one farm can live a healthy, disease-free life.

Please know I am a big-time dairy fan- my family drinks about 2 gallons a week of milk- and I am very much opposed to this project. Please study the issue to determine if this many animals can live in close quarters without disrupting the air, water, and quality of life of the people in the surrounding area.

Thank you!

Claire Lienesch

Wendy Pilot **Letter 653**

Public Comment to the Minnesota Pollution Control Agency

Re: Opposition to Proposed Largest Factory Farm in Minnesota History

To Whom It May Concern,

I am writing to strongly oppose the proposed construction of what would be the largest factory farm in Minnesota's history. The sheer scale of this facility makes my concerns even more urgent.

First, a factory farm of this magnitude would pose an unprecedented environmental threat to our state. The enormous volume of waste generated would put our waterways, air quality, and ecosystems at far greater risk than anything Minnesota has seen before. Once that damage is done, it cannot easily be undone.

Second, despite its massive size, this type of operation is notorious for offering low-wage, unsafe working conditions. Employees often from vulnerable communities face physical hazards, limited benefits, and little job security. Bigger does not mean better for Minnesota workers.

Finally, a facility of this scale would subject an extraordinary number of animals to severe and inhumane conditions, confining them in overcrowded spaces with no regard for their welfare. This is simply not in line with the values Minnesotans hold dear.

We have one chance to stop this before it is built. I urge the Agency to deny this proposal and protect our land, our people, and our animals.

Respectfully,

Wendy Pilot

Ken Koehl **Letter 654**

Ken Koehl

Stevens county resident

I strongly support moving forward with the expansion of the west river dairy. I live 1 mile away from the d45 dairy, Riverview is very capable of handling this expansion in professional manner they take care of the manure according to mpca rules and dont cut corners. Riverview is a benefit to rural economy's providing farmers with high quality fertilizer and a better basis for corn.

A EIS is not necessary for this project Riverview wants the best for the environment and neighbors.

Please move forward with the project I support.

Jocelyn Bullock **Letter 655**

Hello,

These mega farms are horrific.. have you not seen the footage? Because many still refuse to acknowledge animals as feeling creatures with rights to live free from cruelty I will share. Mother cows are impregnated bu human hands which is disgusting over and over so they get pregnant. Then people drag their newborn calf away while the mother bellows for weeks. They kill the calf often just letting them die in a pile or smashing their heads. Some get to live in a crate to become veal or grow a little to become milk producers. They are beaten even sexually assaulted. Yes it's true. Underpaid workers often vent on these poor animals. The air is terrible and they are loosely regulated. Huge polluters these mega farms are. The air and the ground. All the irons and fecal matter gets spread around to eventually destroy rivers and streams. We should be getting off animal products as they are inhumane and unsustainable. People don't want this. Please do your research.

Watch some footage. It's not all about money.

It's a no

Jocelyn Bullock

Kimberly Ped **Letter 656**

Please do NOT allow this to be built. This is absolutely irresponsible and unethical in every way.

Briana Isiminger **Letter 657**

I vehemently oppose this. It is horrific.

The pollution from such a large number of cows is well documented. Not to mention, how would they ensure the humane treatment of over 18,000 cows and how would the state enforce this? Is there oversight for what will be done with all of the non milk producing calves born to these 18,000 cows?

Rylee Erickson **Letter 658**

I am submitting this comment in strong support of the West River Dairy expansion and the issuance of the NPDES Individual Feedlot Permit for this Project.

I have been around Riverview for 7+ years — from participating in their dairy heifer leasing program for 4-H, to benefiting from Riverview's Scholarship program and internship program, to now being a full-time employee. Through all of it, I have had nothing but full faith that Riverview is bettering agriculture and helping the communities where their sites are located. I have also lived in Swift County for 20+ years, where three of Riverview's sites operate. I have seen firsthand how this company conducts itself

as a neighbor and as an employer, and that experience matters to me when I say: this is a company that does things the right way.

The permitting process in Minnesota is extremely rigorous, and the submittal for this Project reflects that. The EAW and its attachments represent over 500 pages of research, analysis, and documentation — including not just internal work, but findings from independent third-party firms such as Barr Engineering for air quality modeling, American Engineering Testing for soil borings and groundwater analysis, Moore Engineering for a historic river flow study, and Agassiz Archaeology for a Phase I archaeological assessment. This is not a rubber-stamp process. It is a thorough, multi-agency review that involves the MPCA, the DNR, the Minnesota Department of Health, the State Historic Preservation Office, the U.S. Fish & Wildlife Service, and Stevens County — all of whom have been engaged throughout this process.

The facts documented in the EAW show a company that consistently goes beyond what is required. Manure storage capacity is designed at 14 months — more than 50% above the 9-month state minimum. The clay liners for the liquid manure storage areas will be 60 inches thick, triple the standard requirement. Stormwater basins are sized more than 20% larger than the minimum required for a 25-year storm event. Independent air quality modeling confirms that odor at nearby residences will remain below the threshold for even faint odors 100% of the time. And post-construction, the Project will actually reduce stormwater sediment discharge from 0.41 tons per acre per year to just 0.05 — leaving the watershed in better condition than it is today.

More than 16,500 acres of cropland have been identified for manure application — over 3,000 acres more than needed annually — providing a buffer that protects neighboring landowners and water resources. Every one of those acres was reviewed using DNR ecological databases, SHPO archaeological records, and state soil and water quality standards before being included.

I encourage all reviewers to take the time to carefully read what has been submitted for public notice. The depth and quality of this submittal speaks for itself.

I respectfully urge the MPCA to issue the West River Dairy expansion permit.

Thank you for your consideration.

Rylee Erickson

John Klein **Letter 659**

To create an area of 26,000 cows is an environmental disaster waiting to happen. Please do not approve such a blow to the average dairy farmer and their conservation practices.

Eric Smith , Flatland Custom Forage LLC. **Letter 660**

ATTN: Charles Peterson

Subject: Support for West River Dairy Expansion

My name is Eric Smith, and I own and operate Flatland Custom Forage LLC and Flatland Farms LLC in Cleveland Township, Lake Norden, SD (Hamlin County). I am writing today to express my full support for the proposed West River Dairy Expansion.

As a local business owner and farmer, my operation is deeply integrated with the dairy industry. We handle all the forage harvesting for Riverview's Garfield Dairy and grow a significant amount of corn and alfalfa specifically for their operations. Based on my direct experience, Riverview operates with an

unmatched level of professionalism and environmental integrity. Their facilities are impeccably maintained, and their team is dedicated to doing things the right way.

In my experience with agriculture in this region, I see firsthand that Riverview doesn't just follow regulations, they strive to exceed them. Whether it is nutrient management planning, soil testing, or precise application timing, their mindset is rooted in responsible stewardship. The use of manure as a nutrient source has provided clear benefits to our local land, improving soil health and organic matter while supporting long-term sustainability.

Beyond the environmental aspects, the economic impact on our rural community cannot be overstated. These dairies provide vital opportunities for the next generation of farm kids to return to the family business—opportunities that simply would not exist otherwise. My own business growth and ability to come back to the farm would not have been possible without Riverview's presence in our area. They reward those willing to work hard and commit to efficiency and quality; if you are dedicated to excellence, Riverview is a loyal partner that stands by your side.

I understand this project is undergoing a rigorous environmental review process. Based on Riverview's proven track record and the existing regulatory oversight, I am confident they will continue to operate responsibly. I believe the current review process is sufficient and that an EIS is not necessary.

I respectfully encourage the appropriate agencies to approve the West River Dairy Expansion to continue supporting local agriculture and the families who depend on it.

Sincerely,

Eric Smith

Deborah Jindra **Letter 661**

I strongly oppose the expansion of the West River dairy due to the environmental and health risks, as well as the animal cruelty. There should never be this many animals in one spot and the pollution to our water and air is unacceptable in a state that values natural resources. Sensible animal husbandry can provide the needs to our community without using "factory" methods, which are inhumane and unworthy of Minnesotans. I will gladly pay more for my gallon of milk if I know that it is sourced from a responsible producer. I also reject the idea that this facility can deal with the massive amount of waste in a sustainable fashion. Please do not let this expansion proceed.

Julie Greenwood **Letter 662**

After reading through many comments, it appears that Riverview is a responsible corporation. That being said most of the positive comments are also from people who will directly or indirectly benefit from this expansion. My biggest concern is the environmental impact to the area, primarily water quality. The health and welfare of livestock, and the impact on smaller farms is also a concern. An EIS is definitely needed for a project of this size.

Laura Haule **Letter 663**

My concern is the enormous size of this project, which would seem to increase the impact on a variety of environmental factors. I think a full environmental review is warranted to evaluate the potential air and water pollution, soil and groundwater runoff, energy use, even noise pollution. I am concerned about animal welfare in a project of this magnitude.

Jerry Nelson **Letter 664**

ATTN: Charles Petersen

My name is Jerry Nelson, and I am a farmer in Norway Township, Roberts County, Veblen SD. I am writing in support of the proposed West River Dairy Expansion.

I've been growing silage corn for the East and West Marshall Dairy by Veblen SD for several years.

They have been applying manure on my land with awesome results for my crops. They soil test and send me results to share with my crop consultant. This allows me to manage my crop nutrient inputs effectively.

They have been instrumental in maintaining our township roads when needed because of wet fields, by graveling our roads where needed because of wear & tear from hauling silage.

I have experienced a better profit margin since I have been raising corn for the Marshall Dairy. This has been very beneficial for my operation, because I am not a large operation.

I am also a volunteer fireman. The Marshall Dairy has donated money for repairing our cement apron in front of the fire truck garage. Also donating money for our fundraisers.

I feel your community will benefit greatly from Riverview Dairy.

Sincerely, Jerry J Nelson

Connie Roche **Letter 665**

I am from Winona and was very aware of the Daley Farm request from Lewiston, MN to increase their dairy expansion. On the same vein, I believe this request would have a great impact not only on local farms but also the great possibility of manure run-off and contamination of groundwater and wells.

Having worked as a Public Health Nurse in Winona County, such a huge operation has health risks for the general population specifically that of bird flu and swine flu.

Treasuring our lakes in the state should be a high priority for all and contamination of our lakes and streams is not a route that we want to take.

Linda Vest Klein **Letter 666**

Please do not approve this expansion. It harms the water and air. It also harms the animals themselves through the inhumane, unnatural treatment of the living beings. And what is the purpose when there's a global OVERSUPPLY of milk?

Thank you for your consideration.

Brian and Betty Rinke **Letter 667**

This letter is being composed in support of the proposed West River Dairy Expansion. My name is Brian Rinke. My wife Betty and myself are residents of Dollymount Township. We live on a third generation farm located 2 miles from the Riverview Dollymount Dairy and are still actively farming mainly due to the opportunities that have been made available by having this facility in our location. We have become a smaller operation due to the fact that finding labor has become a significant issue. Being able to have our corn acres harvested for silage and receive manure for fertilizer has been a blessing allowing us to continue operating on a smaller scale.

We have been working with Riverview Dairy since 2017 and have nothing but positive things to say about this interaction. We have always been very impressed by the appearance and upkeep of the facility and grounds. To us, this only emphasis the organizational skills that are involved in making this happen. This also makes me more confident in Riverview's commitment to make sure that procedures are held in accordance with Minnesota regulations on manure and water management.

Riverview has been a very strong supporter of our community by investing in several of our local projects and organizations and always welcome and encourage any individual or groups to tour their facilities. They have helped us maintain and improve many of our township roads.

We are encouraging approval of the West River Dairy Expansion as we are confident of Riverview's commitment to operate within the necessary regulations. The environmental review should be a sufficient enough process without an unnecessary EIS.

Respectfully submitted,

Brian and Betty Rinke

Nick Hendrickson **Letter 668**

I live in Bryant South Dakota and we have a Riverview dairy 1 mile east of town and another one 4 miles west of town. It has been such a blessing having Riverview come to our area. Their sites are always so neat and clean. The employees are always a pleasure to work with. They have had such a positive impact on our little town. Here is a few things that come to mind. (They have staff that joined the local fire department and donate lots of time, they have donated so much to our local parks, they built several new houses in the area, they support the local businesses, they hire local contractors, they are one of the largest property taxpayers in our county, they attend and support all kinds of local events that happen). There is no doubt many more things that they have positively contributed to this area, and for what it's worth I hope they build many more in Hamlin County.

Micah Norman-Pace **Letter 669**

CAFO operations are harmful for not just the sentient animals who feel pain, fear, and stress, but is also bad for the workers and environment. Workers are often harmed through lax regulation of safety (see JBS plant strike and plenty of other documentation) and through the PTSD of slaughtering thousands of animals. The environmental conditions devastate the living conditions of surrounding properties and households, impacting water supply and breathable air. For me, no factory operation is ethical, but one of this size and scale are easy for all people to be against.

Peg Honkomp **Letter 670**

Being an organic home Gardner for over 50 years I know the importance of toxins, water health, and animal health! All affect my environment and what is done farther from my home DOES have affects locally.

The potential for overcrowding and disease is tremendous especially on a project this size. Open a separate farm somewhere else-they don't because it would cost the company more and lower profits all with no concern for the actual animals and the environment. We can and should do better for our State and health of our extended communities.

Thank you.

Dale Kennen **Letter 671**

I grew up on a dairy and hog farm in Chisago County Minnesota, graduated from the U of M College of Agriculture and worked as an investigator with the U.S. Food and Drug Administration for 30+ years. During those 30+ years, I spent 20 years in CA working alongside of USDA meat inspectors. We had a terrible time with cull dairy cows and male calves being sold for human consumption with residues of drugs and antibiotics in their meat. Those large dairy CAFO's could not, or would not, monitor the various drug withholding times to ensure that the animals were residue free before selling them for slaughter. They had too many other concerns to worry about humans ingesting drugs and/or antibiotics.

The disposing of the manure on these large CAFO's is, and will continue to be, a major concern and problem. The ground can handle only so much before runoff into waterways and seepage into aquifers takes place. And it is bound to happen when you have manure from thousands of cattle to dispose of.

I certainly hope that at the very least you require an Environmental Impact Statement before final decision is made. Otherwise the permit should definitely not be approved.

Rachel Scherf, Davis Immigration Lawyers **Letter 672**

ATTN: Charles Peterson

My name is Rachel Davis Scherf, and I am a Partner at Davis Immigration Lawyers PPLC, an immigration law firm serving agricultural operations in Minnesota like Riverview. I am writing in support of their proposed West River Dairy expansion in Stevens County.

Through our work in the agricultural sector, we depend on a strong and stable livestock industry. Operations like Riverview's create consistent economic activity that supports local jobs, drives investment, and allows businesses like ours to grow and reinvest in our communities.

The proposed expansion represents a meaningful economic benefit to the region. It will generate demand for local vendors, support both construction and long-term employment, and contribute to the vitality of rural communities that rely on agriculture.

From our direct experience, Riverview is a highly professional and reliable partner that contributes positively to the communities where it operates. Their presence strengthens the local economy and supports a broad network of agricultural and service-related businesses.

Projects like this are essential to maintaining a competitive and sustainable rural economy in Minnesota. Continued investment in agriculture ensures that local businesses can continue to provide jobs, services, and economic stability close to home.

No EIS is needed as the state environmental review process is rigorous and very sufficient. I respectfully encourage your support and approval of this important project.

Sincerely,

Rachel Davis Scherf

Michael H. Davis, Davis Immigration Lawyers **Letter 672**

ATTN: Charles Peterson

My name is Michael Davis, and I am the Managing Partner at Davis Immigration Lawyers PPLC, an immigration law firm serving agricultural operations in Minnesota like Riverview. I am writing in support of their proposed West River Dairy expansion in Stevens County.

Through our work in the agricultural sector, we depend on a strong and stable livestock industry. Operations like Riverview's create consistent economic activity that supports local jobs, drives investment, and allows businesses like ours to grow and reinvest in our communities.

The proposed expansion represents a meaningful economic benefit to the region. It will generate demand for local vendors, support both construction and long-term employment, and contribute to the vitality of rural communities that rely on agriculture.

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No EIS is needed as the state environmental review process is rigorous and very sufficient. I respectfully encourage your support and approval of this important project.

Sincerely,

Michael H. Davis

Sandra Sween **Letter 674**

I do not think that large an expansion is necessary small farmers in the area would be impacted also bad environmental damage. neighbors near there would be subjected to noise and odor due to this expansion.

John Riley, John Riley Construction, Inc. **Letter 675**

ATTN: Charles Peterson

My name is John Riley, and I am the owner of John Riley Construction, a construction contractor that works alongside agricultural operations throughout Minnesota, including Riverview. I am writing to express my strong support for the proposed West River Dairy expansion in Stevens County.

Operations like Riverview play a key role in sustaining rural economies by creating jobs, encouraging local investment, and supporting the growth of businesses like ours that provide essential services to the agricultural sector. The planned expansion will deliver clear economic advantages to the area. It will increase opportunities for local suppliers and help strengthen the overall economic stability of communities that rely heavily on agriculture.

In our experience working with Riverview, they have consistently operated with professionalism and integrity. They are a trusted partner whose presence benefits not only agricultural producers but also a wide range of local businesses and service providers.

For these reasons, I strongly urge you to approve this project. Continued investment in agriculture is critical to preserving the strength and sustainability of rural Minnesota. Supporting this expansion will help ensure that local communities remain vibrant, economically stable, and well-positioned for the future.

Thank you for your consideration.

Sincerely,

John Riley

Lenny Stahl **Letter 676**

Agriculture must be supported, and projects like the proposed expansion of West River Dairy are important to the strength and future of rural Minnesota. Dairy farming is a vital part of our economy, our communities, and our food system. If we want agriculture to remain strong for the next generation, we need to support responsible growth opportunities like this one.

Based on the Environmental Assessment Worksheet, this project appears to have been carefully thought through with meaningful attention given to manure storage, water use, stormwater management, and land application. The covered liquid manure storage basins, clay-lined basins, water storage basins, and pumping limits tied to river flow conditions all show that this expansion is not being approached carelessly, but with planning and accountability.

Agriculture is already under enough pressure from regulations, costs, labor challenges, and public criticism. When a farm is willing to invest, grow, and follow the environmental review process, that effort should be recognized and supported. West River Dairy's expansion represents a major investment in agriculture, local jobs, and the rural economy of west central Minnesota.

I support this project and encourage the MPCA to allow it to move forward. Minnesota should be a place where responsible agricultural expansion is welcomed, not discouraged. Supporting this project is one way to support farmers, rural communities, and the future of agriculture in the state.

Mark Martens, Agri Placements International Inc **Letter 677**

On behalf of Agri Placements International Inc, I am submitting this comment regarding the draft Environmental Assessment Worksheet for the proposed West River Dairy Expansion in Stevens County.

Our company supports the continued development of Minnesota's dairy and agricultural economy, and we encourage the MPCA to complete a thorough review of the draft EAW and to ensure that any final approvals and permit conditions protect groundwater, surface water, air quality, and surrounding land uses.

We have a longstanding history of assisting Riverview in accessing its workforce, and the farm, in our experience, always focuses on "doing the right thing", taking care of people and animals, and improving conditions for all parties involved. We support allowing the project to proceed through the normal review and permitting pathway, provided the MPCA determines that applicable legal and environmental standards can be met and maintained.

Thank you for the opportunity to comment.

Brian D. Gjerde, I&S Group, Inc. **Letter 678**

c/o Charles Peterson

RE: Riverview Dairy – West River Dairy Expansion EAW Public Comment

I am writing on behalf of I&S Group, Inc. (ISG) in support of the Environmental Assessment Worksheet prepared for Riverview Dairy. Our firm has provided engineering services for Riverview Dairy at multiple locations, and we are familiar with their facilities, operational practices, and approach to environmental compliance.

Based on our direct involvement, Riverview Dairy consistently demonstrates a commitment to responsible project development, regulatory compliance, and proactive environmental management. The facilities and systems evaluated in the EAW reflect sound engineering design, use proven technologies, and follow established standards commonly applied to modern dairy operations in Minnesota.

The analyses and mitigation measures presented in the EAW align with industry best practices and, in our professional opinion, provide an appropriate and technically sound basis for evaluating potential environmental impacts. Through past projects, we have found Riverview Dairy to be responsive to agency input and willing to refine designs and operations to address environmental considerations.

For these reasons, we support the adequacy and conclusions of the EAW and believe it appropriately supports informed decision-making for the proposed project.

Thank you for the opportunity to submit comment.

Sincerely,

Brian D. Gjerde, PE

Mother Nature **Letter 679**

Hello, Many comments made during this public comment period point to Riverview being well run and following the Minnesota laws. No reason to argue with that. Many also then mention that because they are following Minnesota's laws, the environmental impact is reasonable. HA! That is where we need to dig a little deeper. Right now Minnesota does not require an Environmental Impact Study. Any time residents/ citizens have been successful (like Baker township 10-15 years ago) in requiring an Environmental Impact Study, Riverview has turned to other communities that are either desperate or lethargic enough to not ask if these feedlots impact their environment.

Common sense tells us that this many animals will have an impact, common sense also tells us the milk market does not need more milk. In a scenario like this we are just robbing peter to pay paul. Why not spend the time to see how these short sited economic decisions impact where we live?

Ann Hostler **Letter 680**

C/O Charles Peterson

Regarding: Public comment for proposed dairy expansion, West River Dairy, in Stevens County

Riverview LLP is proposing to expand in Steven's county (West River Dairy Expansion). I am a farmland owner 15 miles away from this CAFO.

It is important to study the impact of this expansion and requires an EIS.

We who own land know that pollution from these CAFOs are impacting our ground water, our land, health and our communities. The Pomme de Terre River watershed is within25 miles from its confluence with the Minnesota River, as an example. In addition, the Minnesota Department of Natural Resources does not have a complete map of Stevens County groundwater resources and aquifers.

Accountability is the job of MPCA. Do not allow this expansion based on unknowns.

EIS needs to be completed before expansion.

Sincerely,

Ann Hostler

Randy Dooley, Dooley's Petroleum **Letter 681**

To whom it may concern,

I am writing in support of the proposed 11,000 cow dairy feedlot in Section 1 of Synnes Township in Stevens County. As someone who works closely with agricultural producers and rural businesses, I believe it is important to recognize projects that strengthen our local economy while demonstrating responsible planning and long-term commitment to the communities they serve. Thoughtful agricultural development is essential to preserving rural vitality, and this proposal represents an opportunity to do exactly that.

One of the most meaningful contributors to that economy in Stevens County is Riverview Dairy. Riverview Dairy has made significant and lasting contributions to the local economy through job creation, capital investment, and ongoing support of local businesses. Beyond their economic impact, they have consistently demonstrated commitment to the communities in which they operate and have proven to be responsible stewards of the land and natural resources.

Dooley's Petroleum has been a fuel and propane provider to Riverview Dairy for several years. Through this business relationship, our company and employees have directly benefited from Riverview Dairy's growth and continued investment in the region. Their success supports not only agricultural operations but also local service providers, suppliers, and workers throughout the rural economy.

In closing, I believe Riverview Dairy's proposed expansion reflects the type of responsible agricultural growth that benefits Stevens County both now and into the future. Their track record of economic contribution, environmental stewardship, and community involvement demonstrates that they are a trusted partner in rural development. For these reasons, we respectfully express our support for this project and encourage decision-makers to recognize the positive impact it will have on our local economy, workforce, and agricultural sustainability.

Sincerely,

Randy Dooley

Dooley's Petroleum

Brandon Efraimson, Efraimson Electric Letter 682

ATTN: Charles Peterson

My name is Brandon Efraimson, and I am the owner Efraimson Electric, an Electrical Contractor serving agricultural operations in South Dakota like Riverview. I am writing in support of their proposed West River Dairy expansion in Stevens County.

Through our work in the agricultural sector, we depend on a strong and stable livestock industry. Operations like Riverview's create consistent economic activity that supports local jobs, drives investment, and allows businesses like ours to grow and reinvest in our communities.

The proposed expansion represents a meaningful economic benefit to the region. It will generate demand for local vendors, support both construction and long-term employment, and contribute to the vitality of rural communities that rely on agriculture.

From our direct experience, Riverview is a professional and reliable partner that contributes positively to the communities where it operates. Their presence strengthens the local economy and supports a broad network of agricultural and service-related businesses.

Projects like this are essential to maintaining a competitive and sustainable rural economy in Minnesota. Continued investment in agriculture ensures that local businesses can continue to provide jobs, services, and economic stability close to home.

No EIS is needed as the state environmental review process is rigorous and very sufficient. I respectfully encourage your support and approval of this important project.

Sincerely,

Brandon Efraimson, Owner

Jerry Lindor **Letter 683**

i do not think one farm should have thst many animal units on one site. A dairy farm this size would keep any young farmers from ever getting a chance to farm . They buy any land that comes up for sale and they increase the rent in the land they do not own . This country was built on small family farms .The communities suffer when u have these mega farms . The churches will close the schools will close because they control all the land and they chase everyone away . If we have to have these big dairy farms let's at least spread them around do they don't completely dominate the community. Thsnk you Jerry Lindor

Tom Walsh **Letter 684**

To whom it may concern

I have had the opportunity to live very close to several riverview sites and wittnes first hand all of the activities

Animal care

Environmental stewardship

Neighbor relationships

Community interactions

The list is long and from what I see it's top notch

I am involved with riverview so it might seem like my comments are biased but my family has been in this community for generations and I hope to continue that on to the next so I would never be a part of something that would put that in jeopardy

Since this is a environmental issue as far as the mpca goes I can tell you that having livestock in the area is a good thing for the environment

And many safe gaurds are In place to insure that Livestock farms of all sizes are such a important part of our rural communities

Please consider your decisions carefully and understand that we have very good environmental protection rules already in place to protect our great state and rural communities

Thank you for your consideration

Judith Riley **Letter 685**

Thank you for this opportunity to comment on the West River Dairy Expansion.

I am not a farmer. I have never even milked a cow.

While I care about the environment and the impact a particular operation might have on it, my knowledge and experience with this type of issue is minimal at best.

What I do know, with more than 50 years of experience working with a variety of individuals and businesses in the area of public relations and communication, is whether or not those individuals or businesses have integrity, work and operate responsibly, and consider the effect they have on those around them.

My knowledge of Riverview comes from an entirely different perspective. I am a townhome owner in one of the many Morris neighborhoods that Riverview is developing. In my experience working with Riverview as they construct and manage new properties in our townhome community, I am impressed even on this small scale with Riverview employees' concern about the impact that their presence has on the existing homeowners. They have consulted with us and included us in the conversation as they build new townhomes in our neighborhood.

In an effort to further understand how this expansion might affect area farmers and land owners, I have talked with both farmers and county officials to get their perspective. To a person, they are not concerned about the impact this expansion would have on the environment.

I have no doubt that Riverview would operate this new facility with the same care and integrity for which they are already known.

Jackson Walsh **Letter 686**

ATTN: Charles Peterson

My name is Jackson im in grace township chippewa county. We farm around 3 riverview dairies. Additionally I am a supervisor for the township. I am writing in support of the proposed West River Dairy Expansion.

Based on my experience and observations, Riverview Dairy operates with professionalism, integrity, and environmental responsibility. Their facilities are well-maintained, clean, and organized, and their teams are committed to doing things the right way.

As someone familiar with agriculture in this region, I recognize that manure management and water use are highly regulated in Minnesota. Riverview strives to follow these regulations, including nutrient management planning, soil testing, proper application rates, and timing based on field conditions. From what I have seen, their mindset is to meet and exceed these standards to ensure responsible stewardship.

The use of manure as a nutrient source has clear benefits for local farms, including improved soil health, increased organic matter and reduced erosion. This supports long-term agricultural sustainability.

Riverview has also been a strong community partner, supporting farmers, creating jobs, maintaining roads, and investing in schools and local programs. Their communication with neighbors and officials reflects their commitment to being a good neighbor.

I understand that this project is undergoing environmental review through the state's established process — one of the most rigorous in the region— and provides adequate oversight for this project.

Based on the available data, existing regulations, and Riverview's proven track record, I am confident this project can continue to operate responsibly. I believe the current review process is sufficient and that additional regulatory burdens are unnecessary.

In closing, I respectfully encourage the appropriate agencies to approve the West River Dairy Expansion. This project supports local agriculture, strengthens rural communities, and reflects a responsible approach to environmental stewardship. I also believe that an EIS is not necessary.

Thanks

Jackson Walsh

Kay Erickson **Letter 687**

I'm opposed to this expansion. Cows treated like factory producers, mega amounts of manure, just the thought of it makes me worried about polluting our lakes and rivers. It needs to be denied.

Nora Hultgren **Letter 688**

I am currently a senior at MACCRAY High School and have spent the last few summers working at the Riverview facility next to my home. I help weigh and grade alfalfa brought in to the dairy from fields around our community four times a summer. I am not an employee of Riverview, I work for the harvesting contractor that my dad is a partner in.

My experience with Riverview has been nothing but great. The employees are respectful and friendly, the site I work at is clean and organized. I have observed the degree of detail that the Riverview workers observe when they care for the lawn and roads by the site and they are immaculate. I've been on smaller livestock farms of some of my other neighbors and they are not nearly as clean or organized.

Riverview has a company program called "Be Kind" and another called "Be Safe". They stress animal welfare and worker safety every day. In all my time being there, I have never seen unsafe behavior or any workers being disrespectful to each other or the cows. The barns are clean, comfortable, and quiet. The cows are happy!

I would definitely recommend approval of a permit to expand West River Dairy as there is nobody better than Riverview when it comes to taking care of dairy cows and living up to the expectations of our communities!

Noah Hultgren, Fieldstock Realty LLC **Letter 689**

I am submitting this comment in regard to the West River Dairy permit. I am in 100% support of the expansion. Being a realtor in a rural area, I can tell you that Riverview's projects between Morris and Willmar have done nothing but bring more activity in an otherwsie stagnant rural sales area. Their sites have caused no negative effects on neighboring properties because they keep them clean and well-maintained.

Anyone that lives in an urban area and is writing comments on the dairy's effect on our rural area should be taken with very little credit.

I can also attest to the positive effects of the addition of more alfalfa in our region and it has reduced wind and water erosion while improving soil health. Farmers here have appreciated the opportunity to have manure applied to their land, and the applicators follow state-mandated setback rules when they apply the manure, staying a safe distance away from open ditches and other bodies of water.

I have observed nothing but the best when it comes to Riverview and I support their permit application.

Blake Klaphake **Letter 690**

I am writing this letter in support of Riverview's expansion at West River Dairy.

When I think of continued growth of the dairy industry in Minnesota, I think of three important factors for success: worker safety, environmental responsibility, and animal welfare. Riverview is the gold standard in all three.

Their "Be Safe" and "Be Kind" initiatives focus on worker safey and animal care. They have a special "SWAT" team that helps their workers anytime there's a special circumstance with any injured animal--if an employee doesn't know how to handle a cow that has a health condition, the team is called in and is specially trained for handling cows in any difficult situations. They are organized, well-trained, and respectful to the animals.

I work on a neighboring farm and deliver corn and other products to Riverview's dairies. The sites are clean and well-maintained. I have observed them applying manure on our farm and they follow state guidelines for rates and for maintaining proper setbacks from the ditches.

They recently built a water capture pond to conserve water on the site. This is so they don't have to use as much groundwater. They recycle water that they use to wash cows. They also recycle bedding so they use far less per cow than your average dairy.

Riverview has been a huge benefit to our local communities, and the farmers that farm around the sites are very happy with the opportunity. NOt only can they sell crops to the dairy, it also means they're not wasting fuel and labor and time shipping corn and hay 20 miles down the road.

I highly support this permit application.

Emily Boecker **Letter 691**

It is vital that the Riverview Dairy be required to submit an environmental impact statement. It is nearly twice as big as any current operations in the state, and its environmental harm would be enormous. Here's what we know now.

Massive water use: Riverview would pump up to 226 million gallons/year from an off-site well—nearly as much as the entire City of Morris (permitted for 300 million gallons/year for 5,000+ residents).

Huge waste output: The facility would generate about 202.7 million gallons of liquid manure and wastewater annually, plus 26,400 tons of solid manure.

Unknown groundwater impacts: The DNR hasn't begun the hydrologic survey or completed the County Geologic Atlas for Stevens County, so aquifers and groundwater resources aren't mapped—making it risky to permit large withdrawals now.

Sensitive, already-impaired waters: The expansion sits in the Pomme de Terre watershed, designated sensitive; the nearest waters—the Pomme de Terre River and a nearby unnamed creek—are already listed as impaired. The project would likely worsen these impairments.

Advancing permits without a full understanding of groundwater and water-quality risks is irresponsible.

It is critical that the MPCA require a full Environmental Impact Statement.

Kennedy Stegner **Letter 692**

Riverview should be required to complete an environmental impact statement regarding this proposed facility. The people of Morris deserve a clear statement on the effect this operation will have on our water supply in both availability and quality. This facility will also be near the Pomme de Terre watershed, part of Stevens County's Soil and Water Protection District, and so many more protected spaces.

Not only is this a threat to our water, this is a threat to local farmers. This large of a facility will have major impacts on smaller dairy farms in the area. We need to consider the long term effects of this expansion.

Kennedy Stegner

Sandra Yost **Letter 693**

My name is Sandra Yost, a neighbor to river Riview Dairy and live in Dublin township. I am writing in support of the proposed West River Dairy expansion.

We have seen, close up the way Riverview operates. You will not find a business that operates with more professionalism, integrity or environmental responsibility. All of their facilities are the exemplary, all you have to do is drive by one of the sites and you will see how committed they are to doing things the right way.

They follow the manure and water regulations as regulated by the state of Minnesota and go above and beyond. Local farmers benefit by the use of manure as a natural fertilizer on their fields., supporting long term sustainability.

Riverview has been a community partner, for farmers, creating jobs, maintaining roads and supporting schools and local programs.

Based on Riverviews track record, I believe that the rigorous review that is in place is sufficient and additional regulatory burdens are not needed.

I strongly support the approval of West River Dairy Expansion,

Sandra Yost

Jeffrey Davis, Bryant State Bank **Letter 694**

ATTN: Charles Peterson

RE: Riverview LLP, West River Dairy Expansion in Stevens County MN.

Dear:

Operations like Riverview's create consistent economic activity that supports local jobs, drives investment, and allows businesses like ours to grow and reinvest in our communities.

I am the president and CEO of a community bank in Northeast South Dakota. Riverview has dairies within 30 miles of our bank; we have several customers that are able to expand and exist because of the presence of Riverview. I have been on several of their dairy properties and find them to be very professional and extremely clean and well maintained.

The proposed expansion represents a meaningful economic benefit to the region. It will generate demand for local vendors, support both construction and long-term employment, and contribute to the vitality of rural communities that rely on agriculture.

From our direct experience, Riverview is a professional and reliable partner that contributes positively to the communities where it operates. Their presence strengthens the local economy and supports a broad network of agricultural and service-related businesses.

Projects like this are essential to maintaining a competitive and sustainable rural economy in Minnesota as well as South Dakota. Continued investment in agriculture ensures that local businesses can continue to provide jobs, services, and economic stability close to home.

The state environmental review process is rigorous and sufficient. I respectfully encourage your support and approval of this important project.

Sincerely,

Jeffrey J Davis

President – CEO

Nate Skindelien, Duninck Concrete **Letter 695**

I am writing to express my strong support for the Riverview Dairy expansion project. I have had the opportunity to work alongside Riverview for the past ten years, and during that time I've come to know not just their operations, but also the people and values behind them.

One of the things that stands out most is their commitment to local communities. Their construction projects consistently use local contractors, creating dependable work for small businesses and skilled workers who truly rely on these opportunities in rural areas. The impact of that kind of investment is both real and lasting.

I have also seen how Riverview works with neighboring farmers. Their partnerships for supplemental feed and manure fertilizer programs create strong, mutually beneficial relationships that support local agriculture as a whole. They are not just operating in these communities—they are actively contributing to their success.

Riverview's care for the land and their facilities is another reason I support this project. They take pride in doing things the right way, and it shows. Their operations are well managed and thoughtfully maintained, to the point that other dairy producers often look to them as an example of how things should be done.

What has impressed me most over the years, though, is how much they value people. That mindset is clear from leadership all the way through their teams, and it extends beyond their organization into the communities they are part of. They treat people with respect and genuinely care about doing right by others.

Projects like this expansion are important for rural communities. They bring jobs, economic growth, and long-term stability to areas that need it. From what I have seen over the past decade, Riverview approaches that responsibility with care and integrity.

For all of these reasons, I strongly support the Riverview Dairy expansion project and respectfully encourage its approval. I am confident it will continue to reflect the same standards and values I have consistently seen over the years.

Thank you for your time and consideration.

Sincerely,

Nate Skindelien

Gail Morris **Letter 696**

I live by Lake Reno in Pope County just a few miles from Alexandria. Alexandria already had a child die of toxic lake algae exposure.

It is actually hard for me to imagine a dairy herd of even a 100 cattle. I'm 80. I grew up milking a few cows. Of course, those days are gone!

However, contemplating over 18,000 dairy cattle raises my every instinct of danger and fear.

*Danger to our Public Health and Natural Resources: where in this world/landscape does all that daily manure, poop and urine of 18,885 cattle go? Toxic poison in our lakes and streams? Poop stinks. 18,885 Cows everyday. Oh my gosh, I bet that's wonderful on a hot stifling day in July. Every day.

*Danger to our Animal Welfare: Yes we need to feed the world. Yes, we need to maximize our dairy industry. It can never be "like it was". But factoring 18,885 dairy cows into one facility is cruel. Cleanliness alone is huge. Danger of Viral Disease is Huge.

But just a few miles from me on Lake Reno we already do have a huge cattle feedlot.

William Bosch **Letter 697**

To whom it may concern,

My name is Will Bosch, and I have the pleasure of farming with my family near several Riverview dairy farms. I have also worked as an intern at Riverview farms in the past, so I have first-hand experience of how Riverview conducts business and manages its farms. I am writing to express my strong support for the West River Dairy Expansion.

Environmental concerns are always top of mind for Riverview management and employees, alongside their strong culture of employee safety, animal welfare, and good neighborliness. More than any other dairy or agricultural operation that I have knowledge of, Riverview is well equipped and pro-active in its efforts to mitigate any negative environmental impacts that may result from its operations. For example, all manure, wastewater, and runoff from feed pads is first recycled if able, then collected and redistributed to the surrounding land as nutrient dense fertilizer in a safe and proper manner. This serves to add economic value to surrounding farms like my family’s as well as mitigating environmental concerns by reducing the amount of commercial synthetic fertilizer needed to grow bountiful crops.

Beyond environmental concerns, the West River Dairy Expansion represents a significant boost in demand for locally grown crops, adding to the economic impact that agriculture has on our part of the state. Additional dairy production in our area serves to fill a large demand for nutritious whole foods in our state, country, and world. Livestock has always been an important aspect of a sustainable agricultural system, returning nutrients to the soil as well as turning row crops into value added ag products, and every effort should be made to allow the growth of this industry in MN’s rural areas.

Lucas Sjostrom, Minnesota Milk Producers Association **Letter 698**

To: Charles Peterson, Minnesota Pollution Control Agency

From: Minnesota Milk Producers Association Board of Directors

The Minnesota Milk Producers Association appreciates the opportunity to comment on the Environmental Assessment Worksheet (EAW) for the West River Dairy expansion. As an organization dedicated to the success of Minnesota's dairy farmers, our focus remains on ensuring that the state's regulatory frameworks are applied consistently, fairly, and based on sound science.

Support for a Science-Based Regulatory Process

We encourage the MPCA to maintain its commitment to a science-based and data-driven process. The current environmental review for this project is comprehensive. We believe the existing regulatory tools—including the EAW and the potential for individual permits with specific conditions—are sufficient to ensure the protection of Minnesota's water and natural resources.

• Proper Jurisdiction: The environmental review process is designed to assess significant environmental impacts, not to dictate public policy regarding the size or structure of dairy farms.

• Legislative Authority: We believe the Minnesota Legislature is the appropriate body to determine broader economic policies that support the dairy industry and its farmers.

• Regulatory Integrity: Utilizing the environmental permitting process to address economic competition issues is inappropriate and risks undermining the integrity of the state's regulatory system.

Conclusion

Minnesota's dairy sector thrives when there is a transparent, predictable, and rigorous permitting process. We support the MPCA's use of the established EAW process to evaluate this project and encourage a final decision based on the technical merits and data presented throughout this review.

Travis Holmgren **Letter 699**

ATTN: Charles Peterson

My name is Travis Holmgren, and I am an employee of a milk processing plant in Minnesota. Agricultural operations in Minnesota like Riverview provide an economical benefit to myself and my family. I am writing in support of their proposed West River Dairy expansion in Stevens County.

Through our work in the agricultural sector, we depend on a strong and stable livestock industry. Operations like Riverview’s create consistent economic activity that supports local jobs, drives investment, and allows businesses like ours to grow and reinvest in our communities.

The proposed expansion represents a meaningful economic benefit to the region. It will generate demand for local vendors, support both construction and long-term employment, and contribute to the vitality of rural communities that rely on agriculture.

From our direct experience, Riverview is a professional and reliable partner that contributes positively to the communities where it operates. Their presence strengthens the local economy and supports a broad network of agricultural and service-related businesses.

Projects like this are essential to maintaining a competitive and sustainable rural economy in Minnesota. Continued investment in agriculture ensures that local businesses can continue to provide jobs, services, and economic stability close to home.

No EIS is needed as the state environmental review process is rigorous and very sufficient.

I respectfully encourage your support and approval of this important project.

Sincerely,

Travis Holmgren

Fabian Hernandez **Letter 700**

ATTN: Charles Peterson

Support for Proposed West River Dairy Expansion

To Whom It May Concern:

My name is Fabian Hernadez. I am a neighbor in Stevens County, and I am writing to express my support for the proposed West River Dairy Expansion.

From what I have observed, Riverview Dairy is operated with care and accountability. The facilities are orderly and well maintained, and staff consistently demonstrate a commitment to safe and responsible day-to-day practices.

I also understand that Minnesota has clear requirements for manure management and water use. Based on my familiarity with agriculture in this region, I recognize the importance of nutrient management planning, soil testing, appropriate application rates, and timing that reflects field and weather conditions.

Riverview's approach appears aligned with those expectations, with an emphasis on meeting—and where possible exceeding—state standards for stewardship.

When managed correctly, manure provides a valuable nutrient source for crop production. It can build soil organic matter, support soil structure, and help reduce erosion—benefits that contribute to long-term farm productivity and sustainability in our area.

Beyond operations, Riverview has been an active community partner. Their presence supports local jobs and area farmers, and they have contributed to community needs such as roads, schools, and local programs. Just as important, they have shown a willingness to communicate and work with neighbors and local officials.

I understand this project is being reviewed through Minnesota's established environmental review and permitting processes, which provide meaningful oversight and accountability. Based on the information available, the existing regulatory framework, and Riverview's track record, I am confident this project can continue to operate responsibly. I believe the current review process is sufficient and that additional regulatory burdens are unnecessary.

Thank you for the opportunity to provide public comment. I respectfully encourage the appropriate agencies to approve the West River Dairy Expansion.

Sincerely,

Fabian Hernandez.

Gene Ward, Webtomix, LLC — Letter 701

Subject: Public Comment regarding Riverview, LLP - MPCA Feedback

To the Minnesota Pollution Control Agency,

I am writing today as a local business owner in Pennock & Kerkhoven to provide feedback regarding our long-standing professional relationship with Riverview Dairy. In the current climate, it is easy for the broader public benefits of a local organization to be overlooked, and I want to share the perspective of a technical partner who sees their community impact firsthand.

My company, Webtomix, provides IT and network infrastructure services. Riverview Dairy has been our primary business partner for nearly a decade. For a small technology firm in rural Minnesota, a partnership of this scale is more than just a contract; it is a cornerstone of our business stability. Their commitment to utilizing local tech services has allowed us to:

- **Invest in the Local Economy: Their consistent business has enabled us to maintain a physical presence in the community, including our recent expansion into a new office in Kerkhoven.**
- **Support Local Infrastructure: By prioritizing modern, efficient network systems, they are bringing high-level technical standards to our small communities-infrastructure that might otherwise be reserved for larger metropolitan areas.**
- **Sustain Local Jobs: The volume of work they provide-from comprehensive hardware upgrades to daily network management-directly supports the livelihoods of those we employ right here in the region.**

Beyond the technical side, we have found them to be a partner that genuinely values the people they do business with. They are a significant driver of the economic health of our small towns, and their presence ensures that local service providers like Webtomix can continue to grow and serve this area.

We value their partnership immensely and hope that the agency considers these vital economic and community contributions during this feedback process.

Sincerely,

Gene Ward Owner Webtomix, LLC

Karen Stettner **Letter 702**

I am opposed to this project because of the large number of animals they plan to have. Air quality, water quality and water availability should all be addressed. A feedlot of this size will impact residents many miles in every direction from the feedlot i.e. Smell. There should be environmental studies carried out by State and Federal agencies. Please deny this permit request from Riverview Dairy.

Carol Wenner **Letter 703**

The West River dairy expansion will be too taxing on our environmental resources. I say no!

David Huang, SeaTac Packaging **Letter 704**

I am writing in support of Riverview LLP's proposed West River Dairy expansion in Stevens County.

Ruth Lovander Foley **Letter 705**

I am respectfully submitting my comments about corporate farming. I oppose West River Dairy expansion as the proposed size of the expansion will be unable to keep environmental safety, is extremely damaging to small family dairy operations and is cruel to the dairy animals. I grew up on a family Holstein dairy operation. Animal husbandry was always practiced on our farm. Our cows were milked two times per day. Between the morning and evening milkings, our cows were let out of the barn to feed on pasture grass and get fresh air and sunshine for the health of the animals. Animals on these corporate farms are denied fresh air and are merely MACHINES for continued breeding until they are physically exhausted. Then they are disposed of (which SADLY may be the best part of their lives). We surely owe our domesticated animals much more empathy than this! When did we begin to put corporate profits above concerns for family farmers and the animals we are entrusted to care for? The tradeoffs for the benefit of huge corporations and their owners/shareholders should not override all other concerns! Please deny all corporate farms in Minnesota the ability to expand and - even to exist.

Amy Ekren **Letter 706**

As a business owner in this community, I want to speak in strong support of the West River Dairy expansion.

I run a company that depends on a healthy, functioning local economy. Agriculture is not just part of that, it is the backbone of it. When farms grow, our communities grow. We see it in jobs, in families staying local, in small businesses being able to operate and expand.

This project represents long-term investment in our county. It supports not only those directly involved in agriculture, but also the ripple effect of suppliers, service providers, and local businesses like ours who rely on a stable and growing customer base.

I understand that growth brings questions, and those should be handled with care and responsibility. But choosing not to grow has consequences too. Without forward movement like this, rural communities risk losing momentum, opportunity, and the next generation.

From both a business and stewardship perspective, I support this project. Thoughtful expansion, done well, is how we build something that lasts...for our families, our employees, and our community.

I believe we are called to be good stewards, not just of land, but of opportunity. This project is part of building a future where people can live, work, and thrive here. I fully support it.

Anthony Ekren **Letter 707**

As a local business owner and community member I am writing in strong support of the proposed West River Dairy Expansion. What must be considered alongside environmental review is the very real and measurable economic and community impact of this dairy farm. For over 30 years, Riverview has contributed to the strength and stability of our local economy in Stevens county. Businesses like this do not operate in isolation. They support local suppliers, create jobs, sustain families, and drive consistent economic activity that allows other small businesses, including my own, to grow and thrive. When agriculture is strong, our entire community benefits. Schools, churches, service providers, and local retailers all feel the ripple effect of a stable, productive agricultural base.

Expansion is a sign of health, stewardship, and long-term investment in our county. It reflects a commitment to doing business here and continuing to provide opportunity for future generations. West River Dairy is a well-managed dairy that has already demonstrated over 20 years of positive presence in both the environment and local economy. I respectfully encourage decision-makers to consider not only the environmental data presented in the EAW, but also the proven track record and the broader community impact this dairy farm has had and will continue to have.

Respectfully,

Anthony Ekren

Talia Koehl **Letter 708**

As a Stevens County resident, I am in support of Riverview's expansion project & I don't believe that the EIS is necessary. Knowing who Riverview is & how responsible they are with their resources, I am in full support of the West River expansion.

Trenton Nelson **Letter 709**

I am submitting this comment to urge the rejection of the proposed livestock facility expansion. A facility of this size creates an unmanageable amount of waste that threatens Minnesota's groundwater and local ecosystems. Beyond the environmental impact, I am concerned about the welfare of the animals involved and the degradation of the surrounding wild animal habitats. We should be moving toward more sustainable and ethical agricultural practices, not doubling down on industrial factory farming.

Kendall Waldbeser **Letter 710**

My name is Kendall Waldbeser, and I am writing to express my strong support for the proposed West River Dairy expansion.

I have lived in close proximity to this project area for my entire life, and with the proposed expansion, my home will be located within approximately one-half mile of the dairy.Because of that, this project is very personal to me and my family.

I have also been connected to Riverview for many years and have had the opportunity to observe their operations firsthand over time. Through that experience, I have seen the level of care, responsibility, and attention to detail that goes into how they manage their dairies.

From an environmental standpoint, I have a high level of confidence in Riverview's practices. I have personally observed their commitment to responsible manure management, including thoughtful application practices that support local crop production while protecting the land. I have also seen their approach to water management and conservation, as well as the steps they take to maintain clean and orderly sites.

Additionally, Riverview has demonstrated a strong commitment to being a good neighbor. This includes maintaining roads, managing tra□ic responsibly, and taking proactive measures such as using synthetic covers on manure lagoons to mitigate odor.

Just as important, I have paid close attention to the environmental review process for this project. It is clear to me that both the MPCA and the Minnesota Department of Natural Resources (DNR) have conducted a thorough, rigorous, and exhaustive review. As someone who lives nearby and will be directly impacted, I am fully confident in the strength and integrity of this process.

Based on my lifelong proximity to this area, my firsthand knowledge of Riverview's operations, and my confidence in the review conducted by the MPCA and DNR, my family and I are completely comfortable with this project moving forward.

For these reasons, I respectfully ask that the MPCA approve the West River Dairy expansion. I also believe the Environmental Assessment Worksheet (EAW) process has been comprehensive and su□icient, and that an Environmental Impact Statement (EIS) is not necessary.

Thank you for your time and consideration.

Sincerely,

Kendall Waldbeser

Michael Green **Letter 711**

ATTN: Charles Peterson

My name is Michael Green and I am an employee of RSP Design Inc serving dairy processing operations in Minnesota like Riverview. I am writing in support of their proposed West River Dairy expansion in Stevens County.

Through our work in the dairy sector, we depend on a strong and stable livestock industry. Operations like Riverview's create consistent economic activity that supports local jobs, drives investment, and allows businesses like ours to grow and reinvest in our communities.

The proposed expansion represents a meaningful economic benefit to the region. It will generate demand for local vendors, support both construction and long-term employment, and contribute to the vitality of rural communities that rely on agriculture.

From our direct experience, Riverview is a professional and reliable partner that contributes positively to the communities where it operates. Their presence strengthens the local economy and supports a broad network of agricultural and service-related businesses.

Projects like this are essential to maintaining a competitive and sustainable rural economy in Minnesota. Continued investment in agriculture ensures that local businesses can continue to provide jobs, services, and economic stability close to home.

No EIS is needed as the state environmental review process is rigorous and very sufficient. I respectfully encourage your support and approval of this important project.

Sincerely,

Michael Green

Wendy Evink **Letter 712**

Dear Commissioner Kessler and MPCA Staff,

I have lived in Stevens County my entire life, and I care deeply about what happens here — to the land, the water, and the people who call this place home. I am writing in strong support of the proposed West River Dairy expansion near Morris.

I'll be honest — I'm not an expert in water management or nutrient regulations. But I've asked a lot of questions over the years, and I've listened carefully to the people who are. What I've come to understand is that the Environmental Assessment Worksheet process the MPCA requires is no rubber stamp. It digs deep. And what Riverview has laid out in this application — from how they handle manure as a soil-building resource rather than a waste product, to how they capture and reuse rainwater runoff on-site — tells me this isn't just about meeting the minimum. Our land and water won't just be protected under this plan. From what I've learned, they stand to genuinely improve. That's not something I expected to be able to say, but the more I looked into it, the more I believed it.

To me, this is what good regulation is supposed to look like — when the rules, the operator's commitment, and smart thinking about the land all come together in the same place at the same time.

What means the most to me personally is what this operation has meant for my family and so many others like us. One of my children was able to come back home, find good work, and raise a family here because of the kind of economic foundation that operations like West River Dairy help provide. That is not a small thing. Keeping rural communities like ours alive depends on being able to offer that to the next generation.

The environmental review process has been thorough. Riverview's track record speaks for itself. I respectfully urge the MPCA to approve this expansion — it's good for our land, good for our water, and good for the future of this community.

Sincerely,

Wendy Evink

Chad Seizert **Letter 713**

The West River Dairy expansion should not be approved. Throughout Minnesota, and the whole nation, family farm operations and small scale independent agricultural enterprises are being squeezed or out and out destroyed by the large scale industrial model of agriculture, in the name of increased efficiency and profitability for stakeholders. The degradation of the land, ground water, air, and habitats are externalities that are invariably left for the community or state to deal with. The industrial model of agriculture devastates their local economies resulting in impoverished and dying small towns with few prospects for people in those regions. Ethically, there is much to oppose this feedlot expansion, from the inhumane treatment of the cows and their offspring, to the questionable treatment of the employees who do not reap the economic benefits that these factory operations provide to the few. Contrary to Riverview's self promoted stewardship of the environment, it should be plain to everyone that all of that manure has to go somewhere, and there are no benign disposal options.

Ron Schlueter **Letter 714**

Hello,

Please include my name in those that OPPOSE the expansion of the West River Dairy!!! This enlargement project is just too large for the area. Often, we hear of large dairy operations that have manure "leaks" that pollute the area. We also have polluted ground water and lakes that have also been impacted by these "accidents". We have a cabin in an adjacent county and would hate to have this expansion set a precedent in additional areas of the state.

Please oppose this expansion!

Robert Valnes **Letter 715**

To whom it may concern,

I have lived and worked in Stevens County my entire 83 years, and have been in the well drilling and water conditioning business for over 50 years. I know this ground. I know what's in it, what flows through it, and what it takes to protect it. I am writing in strong support of the proposed West River Dairy expansion near Morris.

Some people are throwing out big numbers about water usage and manure to scare folks who don't deal with these things for a living. I understand why it works. But I do deal with them, and I can tell you that a big number without context doesn't mean much.

The DNR does not hand out water permits because somebody asks nicely. They look hard at aquifer capacity, existing water users, and long-term sustainability before a single gallon can be appropriated. I have worked alongside that process for decades. It is not a formality. If the water couldn't support this in a sustainable way, the permit wouldn't be granted. Period.

The same is true on the manure side. The MPCA requires detailed nutrient management planning tied to actual field capacity, soil testing, and application timing. Done right, it's not a liability — it's an asset to the farmland surrounding this operation. I've seen it with my own eyes over many years.

I wouldn't be writing this if I had any doubt about what this project means for our water and our land. I've spent my whole life trying to protect both and that's not something I would set aside for anyone.

But this is about more than water and land. People need to understand what an operation like this means for the local economy. Construction alone brings real work to local contractors, electricians, equipment operators, and suppliers. Once it's running, the ripple effect doesn't stop — those same service providers, along with farmers providing feed, harvest crews, and truckers all see activity that wouldn't exist otherwise. That is real money staying right here in Stevens County.

I've lived a good long life in this county and I have no complaints about that. But my biggest hope at this point isn't for myself - it's that the people coming up behind me have the same opportunities I did, and then some. Projects like this one, done the right way and with the right oversight, are how that happens. That's what I care about now.

I respectfully urge the MPCA to approve this expansion. Don't let large numbers without context cloud a process that has been done right. This community deserves the opportunity to grow, and this is the right way to do it.

Sincerely,

Robert Valnes

Shane Seeger **Letter 716**

I recently began working as a contractor on a Riverview Dairy project, and it's immediately clear they operate to an exceptional environmental standard. Their farms are consistently clean, well-managed, and thoughtfully run, with practices that reflect genuine care for sustainability, animal welfare, and responsible agriculture.

Riverview Dairy is a strong example of modern, environmentally conscious farm management.

Based on what I've seen, I'm confident the new facility will be maintained with the same level of cleanliness, care, and professionalism

Sammy Glanzer **Letter 717**

ATTN: Charles Peterson

My name is Sammy Glanzer and I am a neighbor/local resident/farmer/business owner/official in Fordham Township in Clark County I am writing in support of the proposed West River Dairy Expansion.

Based on my experience and observations, Riverview Dairy operates with professionalism, integrity, and environmental responsibility. Their facilities are wellmaintained, clean, and organized, and their teams are committed to doing things the right way.

As someone familiar with agriculture in this region, I recognize that manure management and water use are highly regulated in Minnesota. Riverview strives to follow these regulations, including nutrient management planning, soil testing, proper application rates, and timing based on field conditions. From what I have seen, their mindset is to meet and exceed these standards to ensure responsible stewardship. The use of manure as a nutrient source has clear benefits for local farms, including improved soil health, increased organic matter and reduced erosion. This supports longterm agricultural sustainability.

Riverview has also been a strong community partner, supporting farmers, creating jobs, maintaining roads, and investing in schools and local programs. Their communication with neighbors and officials reflects their commitment to being a good neighbor. I understand that this project is undergoing environmental review through the state's established process — one of the most rigorous in the

region— and provides adequate oversight for this project. Based on the available data, existing regulations, and Riverview's proven track record, I am confident this project can continue to operate responsibly. I believe the current review process is sufficient and that additional regulatory burdens are unnecessary.

In closing, I respectfully encourage the appropriate agencies to approve the West River Dairy Expansion. This project supports local agriculture, strengthens rural communities, and reflects a responsible approach to environmental stewardship. I also believe that an EIS is not necessary.

Sincerely

Sammy

Steven Glanzer **Letter 718**

ATTN: Charles Peterson

My name is Steve Glanzer and I am a neighbor/local resident/farmer/business owner/official in Fordham Township in Clark County I am writing in support of the proposed West River Dairy Expansion.

Based on my experience and observations, Riverview Dairy operates with professionalism, integrity, and environmental responsibility. Their facilities are wellmaintained, clean, and organized, and their teams are committed to doing things the right way.

As someone familiar with agriculture in this region, I recognize that manure management and water use are highly regulated in Minnesota. Riverview strives to follow these regulations, including nutrient management planning, soil testing, proper application rates, and timing based on field conditions. From what I have seen, their mindset is to meet and exceed these standards to ensure responsible stewardship. The use of manure as a nutrient source has clear benefits for local farms, including improved soil health, increased organic matter and reduced erosion. This supports longterm agricultural sustainability.

Riverview has also been a strong community partner, supporting farmers, creating jobs, maintaining roads, and investing in schools and local programs. Their communication with neighbors and officials reflects their commitment to being a good neighbor. I understand that this project is undergoing environmental review through the state's established process — one of the most rigorous in the region— and provides adequate oversight for this project. Based on the available data, existing regulations, and Riverview's proven track record, I am confident this project can continue to operate responsibly. I believe the current review process is sufficient and that additional regulatory burdens are unnecessary.

In closing, I respectfully encourage the appropriate agencies to approve the West River Dairy Expansion. This project supports local agriculture, strengthens rural communities, and reflects a responsible approach to environmental stewardship. I also believe that an EIS is not necessary.

Sincerely

Steve

Holly Grap **Letter 719**

Riverview does not have Minneostans in mind for this expansion. They do no support community farmers, and this expansion is an ecological disaster waiting to happen. Riverview has already had manure leakage in a manure storage tank, and their hog and dairy farms use at least 570 million gallons

of water annually. The proposed expansion would pump and store up to an additional 226 million gallons. We do not need to sacrifice our fresh water for these massive factories. Please vote no. For our water. For our future.

Adam Redlinger, Redlinger Bros. Plumbing & Heating Co. — Letter 720

ATTN: Charles Peterson

My name is Adam Redlinger, and I am the owner of Redlinger Bros. Plumbing & Heating Co., a plumbing and mechanical contractor serving agricultural operations in Minnesota like Riverview. I am writing in support of their proposed West River Dairy expansion in Stevens County.

Through our work in the agricultural sector, we depend on a strong and stable livestock industry. Operations like Riverview's create consistent economic activity that supports local jobs, drives investment, and allows businesses like ours to grow and reinvest in our communities. We have been working with dairy producers and dairy related companies such as Riverview, Valley Queen Cheese (SD), Green Meadows (IA), Agropur (SD) and Bel Brands (SD) and without the stability and future growth of companies in this sector, we wouldn't be in business today. The dairy sector has helped our business survive slower years and even grow while other businesses in construction struggled.

The proposed expansion represents a meaningful economic benefit to the region. It will generate demand for local vendors, support both construction and long-term employment, and contribute to the vitality of rural communities that rely on agriculture.

From our direct experience, Riverview is a professional and reliable partner that contributes positively to the communities where it operates. Their presence strengthens the local economy and supports a broad network of agricultural and service-related businesses. We have a positive experience of working alongside Riverview and its employees.

Projects like this are essential to maintaining a competitive and sustainable rural economy in Minnesota. Continued investment in agriculture ensures that local businesses can continue to provide jobs, services, and economic stability close to home.

No EIS is needed as the state environmental review process is rigorous and very sufficient. I respectfully encourage your support and approval of this important project.

Sincerely,

Adam Redlinger

David Munn — Letter 721

This expansion is very concerning. A project of this size should require an environmental impact statement. The citizens of Minnesota should be able to expect this level of oversight from the MCPA.

Thank you

Jackie Junker — Letter 722

To the Minnesota Pollution Control Agency,

I am writing as a concerned citizen regarding the proposed West River Dairy Expansion in Stevens County. While I understand the importance of agriculture to Minnesota's economy, I have serious concerns about the scale of this project and its potential impacts on both animal welfare and the environment.

An operation of this size, housing nearly 19,000 dairy cows, raises significant questions about the humane treatment of animals. Industrial-scale dairies often limit natural behaviors, increase stress, and can lead to higher rates of injury and illness if not carefully managed. I urge the MPCA to closely evaluate how animal welfare standards will be maintained at this facility and whether current oversight is sufficient at this scale.

Additionally, the environmental risks are substantial. Large dairy operations produce enormous quantities of manure, which can threaten groundwater, surface water, and air quality if not properly handled. In a rural area like Stevens County, where many residents rely on well water, the potential for contamination is especially concerning. Odor, emissions, and nutrient runoff could also negatively impact nearby communities and ecosystems.

I respectfully ask the MPCA to ensure that this Environmental Assessment Worksheet fully and transparently addresses these concerns, and to require the highest standards of environmental protection and animal care before any permits are considered.

Thank you for the opportunity to provide input and for your commitment to protecting Minnesota's environment and communities. Jackie

Todd Malecha **Letter 723**

Hi My Name is Todd Malecha,

We are life long residents of Pope County and life long multi Generational dairy farmers. I am writing in support of Riverview LLP's proposed West River Dairy expansion in Stevens County.

My support is based on belief that Riverview has shown itself to be a serious capable agricultural operator and an important contributor to West-central Minnesota.

For my perspective, this proposal should not be reduced to a simple debate of Big versus small. This is about whether a company with experience resources and long-term stake in the area should be allowed to invest in the future. Riverview's presence supports jobs, local businesses schools, and neighboring farms. It also reflects a family business, choosing to contribute and investing in Minnesota rather than taking the investment elsewhere. In short, I support the West River Dairy expansion because I believe Riverview is a strong operator, an important economic partner in the region and a company willing to make substantial long-term investments in Minnesota communities. I respectfully ask the MPCA to give this project a fair review and let the science, the engineering and their records speak for themselves-thank you for your time and consideration sincerely Todd Malecha.

Jane Amberg **Letter 724**

I am not in favor of the proposed West River Dairy Expansion. My three main reasons include animal welfare, manure runoff with all the environmental concerns associated with that and I oppose factory farming.

Gabi Joos **Letter 725**

To whom it may concern,

I strongly support the proposed expansion of the West River Dairy in Stevens County. This project represents a meaningful opportunity to advance both the dairy industry and the broader agricultural community in our region. As a former employee of Riverview LLP, I have had the privilege of witnessing firsthand the depth of research, planning, and diligence that goes into evaluating the feasibility of a new

dairy. Every aspect, down to individual animal units, is carefully analyzed, reflecting a thorough and time-intensive process that prioritizes both sustainability and operational excellence.

As someone deeply connected to agriculture and passionate about advocacy, I believe in supporting farmers and organizations like Riverview, whose mission centers on strengthening the industry and addressing critical gaps. While concerns are sometimes raised about the impact of expansion, such as increased manure production, it is important to recognize that manure is a valuable resource. When managed responsibly, it serves as an essential nutrient source that supports neighboring farms, many of which are smaller operations that benefit from these partnerships.

My personal experience with Riverview, from employment during high school and college to being a recipient of the Riverview Connect Scholarship, has shown me the organization's genuine commitment to its employees, local communities, and agricultural partners. Their investment in people and their emphasis on opportunity set them apart as a company that adds long-term value wherever they operate.

For these reasons, I fully support the West River Dairy expansion. It is a project that not only contributes to the continued growth and sustainability of local agriculture but also reflects the values of a company that consistently demonstrates integrity, innovation, and community engagement.

Sincerely,

Gabi Joos

Mike Deseth **Letter 726**

After review and research of this situation and reading many of these comments, if this expansion is such a benefit for the community, no one should be afraid to do an EIS. Many commenting in support seem to be businesses involved directly with Riverview and others related to the business which is not impartial by any means. One can have the best intentions and character but deeper study can only assist with determining if this huge expansion is right for our area at this time.

Looking at Riverview's history in SD, ND, AZ and their ND impacts into Canada- there seems to be some strong opposition to projects already completed and also those with permits for expansions ready to be started. Some have been met with legal opposition. It would seem wise of MN to look a bit deeper into this now than pay a price later. I would be concerned about water usage and the overall water tables ability to trend through changing environmental impacts as well as where expansion stops. Two major Riverview locations are already situated approximately 12 miles near each other, one being another currently expanding to offer milk plant service. Thank you for your time. Mike Deseth

Kevin Mills, Pinion **Letter 727**

My name is Kevin Mills, and I am a Principal of Pinion, a Consulting and Accounting Firm serving agricultural operations in Minnesota like Riverview. I am writing in support of their proposed West River Dairy expansion in Stevens County.

Through our work in the agricultural sector, we depend on a strong and stable livestock industry. Operations like Riverview's create consistent economic activity that supports local jobs, drives investment, and allows businesses like ours to grow and reinvest in our communities.

The proposed expansion represents a meaningful economic benefit to the region. It will generate demand for local vendors, support both construction and long-term employment, and contribute to the vitality of rural communities that rely on agriculture.

From our direct experience, Riverview is a professional and reliable partner that contributes positively to the communities where it operates. Their presence strengthens the local economy and supports a broad network of agricultural and service-related businesses.

Projects like this are essential to maintaining a competitive and sustainable rural economy in Minnesota. Continued investment in agriculture ensures that local businesses can continue to provide jobs, services, and economic stability close to home.

No EIS is needed as the state environmental review process is rigorous and very sufficient. I respectfully encourage your support and approval of this important project.

Sincerely,

Kevin Mills

Samantha Deseth **Letter 728**

To Whom It May Concern,

I am a resident living within a few miles of the proposed West River Dairy expansion in Synnes Township. I am writing to respectfully request that the Minnesota Pollution Control Agency require a full Environmental Impact Statement (EIS) before any permits are approved for this project.

My primary concern is water—both the quantity being withdrawn and the quality that will remain for nearby residents. The scale of this proposed expansion raises serious questions about groundwater sustainability. The amount of water required for a facility of this size has the potential to impact local aquifers, private wells, and long-term water availability in our area. As a nearby resident who relies on groundwater, I am deeply concerned that the current level of environmental review does not fully evaluate these risks.

Equally important are the potential health impacts associated with this project. I am the parent of a medically complex adult child with special needs. Recent lab work has shown elevated levels of pesticides in his system. This makes environmental exposures a critical and personal concern for our family. Any increase in contaminants—whether through manure application, runoff, groundwater movement, or air emissions—could further compromise his already fragile health.

Given the scale of this operation, the volume of manure to be generated and applied to surrounding land, and the uncertainty around cumulative impacts, I do not believe that an Environmental Assessment Worksheet provides sufficient analysis.

A full EIS is necessary to:

Thoroughly evaluate groundwater withdrawal impacts on local wells and aquifers

Assess the risk of contamination from manure, nutrients, and associated chemicals

Examine cumulative environmental and health impacts over time

Consider the vulnerability of sensitive populations, including children and individuals with pre-existing health conditions.

This decision will have long-term consequences for our community's health, water resources, and quality of life. As someone directly affected and responsible for protecting a medically vulnerable child, I urge the MPCA to take a precautionary approach and require a full Environmental Impact Statement.

Thank you for your time and consideration.

Sincerely,

Sam Deseth

Ashley Nietfeld **Letter 729**

Allowing this expansion is immoral. They are damaging the dairy industry everyday. There is already too much milk on the market and they just keep growing and for what? They don't care for the livestock they're all just managers with who knows what agenda. Nothing positive comes from them continuously expanding. Rumor has it that instead of paying investors they just keep growing, like a giant ponzi scheme. Allowing them to continue is unreasonable.

Cheryl Rempel **Letter 730**

At the very least, I am in favor of requiring an EIS for this project before any further decisions are made on allowing the expansion. I lived in Stevens County for 30 years. It's unfortunate that Riverview does not have the integrity to support in depth studies of the impacts of increasing their already massive operations. I would hope that the company leaders would model caring for their neighbors, smaller dairy operations and the environment. They apparently don't rate those concerns higher than making more money.

Nick Elms **Letter 731**

Multiple EIS's should be done for a proposed dairy of this magnatude! This dairy may likely have generational impacts to the local environment and watershead and needs to be thoroughly reviewed!

Sue Kulberg **Letter 732**

I am a resident of and farm land owner in Stevens County. I care about our environment for us and future residents of generations to come.

An EIS definitely needs to be done on this proposed project. Why wouldn't one be done on a project of this size? Why wouldn't Riverview welcome that?

I am concerned that this project could affect ground water supply for others much like happened in Arizona with this same company. There Riverview dug wells as deep as needed while others not associated with them often could not afford to when their wells went dry. It isn't obvious to me `that Riverview cared about surrounding residents lack of water caused by their business in Arizona. Let's not have that happen here.

A full environmental review of the proposed facility should be done to protect resources and help Riverview be good stewards of those resources.

Louise Malecha **Letter 733**

My name is Louise Malecha. I am a lifelong dairy farmer from rural Minnesota, a co-founder of a multi-generational dairy enterprise, and now a founder of a family-based food business rooted in agriculture.

Having spent decades in production agriculture, I understand firsthand the level of responsibility, planning, and stewardship required to operate a dairy of this scale. Modern dairy farms today are highly regulated, technologically advanced, and deeply committed to caring for their animals, protecting natural resources, and contributing positively to their communities.

Operations like West River Dairy represent more than agriculture—they represent opportunity. They bring jobs, support local businesses, strengthen rural communities, and help sustain the agricultural economy that so many families depend on.

In my experience, successful dairies are built on strong values: stewardship of the land, responsible nutrient management, animal care, and a long-term commitment to doing things right. Producers at this level understand that their livelihood depends on maintaining the trust of the community and protecting the resources they've been entrusted with.

I strongly support this project and believe it reflects the kind of thoughtful agricultural growth that can benefit both the local community and the broader region. It is important that we continue to support responsible farmers who are working to feed families while caring for the land for future generations.

Thank you for the opportunity to provide input.

Sincerely,

Louise Malecha

C Ewalt **Letter 734**

We don't support this. It is not reasonable to expect the environment can survive the mass of this assault.

Adam Yucuis **Letter 735**

I'm of the opinion that Riverview must be required to undergo a full Environmental Impact Statement for their proposed West River Dairy Expansion. That potential number of cows all located in one concentrated area would produce a very large amount of manure and would require vast amounts of water, posing a large risk to the local groundwater resources. We need to know of the potential environmental impacts of the proposed expansion before it can move forward.

Robert Lee **Letter 736**

I work with a Riverview dairy, I sell the silage and purchase manure from them. They are a good neighbor and have had a positive impact on my farming operation. Having diverse end users for our crop is important for stability of the corn market. I am in favor of the expansion.

Shane Frahm, AgCountry Farm Credit Services **Letter 737**

ATTN: Charles Peterson

AgCountry Farm Credit Services is a cooperative lender that finances agricultural operations of all sizes across Minnesota. Our lending portfolio reflects the full diversity of the state's agricultural economy. We actively support growth in Minnesota's agricultural sector. A thriving animal agriculture industry is a cornerstone of strong rural economies - sustaining jobs, supporting local businesses, and driving demand for crops grown by producers across the region.

The proposed Riverview expansion represents a meaningful economic benefit to the region. It will generate demand for local vendors, support both construction and long-term employment, and contribute to the vitality of rural communities that rely on agriculture.

From our direct experience, Riverview is a professional and reliable partner that contributes positively to the communities where it operates. Their presence strengthens the local economy and supports a broad network of agricultural and service-related businesses.

Projects big and small are essential to maintaining a competitive and sustainable rural economy in Minnesota. Continued investment in agriculture ensures that local businesses can continue to provide jobs, services, and economic stability close to home.

Sincerely,

Shane D. Frahm

Executive Vice President

Corey Poepping, Tri County Insulation, Concrete Lifting & Painting **Letter 738**

ATTN: Charles Peterson

My name is Corey Poepping and I am the owner ofTri County Insulation, Concrete Lifting & Painting, a business serving agricultural operations in Minnesota like Riverview. I am writing in support of their proposed West River Dairy expansion in Stevens County.

Through our work in the agricultural sector, we depend on a strong and stable livestock industry. Operations like Riverview's create consistent economic activity that supports local jobs, drives investment, and allows businesses like ours to grow and reinvest in our communities.

The proposed expansion represents a meaningful economic benefit to the region. It will generate demand for local vendors, support both construction and long•term employment, and contribute to the vitality of rural communities that rely on agriculture.

From our direct experience, Riverview is a professional and reliable partner that contributes positively to the communities where it operates. Their presence strengthens the local economy and supports a broad network of agricultural and service-related businesses.

Projects like this are essential to maintaining a competitive and sustainable rural economy in Minnesota. Continued investment in agriculture ensures that local businesses can continue to provide jobs, services, and economic stability close to home.

No EIS is needed as the state environmental review process is rigorous and very sufficient. I respectfully encourage your support and approval of this important project.

Sincerely,

Corey Poepping

Owner/President

Patricia Rhoades **Letter 739**

Please require a full environmental impact statement on the proposed expansion of West River Dairy. Riverview Dairy is already the largest factory farm in the state with a history of manure spills. This expansion would generate significant greenhouse gas emissions and the manure runoff would lead to increased nitrates and phosphorus. The state needs to consider the impact on our waterways and on human health.

Dick Metzger **Letter 740**

To Whom It May Concern:

Riverview is a good, reliable, and valuable neighbor. For 23 years, my family and I have been living one mile west of the original Riverview Dairy site. There have been no issues or annoyances in 23 years. I have no concerns that they will continue to be a responsible neighbor. If I didn't look out my windows I wouldn't even know they exist. Riverview has been, and I'm very confident that they will be, a responsible and good neighbor in the future.

In addition, I live 125 feet off the Pomme de Terre River and approximately one mile downstream from the original site and if anyone has a reason to be nervous, it is myself and my family. We have no reservations about this dairy expanding either, if that would be the case in the future.

Is life perfect? No. Does change happen? Yes. Can accidents happen? Yes. And if anything would happen at this site or any other site for that matter, Riverview would do everything in their power to make the situation right. I have complete confidence in their ethics and their practices.

I am an enthusiastic and informed dairy supporter. I grew up on a dairy farm in NW Iowa and I am a 1984 graduate of South Dakota State University's dairy manufacturing program, which is the science and processing of milk and dairy products. We need the stability that Riverview provides to the dairy industry as a whole.

Riverview is not driving small dairy farmers out of business. Small dairy farmers are retiring and there are very few if no successors that are willing to step into this most grueling, labor-intensive, and very time-intensive operation. This is not an 8-5 job. It is 24/7, 365 days a year with little to no vacation time because cows don't stop giving milk on weekends and holidays. This industry is not for the faint of heart, lazy, or people that can't stand up to hard work and taking risks.

In the early to mid-80's I was just entering the dairy industry. In the midwest the milk supply was cyclical, existing dairy plants were older and in need of updating, and California was seen as the only state where the dairy industry was viable and profitable. Over the next several decades, the dairy industry in the Midwest has stabilized and is in a growth mode, thanks in part to companies such as Riverview that have provided a steady supply of milk to dairy plants in the area. This steady milk supply has allowed the dairy industry stability with steady supplies of nature's most nutritious product (milk) that have enhanced the communities where they are located.

As a member of the Morris Area school board from 2008-2018 with four years serving as board president, the Morris area community saw the stabilization of the general population and subsequent growth of the student population. The population in Stevens County in 1990 was 10,621 citizens and by 2010 the population had decreased to 9,726 citizens. From 2010 on, our community has seen a bottoming out of the population, and then has experienced subsequent growth, with the present population being 9,819. I believe this is due in large part, to the investment and growth of companies in our county such as Riverview. People don't just show up in west central Minnesota without available jobs waiting to be filled.

The town of Morris (population of approximately 5,000 citizens) is thriving, rather than dying, like so many detractors would like you to believe. Our downtown has been revitalized. We have a new department store, a new hotel, a new steakhouse, and many thriving businesses and restaurants. Operations people and professionals alike eat, shop, and enjoy our natural resources in Morris.

I find it remarkable, and very exciting to see Riverview playing a key role in providing stability not only to the dairy industry, but to our county and the surrounding area. With this dairy expansion, there would be good paying jobs and satisfying work for the Riverview employees, new tax revenue for the county,

all while knowing they are helping to provide dairy products to not only you and I, but to our fellow citizens.

I want to reiterate my enthusiastic support for this project and thank you for your consideration in this matter. I encourage you to stand behind this project and all the benefits it will bring to our local and surrounding communities.

Sincerely,

Dick Metzger

Lonnie Fosso **Letter 741**

ATTN: Charles Peterson

My name is Lonnie Fosso, and I am a farmer in Manuel Township, Kandiyohi County. I am writing in support of the proposed West River Dairy Expansion.

Based on my experience and observations, Riverview Dairy operates with professionalism, integrity, and environmental responsibility. Their facilities are well-maintained, clean, and organized, and their teams are committed to doing things the right way.

As someone familiar with agriculture in this region, I recognize that manure management and water use are highly regulated in Minnesota. Riverview strives to follow these regulations, including nutrient management planning, soil testing, proper application rates, and timing based on field conditions. From what I have seen, their mindset is to meet and exceed these standards to ensure responsible stewardship.

The use of manure as a nutrient source has clear benefits for local farms, including improved soil health, increased organic matter and reduced erosion. This supports long-term agricultural sustainability.

Riverview has also been a strong community partner, supporting farmers, creating jobs, maintaining roads, and investing in schools and local programs. Their communication with neighbors and officials reflects their commitment to being a good neighbor.

I understand that this project is undergoing environmental review through the state's established process - one of the most rigorous in the region- and provides adequate oversight for this project. Based on the available data, existing regulations, and Riverview's proven track record, I am confident this project can continue to operate responsibly. I believe the current review process is sufficient and that additional regulatory burdens are unnecessary.

In closing, I respectfully encourage the appropriate agencies to approve the West River Dairy Expansion. This project supports local agriculture, strengthens rural communities, and reflects a responsible approach to environmental stewardship. I also believe that an EIS is not necessary.

Sincerely,

Lonnie Fosso

Excellent company to work with. Care deeply for anything they are involved in, in my observations Thanks for you consideration.

Judy Lubenow **Letter 742**

I am writing this letter concerning the expansion of Riverview Dairy, which is about 2 ½ miles south of me. I have lived here since 1982.

1. **The odor from manure.**
2. **Dust from the roads both township and county.**
3. **My well water.**
4. **The increase of lines and hook ups along the ditches. (Road)**
5. **The movement of cattle – both cows and calves. In state – out state.**
6. **The effect on the land year after year.**
7. **The effect on surface water. There are lots of lakes, sloughs, creeks and rivers in this area. Also protected areas like wet lands and waterfowl areas. Where does the water (tiled or not) run into?**
8. **Who keeps track of spills, water quality, and so forth. Are they independent of the dairies??**

Judy Lubenow

Joe Neaton, MN National Farmers Board — Letter 743

Governor Tim Walz

LT. Governor Peggy Flanagan

Re: **Request for an Environmental Impact Statement (EIS} for Riverview LLP's Proposed Expansion of West River Dairy, Stevens County**

On behalf of Minnesota National Farmers with our state board voting on this action, I am writing to request that the Minnesota Pollution Control Agency require a full Environmental Impact Statement (EIS} before any permit is approved for the expansion of the Riverview LLP's West River Dairy in Stevens County. The scale of this expansion poses significant environmental, economic, and community risks that cannot be adequately evaluated through a simple Environmental Assessment Worksheet (EAW).

Environmental and Public Health Concerns

- **Groundwater depletion and contamination: Large dairies of this scale require millions of gallons of water annually, placing pressure on aquifers already stressed by agricultural use. Nitrate contamination from manure is a documented risk in regions with similar operations, threatening drinking water safety for rural households and municipal systems.**
- **Surface water pollution: Runoff from manure storage, land application, and feed storage areas increases the risk of phosphorus and nitrogen loading into nearby rivers, streams, and wetlands. This contributes to algal blooms, fish kills, and long-term ecosystem degradation.**
- **Air quality impacts: Emissions of ammonia, hydrogen sulfide, methane, and particulate matter from large dairies can harm respiratory health, reduce quality of life, and contribute to climate change. These impacts are especially concerning for nearby residents, schools, and vulnerable populations.**

Economic and Community Impacts

- **Local infrastructure strain: Heavy truck traffic associated with feed delivery, manure hauling, and milk transport accelerates road deterioration and increases maintenance costs for county and township governments.**

- **Depressed property values: Numerous studies show that proximity to large concentrated animal feeding operations {CAFOs) reduces residential property values due to odor, noise, and perceived health risks.**
- **Harm to independent farmers: Sadly, Minnesota is losing many dairy farms annually due to unreliable and most often below cost of production milk prices. Massive dairy operations like this one affects the market in a way that small and medium sizes family farms are put out of business and off the land. Any new producers will find it hard for a creamery to accept their milk because of the large amount of milk that is produced by these larger dairies. Loss of family farms have a trickle down effect on the local economy which affects Main Street Minnesota.**

Cumulative Impacts and Precedent

Riverview LLP's Dairy is one of the largest milk producers in the country. They own 16 permitted dairy Concentrated Feeding Operations (CAFOs) in Minnesota. The cumulative environmental burden-including groundwater withdrawals, manure spreading, and air emissions-must be evaluated comprehensively. Approving this type of expansion without a full EIS would ignore the broader regional impacts and set a troubling precedent for unchecked growth of industrial-scale livestock operations.

Need for a Full Environmental Impact Statement

Given the scale of the proposed expansion, the potential for significant environmental harm, and the long-term economic consequences for local communities, a full EIS is not only justified but necessary. An EIS would provide:

- A thorough analysis of cumulative impacts
- Transparent evaluation of alternatives
- Opportunities for meaningful public participation
- A science-based foundation for regulatory decision-making

For these reasons, I respectfully urge the MPCA to require a full Environmental Impact Statement before considering any permit approval for Riverview LLP's West River Dairy expansion.

Thank you for your attention to this matter and for your commitment to protecting Minnesota's environment and rural communities. Please feel free to contact me with any questions.

Sincerely,

Joe Neaton

State President

MN National Farmers Board

CC: Commissioner Thom Peterson, Mn Department of Agriculture

Commissioner Katrina Kessler, MN Pollution Control Agency

Dave Rozenboom, First Premier Bank — Letter 744

ATTN: Charles Peterson

My name is Dave Rozenboom, and I am the President of First PREMIER Bank, serving agricultural operations in Minnesota like Riverview. I am writing in support of their proposed West River Dairy expansion in Stevens County.

The agricultural sector is such a key driver in our local rural economies, and we are particularly dependent on a strong and stable livestock industry. Operations like Riverview's create consistent economic activity that supports local jobs, drives investment, and allows businesses like ours to grow and reinvest in our communities.

The proposed expansion represents a meaningful economic benefit to the region. It will generate demand for local vendors, support both construction and long-term employment, and contribute to the vitality of rural communities that rely on agriculture.

From our direct experience, Riverview is a professional and reliable partner that contributes positively to the communities where it operates. Their presence strengthens the local economy and supports a broad network of agricultural and service-related businesses.

Projects like this are essential to maintaining a competitive and sustainable rural economy in Minnesota. Continued investment in agriculture ensures that local businesses can continue to provide jobs, services, and economic stability close to home.

No EIS is needed as the state environmental review process is rigorous and very sufficient. I respectfully encourage your support and approval of this important project.

Sincerely,

Dave Rozenboom

President

Laurie Golden **Letter 745**

Please complete an Environmental Impact Statement on the proposed Riverview Dairy Expansion. My family lives in an area with 6 Riverview Dairies. Given the high concentration of dairies and heavy daily water use, how will water quality and supply change in 5, 10, or 20 years.

What impact will rivers, streams, aquifers, and wells face?

Land ownership and rental arrangements are becoming more concentrated among a small group of individuals or entities that are associated with the dairies.

How will the roads stand up to the constant heavy traffic of the equipment and trucks used during their harvest of hay ledge and silage? The equipment moves regardless of the weather or road conditions.

I encourage you to protect the future of our land and environment.

The decisions made now will have a profound impact on the quality of life for future generations.

We all need to open our eyes and see what is happening!

If this massive expansion is approved, what is to stop them from expanding every existing dairy?

There are still many unanswered questions about the impact of large dairy farms on communities, such as nearby towns, businesses, schools, churches, cooperatives, and grain elevators.

So, again I ask, please complete an Environmental Impact Statement on the proposed Riverview Dairy Expansion.

Sean Indrelie **Letter 746**

The dairy industry couldn't even survive without generous support from taxpayers, and this is how they repay us? Polluting our air and water? Rural Minnesota smells like feces because of farms like this. Bring back the sea of grass, save the soil and the pollinators. We're headed for global famine by the end of the century if we keep allowing industries like this to trash our only planet.

Sally Carlson-Bancroft **Letter 747**

This is way too big of a livestock operation. Can the company divide it into smaller pieces? Also, it would present unfair competition with traditional family farms. What will become of Princess Kay if all that's left are giant corporations?

Troy Metzger **Letter 748**

After reviewing the comprehensive Environmental Assessment Worksheet for the proposed West River Dairy Expansion, I am writing to support this project and am confident that the EAW document provides a thorough and well-supported analysis of the project's potential impacts. The level of detail already presented demonstrates that key environmental considerations have been carefully evaluated, and the information is more than sufficient to guide responsible permitting decisions. This expansion project represents an important opportunity for economic growth, job creation, and long-term investment in Minnesota and the EAW, and just as important Riverview's past performance and integrity, clearly show that it can move forward responsibly working within this appropriate and well-understood regulatory framework.

Kris Mielnik, Sterling Water Inc. **Letter 749**

ATTN: Charles Peterson

My name is Kris Mielnik, and I am with Sterling Water Inc. in Sauk Centre, Minnesota. Through my work, I collaborate closely with Riverview LLP, providing service and support for their dairy water treatment systems and assisting in maintaining high standards of water quality and efficiency across multiple operations. I am writing to express my support for Riverview’s proposed West River Dairy expansion in Stevens County.

From my direct, hands-on experience, Riverview has consistently demonstrated a high level of professionalism, accountability, and commitment to doing things the right way. Their operations reflect a strong focus on cleanliness, organization, and environmental responsibility. They invest in proper systems, maintenance, and oversight to ensure their facilities operate efficiently and in compliance with regulatory expectations.

Riverview also prioritizes providing a quality environment for their livestock. Their attention to water quality, system performance, and overall facility management contributes to animal health and productivity, which are critical components of responsible agricultural practices. This level of care is not only good for their operation but also supports broader environmental and sustainability goals.

Beyond their operational standards, Riverview is a dependable partner to those of us who work alongside them. They are proactive, responsive, and committed to continuous improvement. This reliability creates confidence for vendors, service providers, and regulators alike, knowing that they take their responsibilities seriously and follow through on their commitments. The proposed expansion represents a positive step for rural Minnesota. It will support local economies through job creation, increased demand for services, and continued investment in agricultural infrastructure. Businesses like

ours depend on stable, well-managed operations like Riverview's to sustain growth and continue serving communities across the region.

Based on my experience working with Riverview, I am confident in their ability to continue operating in a professional, clean, and environmentally responsible manner.

Thank you for your time and consideration. I respectfully encourage the MPCA to support and approve this project.

Sincerely,

Kris Mielnik

Sterling Water Inc.

Andrew Morley, Minnesota Chamber of Commerce **Letter 750**

c/o Charles Peterson

I write today on behalf of the Minnesota Chamber of Commerce (Chamber), a statewide organization representing more than 6,300 businesses and more than 500,000 employees throughout Minnesota. Thank you for completing a draft Environmental Assessment Worksheet (EAW) for the proposed West River Dairy Expansion.

The Minnesota Pollution Control Agency (MPCA) conducted a robust draft EAW that details the project's potential impacts. Evaluating and permitting livestock facilities is not a novel concept for MPCA and other regulatory bodies in Minnesota. The information provided in the draft EAW adequately captures potential impacts to air, water, land, and climate, while detailing the likely required permits.

Minnesota's detailed EAW process is designed to capture all potential impacts of an action. Responsible Government Units such as the MPCA are well equipped and experienced in drafting EAWs with project proposers to ensure Minnesotans understand the project. An Environmental Impact Statement (EIS) is not necessary because the EAW provides the agency with the information it needs for this type of project, per Minn. Rule 4410.4300.

As detailed in the EAW, the proposed West River Dairy Expansion proposes several water retention measures to continue being a leader in sustainability. Building retention basins, reusing an average of 90 million gallons per year of stormwater, and other efforts will help with water use. Further, the expansion must undergo a significant regulatory process for water managed by the Department of Natural Resources.

The dairy sector is an important piece of Minnesota's diverse economy. Expanding the West River Dairy will help Minnesota continue to be a national leader in milk and cheese production and remain as a net exporter of dairy products. The Minnesota Chamber supports the expansion and the benefits it will provide and looks forward to the next step in the process.

Sincerely,

Andrew Morley

Director, Environmental Policy

Minnesota Chamber of Commerce

James Murphy **Letter 751**

To whom it may concern. I am writing to provide some thoughts about Riverview LLP's proposed expansion in Morris of the West River Dairy.

I cannot speak to a lot of what I am reading in the various Minnesota publications' articles about this expansion. That being said, I can speak to my experiences with Riverview LLP.

I have a professional relationship with this company through my position as Executive Director of Traill County EDC. We have had a relationship with Riverview LLP since June of 2024 when they announced the project. Riverview LLP is currently building Herberg Dairy in our community of Hillsboro North Dakota.

At every point in this continuum, I have found the entire Riverview team to be honest, transparent and thorough. All you do is ask and you will get an answer. Part of that information gathering is going to view one of their existing dairies first hand. They are eager to show you how they do business and comply with the standards required. Go and take a tour, you will be glad you did.

From an economic perspective, it's been our community's experience that Riverview LLP is using local vendors, contractors and labor when practicable. That's exactly what I would expect of anyone building in any market. We are looking forward to a long and valuable partnership with Riverview and are excited for the opportunities that lay ahead.

Amanda Mayer **Letter 752**

I'm a concerned citizen of Minnesota that recently learned about the proposed expansion of the dairy farm. I feel the potential impact on our MN natural resources by this private company's expansion of operations is potentially enormous. To me, this very much warrants further exploration and closer examination of the details of this situation. I think a comprehensive environmental review of West River's plans would be extremely appropriate given the magnitude of impact this could have. The scope of this dairy farm expansion is unique. I support getting an Environmental Impact Statement before any permit approval and I hope you do too. Thank you for considering public commentary. We all share this beautiful state together.

Robert Padula **Letter 753**

I strongly support the West River Dairy Expansion near Morris, Minnesota by Riverview Dairy.

Riverview LLC has been an exemplary business and a role model for Agriculture companies. This local Minnesota Agribusiness has been open and honest in promoting their expansion plans to the general public prior to expanding and has gone above and beyond the legal thresholds to ensure compliance with the strict state feedlot rules and environmental requirements. If a proposed site has apprehension by local nearby residents, the company arranges for meetings and site tours of other facilities nearby to assure the local residents how a new site will operate. They have routinely been a good neighbor and work hard to maintain a positive relationships in the local area/community.

Family members of the dairy, farmers who supply feed to the dairy, the on-site workers and others who supply supportive services to Riverview LLC are active members in the community; Positive community relations are part of the business model. The people investing in Riverview are local owners, not "outside investors" - they are citizens that live in the communities where their dairy operations exist. It is not just the dairy owners, but all the supportive service providers that also live in the community. The Lauriston Dairy site is very close to MN highway 40 and is highly visible showing the public how they operate all the facilities. One only needs to drive near their other facilities to see that all of them are

well kept, maintained, neat & tidy demonstrating Riverview's commitment to being good neighbors in the local community.

Dairy farming in the area helps diversify agriculture away from the prevalent "mono-crop" rotation of Corn/Soybeans. This decreases the reliance on agricultural exports and provides a local outlet and value-added benefit to the crops grown locally. Not only will this benefit the farmers in the area, but all the supportive services that rely upon Agriculture and diversification of crops grown in the area will benefit. Diversification of agriculture in the area is also beneficial to wildlife and pollinators.

From the environmental and regulation point of view, feedlots of this size and capacity are heavily regulated and scrutinized to ensure compliance with the strict state regulations for water usage, runoff containment, manure management, dust, odor, pest control and animal health/well-being. This is done well before the first shovel of dirt is moved, prior to construction. The state does not allow a site to begin construction until all the environmental and regulatory permits have been granted. Riverview has always been open and upfront with expansion projects, complying with all the necessary local, state and federal guidelines. They employ staff that are trained and certified to maintain the requirements to ensure compliance. Being a large existing operation, they are constantly under the microscope and subject to outside scrutiny. If there is an area that needs improvement, staff and sites are willing to work with local, state and federal agencies to correct any issues and problems; in fact they seek out ways to be proactive, rather than reactive.

As a livestock farmer and former University of Minnesota Extension Service Livestock Production Systems Agent in West Central Minnesota, I managed a 10 county manure management in West Central Minnesota for 4 years. I know that Riverview has a proven track record of positive compliance and how they have been innovative and proactive in ensuring environmental safety and protection of the environment and local resources. The owners and farmers associated with Riverview also live in the community, and want to ensure that operations are not just "technically legal" but beneficial for the land and everyone who depends on it.

In closing, I fully and whole-heartedly support the expansion of of West River Dairy.

Steven Landwehr **Letter 754**

The Environmental Assessment Worksheet for this project looks very thorough and complete. Riverview has been a great role model in the industry at both designing and operating facilities that meet the strict guidelines that MPCA has laid out, the documents provided in the EAW supports that evidence. Their continued investment in rural Minnesota has helped many communities and farmers remain financial viable for the foreseeable future. These projects bring a valuable nutrient resource to local crop farmers instead of relying solely on commercial fertilizer imported from all over the world. In return these farmers are able to sell their crops locally, this process really reduces the environmental impact related to harvesting crops and getting them to a usable local source. The milk from the project ensures we have high quality food produced and processed locally for all to consume. I am in support of this as this is another project for rural Minnesota that provides new jobs, local economic growth, and an investment that will be there for generations to come that supports many other local residents and industries.

Maureen Mullen **Letter 755**

A dairy farm of this size is not a farm, it's an industrial facility. The water use and the pollution potential is outrageous. The treatment of 18,000 animals in a production facility is inhumane. This is not farming!

We need to support sustainable and healthy agriculture and actual farms, not industrial facilities.

I am concerned both about the potential pollution that this facility could cause to our ground water as well as the precedent. It could set for other facilities in our state. Our ground water is too precious to risk it!

Kara Lundin **Letter 756**

I oppose this expansion because it is an extreme environmental hazard, puts public health at risk, increases the elimination of family farms, and I do not support the poor animal welfare that happens at these large farms. This is not how we should be operating dairy farms. It is inhumane and disgusting. I will not purchase food for my family from dairy industries like this. Our water and our treatment of the life that sustains us should be priority. I strongly oppose the West River Dairy Expansion and would be deeply disappointed if the MPCA provided a permit for this facility.

Debra Ost **Letter 757**

I am strongly opposed to the proposed expansion of the West River Dairy which would create a "farm" totaling 18,855 dairy cows (over 26,000 + AU). I grew up on a small dairy farm in southeastern Ottertail County. Our livestock were treated humanely, the land was stewarded sustainably, profits were fair and competitive, and we were committed to a community that depended upon one another for mutual success. I feel that such a mega-farm, as proposed, is not consistent with the values of average Minnesota farmers, nor of the important agricultural history of our state.

Carrie Redden **Letter 758**

Dear Minnesota Pollution Control Agency,

I am writing to respectfully request that the MPCA require a full Environmental Impact Statement (EIS) for the proposed West River Dairy expansion project. I am a Stevens County livestock farmer, and former dairy farmer, with firsthand experience of the effect that consolidation in the dairy industry has had on limiting access to markets for small and mid-sized dairy farms.

Given the unprecedented scale of this project, a more comprehensive environmental review is both reasonable and necessary. A project of this magnitude carries the potential for significant environmental effects that extend beyond what can be adequately evaluated in an Environmental Assessment Worksheet (EAW).

I am particularly concerned about the projected water use and the cumulative impact on regional aquifers. An EIS would provide a more detailed assessment of these demands and their sustainability over time.

Additionally, the potential impacts on groundwater and surface water quality in the region warrants deeper examination. The proposed manure storage and land application plan raises important questions about nutrient runoff and nitrate contamination. Given the vulnerability of local water resources, including those connected to the Pomme de Terre watershed, these risks deserve a more rigorous and transparent analysis.

Beyond environmental concerns, the size and scope of this project raise broader questions about the long term socioecomonic impact across the state and region. I am passionate about thriving rural communities and feel strongly that we all benefit from more farmers on the land.

In this instance specifically, an EIS feels like commonsense guardrails that serve the greater good. An EIS would ensure that all potential impacts are thoroughly studied, that alternatives are meaningfully

considered, and that the public has a fuller opportunity to engage with the decision-making process. Given the significance of this proposal, anything less would fall short of the level of scrutiny this project deserves.

Thank you for your time and consideration, and for your commitment to protecting Minnesota's natural resources and communities.

Sincerely,

Carrie Redden

Lyn Kerschen **Letter 759**

Concerning the West river Dairy Expansion, an environmental impact study needs to be done. Morris is located along the watershed that channels many streams and lakes into the Pomme de Terre River. Many of these waterways are categorized as impaired by the Minnesota Pollution Control Agency because they failed to meet water quality standards.

Riverview's expansion would more than double its liquid manure storage capacity in Morris, from 102 million gallons to 250 million gallons. This expansion needs further review.

Jane Bartlett **Letter 760**

This is a bad idea all around. The site is in an environmentally sensitive watershed, there aren't people to work in the dairy, and most importantly we don't need it. Please vote "no".

Karen Rom **Letter 761**

Absolutely an EIS for starters; tho I live in Wisconsin now, I am well aware of the huge negative impacts CAFOs have everywhere; there are good reasons for supporting small farms, understanding why we need to limit our appetites for meat and dairy, including running out of water, the spread of disease among animals, the use of antibiotics which will affect human health, and the pollution to air, water, and soil from the enormous amounts of manure, etc. Biohazards need to be considered as well, and the treatment of animals is reprehensible. I don't believe current analysis by West Dairy would meet the standards we perhaps need to raise. Thank you for the EIS! We are trying to get more of them in Wisconsin as well as strong ordinances.

Becca R. **Letter 762**

ATTN: Charles Peterson

My name is Becca and I am writing in support of the proposed West River Dairy expansion in Stevens County.

Through their work in the agricultural sector, they depend on a strong and stable livestock industry. Operations like Riverview's create consistent economic activity that supports local jobs, drives investment, and allows businesses like ours to grow and reinvest in our communities.

The proposed expansion represents a meaningful economic benefit to the region. It will generate demand for local vendors, support both construction and long-term employment, and contribute to the vitality of rural communities that rely on agriculture.

Riverview is a professional and reliable partner that contributes positively to the communities where it operates. Their presence strengthens the local economy and supports a broad network of agricultural and service-related businesses.

Projects like this are essential to maintaining a competitive and sustainable rural economy in Minnesota. Continued investment in agriculture ensures that local businesses can continue to provide jobs, services, and economic stability close to home.

No EIS is needed as the state environmental review process is rigorous and very sufficient. I respectfully encourage your support and approval of this important project.

Sincerely,

Becca

Elias Hultgren **Letter 763**

I am writing today in support of the Riverview application to expand West River Dairy. As a young man trying to get my start in farming in the area shared with Riverview, I have seen first-hand the opportunities working with their dairies brings to our neighborhood.

One of my summer jobs has been running hay merger for our farm and we hire on with them to harvest their forages. I also work in hauling fuel in the silage season. The operations in forage harvesting for Riverview are partnerships between dozens of local farms and the dairy, working together toward a common goal which is quality feed for the cows. Safety is always the most important in all we do, and we work very hard to keep the roads clean and to operate with respect to motorists. We take pride in how good a field looks when we get done harvesting.

My family's farm has worked with Riverview for about 10 years and it has provided a good opportunity to add alfalfa to our crop mix and that strengthens soil quality. We put manure on as many acres as possible as it is very cost-effective compared to commercial fertilizer but also great for the soil.

I think that for my generation to be successful, we need to support progress in our rural areas and partner together to do something bigger than what we could do by ourselves. The West River expansion is a good example of what can be done when local farmers, rural neighbors, and dairy employees can do when they are all working together toward the common goal of safety, utmost care for the animals, and providing an opportunity for young people.

I encourage the MPCA to grant this permit to Riverview.

Sincerely,

Elias Hultgren

Paula Boogaard **Letter 764**

ATTN: Charles Peterson

My name is Paula and I am writing in support of the proposed West River Dairy expansion in Stevens County.

Operations like Riverview's create consistent economic activity that supports local jobs, drives investment, and allows businesses like ours to grow and reinvest in our communities.

Riverview is a professional and reliable partner that contributes positively to the communities where it operates. Their presence strengthens the local economy and supports a broad network of agricultural and service-related businesses.

Best,

Paula B.

Katherine Myers **Letter 765**

This dairy expansion recently came to my attention, and it's very concerning to me as a citizen of Minnesota. I value our clean water and beautiful land. I fear a massive dairy of this size will only increase water consumption and nitrate levels. These are decisions that can't be reversed and could have lasting environmental effects. I've also been a lifelong supporter of our local co-ops, so I value small family farming and cooperative farming. These corporate dairies are putting local small farms across the state out of business. On top of those considerations, I also have concerns about the animal welfare of a dairy that size. Animals are treated like numbers and dollar signs, which isn't the direction we need to be moving as a community.

Sharon Mansur **Letter 766**

I support the Land Stewardship Project's recommendation that this proposal by Riverview, LLP must be required to undergo a full Environmental Impact Statement (EIS). A facility of this scale located in such a vulnerable area calls for a thorough environmental review, and just as importantly, an EIS of the West River Dairy Expansion proposal would address socio-economic impacts. Industrial-Scale Projects Need Industrial-Scale Review! Thank you.

Aubree Derksen **Letter 767**

There needs to be analysis regarding water availability across industries given aquifers stretch across the region, the state and across state lines. Riverview is not happening in a vacuum, it is happening in the context of data centers that are also popping up exponentially wanting to draw from the same water sources as Riverview and use similar and higher amounts of water. We're also facing the same battle with them in trying to have it be required that they also must complete an EIS-not a single one of the now 20 some hyperscale proposals has completed an EIS and 7 are in court. 75% of Minnesotans rely on groundwater for their source of drinking water. The MPCAs own site lists 1800 old, unpermitted, mostly unlined solid waste dump sites that are contaminating our groundwater, with 43 construction and demolition dump sites being monitored only as of 2010 showing arsenic, boron and manganese at levels beyond human and environmental standards and mitigation efforts are not helping. That's only 43 out of 1800 that are even monitored? And the data centers alone could use millions of gallons of water a day each plus chemical contamination from industrial wastewater they claim is nonexistent (Pine Island) and they're not doing an EIS, and now Riverview wants 316 MGY plus contamination from manure. It is absolutely essential that MPCA require an EIS if it stakes any claim at all to caring about protecting clean water.

David Hauge **Letter 768**

Groundwater contamination issues shud b forefront of such expansion. That much manure in one location, creates potential problems overtime. Is a digester plan involved. Maybe the greatest issue will be the affect on smaller dairies. A farm of this magnitude will get all the business breaks smaller dairies will b unable to compete with

Faith Rudnitski **Letter 769**

The concentration of 18,855 dairy cows at one site and storage and spreading of the resulting liquid manure creates a risk of contamination of ground and surface water in the Pomme de Terre rivershed. An expansion of this size should be investigated more fully before a permit to construct and operate a facility with this many animals goes forward.

Tara Nelson **Letter 770**

I'm interested in MN investing in less dairy expansion and more wildlife conservation. There are awesome wildlife areas in Morris MN that I am worried could be impacted long term

Abby Konz **Letter 771**

Concern over one business owning 1/3 of the dairy cows in Minnesota. Also concerns over that much manure in one area as well as the water demand.

Garrett Luthens **Letter 772**

Dear Mr. Peterson,

I am a dairy farmer, and I am writing in support of Riverview LLP's proposed expansion of West River Dairy near Morris, Minnesota. My family owns and operates Skyview Dairy, a second-generation dairy that has been in operation since 1968, when my father started milking seven cows.

I am not writing this letter merely to support one company's project. I am writing because a growing milk supply benefits every dairy farmer in this state, and because Minnesota's environmental regulations are comprehensive, robust, and fully capable of protecting the environment without the need for an Environmental Impact Statement.

The economics of our industry are straightforward: when milk supply grows, processors invest. When processors invest, every dairy farmer — regardless of size — has a stronger, more reliable market for their milk. We are seeing significant growth in dairy processing capacity across the Upper Midwest and throughout the country right now, and a growing milk supply is needed to support those investments. The U.S. dairy industry has a great opportunity in front of it to grow. Minnesota should be leading that opportunity, not creating barriers to it.

I know from personal experience what it means to have a strong dairy industry behind you. When Skyview Dairy wanted to increase the size of our herd in 2008, the dairy community came to our support and spoke on behalf of the industry's positive financial impact on communities and the counties where we operate. A growing milk supply allows us to maintain the economic ecosystem that makes dairy viable for all of us.

Calls for an Environmental Impact Statement: they are not warranted by the facts or by the law. Minnesota already has one of the most robust environmental review and permitting systems for livestock facilities of any state in the country. This project has undergone lengthy and rigorous analysis through the EAW process. And the expansion will operate under an Individual NPDES Feedlot Permit — more stringent and site-specific than the general permits most Minnesota feedlots operate under — requiring zero discharge of pollutants to waters of the state. Coupled with the DNR's protective groundwater permits, the environment will be protected.

Furthermore, the individual permit set to be in place here was developed after a collaborative process with the MPCA to develop enhanced permit requirements. That kind of good-faith engagement with

regulators should be encouraged, not punished by an unnecessary EIS that would only delay a well-reviewed project.

I believe a strong, growing dairy industry is good for every farmer in this state. The West River Dairy expansion supports that. It creates jobs, provides a market for locally grown crops, and supplies locally produced fertilizer (manure) to. I respectfully urge the MPCA to follow the facts and the science. The EAW is thorough and complete. The environmental protections are robust and enforceable. No EIS is needed. Please allow this project to move forward without further delay so that Minnesota's dairy industry can continue to grow — for our communities and for the next generation of farm families.

Thank you for the opportunity to provide this comment.

Garrett Luthens Skyview Dairy

Tony Domnick **Letter 773**

Public Comment – Support for West River Dairy Expansion

My name is Tony Domnick, and I live approximately 3.2 miles from West River Dairy. I have lived here since the dairy was first established, and I am writing in support of the proposed expansion.

As I sat down to write this, I came to the conclusion that this isn't something we need to ruminate on forever. We can't milk these concerns beyond reason. At some point, we need to be honest with ourselves, has Riverview hurt me, or have they helped me? Have they hurt the community, or have they helped it?

Let's separate the cream from the milk, the facts from the fluff.

Businesses that have chosen to work with Riverview have continued to grow and prosper, bringing additional opportunities and jobs into our area. A thriving community leads to stronger local businesses, more opportunities for families, increased school enrollment, and a safe, clean place to live. Even those without direct ties to the dairy still benefit from that growth.

Like any operation, there are occasional growing pains, minor nuisances, frustrations, and differing opinions. No business is perfect. But from what I've seen, Riverview has been willing to address issues and take responsibility when needed.

From a neighbor's perspective, living just over three miles away: our shallow well still provides clear water. Road concerns like mud or dust from truck traffic are addressed quickly. What is a problem one day is typically resolved the next. We've also had the opportunity to sell alfalfa and silage to the dairy and receive manure in return, which has been a significant benefit to our family farm.

Some may ask, "When is enough, enough?" And maybe I'm blinded by my addiction for cheese, but this is the community where Riverview started, and it's clear they are committed to staying here. Expanding in an area where they are already established, among neighbors who are familiar with their operation, seems to bring more benefits than drawbacks. Increased demand for feed and additional acres for manure application both support local farmers and strengthen the agricultural economy.

This expansion represents continued growth and opportunity for our community, and I believe it deserves our support.

Sincerely,

Tony Domnick

Kent Bosch **Letter 774**

I am commenting to support Riverview's expansion project near Morris. We consider ourselves lucky to farm in close proximity to two of Riverview's newer facilities in Chippewa County Minnesota. Our county was void of livestock for the most part before Riverview got involved. They are adding a needed dimension and diversity to our farmland. The liquid dairy manure is great for the soil health and better quality and lower cost than commercial Fertilizer. Putting alfalfa into our sugarbeet and corn rotation adds diversity to our other wise fairly monocrop system. Also, we are adding value to our corn Crop locally rather than shipping it overseas or out of our area on rail. This alone helps with the price by creating a lower basis for all corn producers in western Minnesota. And I can say that Riverview has been a very good environmental steward and super good neighbors while providing good jobs and opportunity for young families wanting to stay involved in farming. Most of the negative comments I see on these dairies has to do with size and scale. My thought on that is that it is better to have this type of animal agriculture than to not have any. That is where we were headed in my neighborhood. I am third generation living and farming where I am and have been around, livestock most all of my life. I know of no other smaller farm that takes better care of their animals and the environment than Riverview does.

Evan Grong, Valley Queen Cheese Factory, Inc. **Letter 775**

c/o Charles Peterson

I am writing on behalf of Valley Queen Cheese Factory, Inc. to formally express our strong support for the Minnesota Pollution Control Agency’s approval of Riverview LLP’s permit application for the proposed expansion of the West River Dairy.

Valley Queen Cheese Factory, Inc. is a South Dakota-based, privately held cheese and dairy ingredients manufacturer headquartered in Milbank, South Dakota, where we have operated since 1929. Today, Valley Queen employs more than 450 people and remains deeply committed to providing long-term economic opportunity for our employees, business partners, and the rural communities in which we operate. Valley Queen has grown in step with the dairy industry. Most recently, we completed a significant expansion project in 2025 representing an investment of more than $200 million, which increased our milk processing capacity by over three million pounds per day. Looking forward, Valley Queen intends to continue growing to meet increasing customer demand for dairy products. That growth relies on a stable supply of high-quality milk from progressive, well-managed dairy farms.

Riverview LLP has been a trusted and valued dairy producer partner of Valley Queen for more than two decades. Throughout this relationship, Riverview has demonstrated exceptional standards in milk quality, animal care, operational management, and environmental responsibility. Based on our longstanding experience working with Riverview, we are confident in their ability to responsibly execute the proposed expansion at the West River Dairy in full compliance with applicable environmental regulations and MPCA permit requirements.

Continued, well-regulated growth within the regional dairy industry provides meaningful benefits to local and state economies while maintaining strong environmental oversight. Dairy operations generate significant economic activity across rural communities, supporting employment, local businesses, and agricultural stability throughout the region. Responsible expansion projects such as this one help ensure

that dairy production growth occurs within a regulated framework that protects natural resources while sustaining economic vitality.

For these reasons, Valley Queen Cheese Factory, Inc. respectfully encourages the Minnesota Pollution Control Agency to approve Riverview LLP's permit application for the West River Dairy expansion. We appreciate the Agency's careful review and its role in ensuring environmentally responsible development across Minnesota.

Sincerely,

Evan Grong

Dairy Ingredient Sales Manager

Nathan DeLeeuw, Dooley's Natural Gas **Letter 776**

To whom it may concern,

I am writing on behalf of Dooley's Natural Gas in support of the proposed 11,000 cow dairy in Section 1 of Synnes Township in Stevens County. As an organization who works closely with agricultural producers and rural businesses, we believe it is important to recognize projects that strengthen our local economy while demonstrating responsible planning and long-term commitment to the communities they serve. Thoughtful agricultural development is essential to preserving rural vitality, and this proposal represents an opportunity to do exactly that.

One of the most meaningful contributors to that economy in Stevens County is Riverview Dairy. Riverview Dairy has made significant and lasting contributions to the local economy through job creation, capital investment, and ongoing support of local businesses. Beyond their economic impact, they have consistently demonstrated commitment to the communities in which they operate and have proven to be responsible stewards of the land and natural resources.

Dooley's has been a fuel and propane provider to Riverview Dairy for several years. Through this business relationship, our company and employees have directly benefited from Riverview Dairy's growth and continued investment in the region. Their success supports not only agricultural operations but also local service providers, suppliers, and workers throughout the rural economy.

In closing, we believe Riverview Dairy's proposed expansion reflects the type of responsible agricultural growth that benefits Stevens County both now and into the future. Their track record of economic contribution, environmental stewardship, and community involvement demonstrates that they are a trusted partner in rural development. For these reasons, we respectfully express our support for this project and encourage decision-makers to recognize the positive impact it will have on our local economy, workforce, and agricultural sustainability.

Sincerely,

Nate DeLeeuw

General Manager

Dooley's Natural Gas

Kathy Arthun **Letter 777**

Dear MPCA Officials,

I am writing as a concerned resident to strongly urge the Minnesota Pollution Control Agency (MPCA) to require a full Environmental Impact Statement (EIS) for the proposed expansion of Riverview, LLP's dairy concentrated animal feeding operation (CAFO) in Stevens County.

Due to the unprecedented magnitude of this proposal, Minnesotans deserve the highest level of environmental review available. This would be the largest livestock operation in state history, and a project of this scale warrants far greater scrutiny than a standard review process provides.

I have been a volunteer lake and stream monitor for the MPCA since 2019. I monitor Barrett Lake, which is part of the Pomme de Terre watershed downstream of the proposed site, and I have also monitored the Pomme de Terre River where it enters Barrett Lake. Over that time, I have observed a decline in water quality. Even without a facility of this size upstream, there are already many weeks each year when Barrett Lake is not suitable for recreation. The addition of a 26,000+ animal operation raises serious concerns about further degradation.

This proposal presents several significant risks:

Water Use and Water Quality

A facility of this size would require substantial water use and generate an enormous volume of manure. Given the location within the Pomme de Terre River watershed, near already impaired waters, the risks of nutrient runoff, groundwater contamination, and accidental spills must be thoroughly evaluated.

Proximity to Sensitive Areas

The site is within five miles of multiple protected waterfowl and wildlife production areas. These are sensitive ecosystems that could be significantly impacted by contamination or runoff.

History of Environmental Incidents

Riverview has experienced manure management issues in the past, including a 2025 leak at its Meadow Star Dairy facility in Kandiyohi County. This history underscores the need for careful, comprehensive review.

Impacts on Rural Communities

An operation more than 60 times larger than the average Minnesota dairy farm could accelerate consolidation, harm small and mid-sized farms and alter the character of rural communities. Residents may also experience increased traffic, odor, and air quality concerns, along with potential declines in property values.

I value living in this area and the natural resources it offers. However, a project of this scale raises serious concerns about long-term environmental quality and community sustainability.

For all of these reasons, I respectfully request that the MPCA require a full Environmental Impact Statement before proceeding with any approvals for this project.

Sincerely,

Kathy Arthun

Steve Veverka **Letter 778**

I am writing this communication to express my full support for the expansion of the Riverview West River dairy expansion. Modern agriculture is complicated. No ag business in Minnesota navigates that complicated system better than Riverview . The fact that they incorporate a diverse, highly paid work

force and are excellent stewards of the environments is really one of the great agricultural success stories in Minnesota . The current review process is completely adequate and an EIS is not necessary.

Margie Diggins **Letter 779**

I'm against forcing animals into these crowded, non pastured, conditions for the sake of more efficient milk production. Cows should be out in green pastures under sunshine & called in twice a day to be milked, like I was raised on our small hobby farm. I no longer support dairy from these big industrialized facilities. Grass fed naturally is where food production is going...catch a clue... It's much healthier for us & our children & the animals. Thank you for listening.

William Henke **Letter 780**

Hello and thank you for allowing the public to comment on this project. In my opinion this project should not be allowed to proceed. I believe that this project is environmentally dangerous in terms of the mammoth amount of manure that it will distribute and the quantity of water needed to support it. An EIS should absolutely be required before any further steps are taken. In addition, I believe that CAFO's are inhumane, a severe risk for zoonotic infections and a public health risk in terms of increasing antibiotic resistance. Lastly, these huge confinement operations have been the death knell to the small dairyman (woman) and the small rural communities that support them. We can do so much better! William Henke

Cody Harford **Letter 781**

I am commenting to express concern about the proposed Riverview West River dairy. This 18,500-cow facility would add to Riverview's already extensive operations in Minnesota, where the company houses more than 133,000 cows—about one-third of the state's dairy herd. Continued consolidation on this scale has contributed to the steep decline of family dairies, which are essential to the economic and social health of rural communities.

A single facility of this size also carries significant environmental risks, including manure management, water use, and air quality impacts. These cumulative effects should be carefully evaluated.

I urge the MPCA to fully consider both the environmental and community consequences before approving a project of this magnitude.

Kathleen Von Rueden **Letter 782**

These large livestock produce huge pollution to ground water risk, manure spill risk and crowded living conditions for livestock.

Scott Savage, E. A. Bonelli + Associates, Inc. **Letter 783**

ATTN: Charles Peterson

My name is Scott Savage, President of E.A. Bonelli + Associates, an architectural and engineering consulting firm that serves the dairy industry and supports operations in Minnesota like Riverview. I strongly support their proposed West River Dairy expansion in Stevens county.

The proposed expansion represents a meaningful economic benefit to the region. It will generate demand for local vendors, support both construction and long-term employment, and contribute to the vitality of rural communities that rely on agriculture.

Our firm has been working closely with Riverview for over five years and, in that time, we have known Riverview to be a professional and reliable partner that contributes positively to the communities where they operate. We believe in Riverview's mission to strengthen the industry and address critical gaps. Riverview has a genuine commitment to their employees, the local communities in which they operate, and their agricultural partners. Their presence strengthens the local economy and supports a broad network of agricultural and service-related businesses.

Projects like this are essential to maintaining a competitive and sustainable rural economy in Minnesota. Continued investment in agriculture ensures that local businesses can continue to provide jobs, services, and economic stability close to home.

No EIS is needed as the state environmental review process is rigorous and very sufficient. I respectfully encourage your support and approval of this important project

Sincerely,

Scott Savage

President

E. A. Bonelli + Associates, Inc.

Cody Suter **Letter 784**

Cody Suter

To Whom this may Concern. I live 1.5 miles from a Riverview Dairy. They run a top tier operation, clean facilities, care for the land, do what is right for the local communities, and give great care to the livestock in their operations. These Dairy's I believe help the local Ag community in a number of different ways such as 1. providing manure for fertilizer so we do not need to rely on foreign Fertilizers that are controlled by a few major producers around the world 2. Giving local farmers another place and market to sell their crops they produce, this helps create demand and increases local basis markets that adds value to every producer in the area no matter if you are in favor of this project or against. From the outside looking in I know they follow a long list of rules and regulations; they are doing things correctly. This project and other projects like this add value to rural America. I support their expansion project in Stevens County

Michelle Peterson **Letter 785**

I want to continue living in a state with higher standards than other states. I want to be proud of the environmental firsts Minnesota can show in this Era of backsliding.

Audrey Kruger **Letter 786**

I vehemently oppose this expansion. Small, regenerative farms are the only future I want to see in farming.

Amie Tatosian **Letter 787**

We should be supporting small, local farmers, not promoting and allowing for massive operations like this one. This is beyond the environmental impact of having so many animals in a small area, it is also about caring about our local farm families that have been around for generations. Mass production is not the answer.

Sean Gallant, Industrial Environmental Concepts **Letter 788**

ATTN: Charles Peterson

My name is Sean Gallant, and I am one of the owners of Industrial Environmental Concepts, a Geomembrane Cover/Liner Business serving agricultural operations in Minnesota like Riverview. I am writing in support of their proposed West River Dairy expansion in Stevens County.

Through our work in the agricultural sector, we depend on a strong and stable livestock industry. Operations like Riverview's create consistent economic activity that supports local jobs, drives investment, and allows businesses like ours to grow and reinvest in our communities.

The proposed expansion represents a meaningful economic benefit to the region. It will generate demand for local vendors, support both construction and long-term employment, and contribute to the vitality of rural communities that rely on agriculture.

From our direct experience, Riverview is a professional and reliable partner that contributes positively to the communities where it operates. Their presence strengthens the local economy and supports a broad network of agricultural and service-related businesses.

Projects like this are essential to maintaining a competitive and sustainable rural economy in Minnesota. Continued investment in agriculture ensures that local businesses can continue to provide jobs, services, and economic stability close to home.

No EIS is needed as the state environmental review process is rigorous and very sufficient. I respectfully encourage your support and approval of this important project.

Sincerely,

Sincerely,

M. Sean Gallant

Director of Operations

Lori Peterson **Letter 789**

Do not allow this monstrosity to expand!!! Horrific for animals and the environment

Cassie Dudley **Letter 790**

I am writing in earnest opposition of this expansion and in favor of an obligatory EIS. Progress can no longer equal capital growth and expansion if we are to continue to inhabit this planet. Shortsighted economics are causing incredible suffering to numerous species whose sentience should not be ignored. Agricultural workers in feedlots incredible health risks. West River Dairy and CAFOs in general need to be phased out, not expanded! They displace small scale MN family farms, reduce rural property values, impose numerous environmental impacts including water and air quality degradation, and inflict public health concerns such as respiratory illnesses and disease transmission. The long-term pollution impacts cannot be overlooked while regulations aimed at tracking manure application face backlash. As is obvious in the letters of support, the only people in favor of this expansion are those who will fatten their wallets out of the deal. MPCA must enforce policy that protects our planet and people. "Only when the last tree has been cut down, the last fish caught, and the last stream poisoned, will you realize you cannot eat money."

Shane Wiercinski, Complete Filtration Resources, Inc. **Letter 791**

Dear Mr. Peterson,

My name is Shane Wiercinski, and I am the Director of Business Development for Complete Filtration Resources, Inc. (Complete Filtration), a filtration and wastewater treatment solutions provider serving dairy operations across the country, including Riverview, a valued partner and customer. I am writing in strong support of Riverview's proposed West River Dairy expansion in Stevens County.

At Complete Filtration, our work is deeply tied to the health and growth of the agricultural and dairy industries. Projects like the West River Dairy are exactly the type of responsible, well-managed operations that anchor rural communities and create lasting economic opportunity.

This proposed 11,000-cow expansion is a significant investment in Minnesota agriculture and in the communities that depend on it. Projects of this scale generate substantial demand for vendors, suppliers, and service providers, including companies like Complete Filtration, and support both direct and indirect employment throughout the region. They also reinforce the infrastructure needed to sustain a competitive dairy industry in the Upper Midwest for years to come.

From our direct working experience, Riverview is a professional, forward-thinking operation that takes its responsibilities seriously. They invest in the right equipment, maintain their systems to a high standard, and engage meaningfully with the vendors and partners who support them. We have every confidence that they approach environmental stewardship with the same level of commitment.

We understand that Minnesota's environmental review process is thorough and rigorous, and we trust that Riverview has engaged fully with that process. An Environmental Impact Statement does not appear necessary given the existing review framework and the demonstrated track record of operations like this one. We respectfully urge the Minnesota Pollution Control Agency to support approval of this important project.

Continued investment in production agriculture is essential to keeping rural Minnesota vibrant. Thank you for the opportunity to comment, and for your consideration of the voices of the businesses that depend on and contribute to this industry.

Sincerely,

Shane Wiercinski

Director of Business Development

Complete Filtration Resources, Inc.

Paul Burck **Letter 792**

The proposed Riverview Dairy expansion is so huge that it should be required to complete an Environmental Impact Statement before a permit is granted by the MPCA.

Jeff Steiner **Letter 793**

To Whom It May Concern,

I am a longtime resident of the Morris area with a degree in Agronomy, and I worked for many years as a Certified Crop Advisor in Stevens County, including working directly with Riverview Dairy in 1995 when the very first dairy was built. In addition, I have had the opportunity to tour Riverview's facilities on multiple occasions over the years. I am also personally acquainted with many Riverview employees and managers. Based on these firsthand experiences, I fully support the proposed project and believe the

Environmental Assessment Worksheet (EAW) provides an adequate level of review; I do not see the need for a full Environmental Impact Statement (EIS).

Some of the concerns expressed about manure management seem to overlook the existing regulatory framework. Facilities of this type are already subject to strict oversight through MPCA feedlot permits and detailed manure management plans. This proposal includes more than a full year of manure storage capacity and access to significantly more land for application than is required by regulation. These requirements are specifically designed to protect water quality and ensure responsible nutrient use. As an agronomist, I can attest to the superior value and desirability of using manure as a fertilizer and nutrient source for crops, both for crop productivity and for enhanced biome management and excellent soil health.

I would also urge reviewers to consider the actual long-term water monitoring data for the Pomme de Terre River watershed. Information collected over the past decade shows that water quality and biological health in the watershed has remained stable, despite agriculture being a dominant land use in the region for many years. Any concerns regarding potential impacts to the Pomme de Terre River, Drywood Creek, or Muddy Creek should be weighed against this historical data.

Furthermore, with regard to water use, it is important to note that groundwater withdrawals for projects like this are carefully reviewed and permitted by the Minnesota Department of Natural Resources. This permitting process is intended to ensure sustainable use of aquifers, and it applies equally to agricultural operations, other industries, and communities.

It is disappointing to read comments from individuals who appear to have limited familiarity with the local area and the way in which Riverview operates. The company has earned a strong reputation in our community for running well-managed facilities. Whenever I have visited, the sites have consistently been clean, orderly, and clearly operated with a high degree of professionalism and care. In contrast, many of the small dairies I see in the area often have significant manure run-o concerns and excessively untidy facilities. The pollution potential from the 220 “small” dairies, each with 50 cows, needed to supply equivalent milk for our needs would have significantly more impact on our environment than what I have seen from the highly skilled operators at Riverview Dairy.

In addition to the environmental considerations, Riverview has been a strong partner for the young people in our communities, promoting modern, science-based farming practices, hosting student tours that provide meaningful learning opportunities about animal care, technology, and sustainable food production, and encouraging pursuit of higher education through scholarships, internships, and on-the-job training, and generally providing experiences that benefit countless young people exploring careers in agriculture and environmental fields.

Riverview plays a vital role in supporting the local economy. As a resident of our small community and the surrounding county, I have observed how major employers like Riverview help provide stability for rural communities by supporting local suppliers, contractors, and other businesses across the region. Many of the employees’ children attend our small independent Hancock School District and have helped sustain and grow a school that had 225 students in 2011 and now has more than 450 students!

In summary, I encourage the reviewing agencies to base their decision on the available data and the established regulatory processes. The EAW appears to offer a thorough evaluation of potential environmental impacts. For these reasons, I believe the EAW is sufficient and that a full Environmental Impact Statement is not required.

Thank you for your attention to this matter.

Sincerely,

Jeff Steiner, BS Agronomy, University of Illinois ‘90

Patricia Cole **Letter 794**

To Whom it May Concern,

I am writing to formally express my strong opposition to the proposed expansion of the Riverview dairy operation in Morris, Minnesota. As a concerned citizen who worked for over 40 years as a Registered Professional Engineer, I believe this project—which would become the largest livestock farm in state history—poses unacceptable risks to our local environment, our groundwater and the health of our community.

My primary concerns include:

Water Depletion: The facility is permitted to pump up to 226 million gallons of water per year. This massive appropriation rivals the consumption of the entire City of Morris (permitted for 300 million gallons) and threatens to deplete local groundwater and impact the Pomme de Terre River.

Nitrate Pollution: The collection and application of manure from such a massive number of animals significantly increases the risk of nitrates leaking into groundwater. Given Riverview's history of manure spills in western Minnesota, I am deeply concerned about the long-term safety of our drinking water, and the impact that will have on the cancer rates of those living in the area.

Inadequate Environmental Review: I join organizations like the Land Stewardship Project in calling for a full Environmental Impact Statement (EIS). The current Environmental Assessment Worksheet (EAW) is insufficient to address the unprecedented scale of this facility and its cumulative impacts on the region's land and water.

I urge the MPCA to deny the current permit and require a more rigorous environmental review to protect the health and resources of Stevens County residents. The impact of these large scale corporate farms and livestock enclosures on the health of our groundwater aquifers needs to be of concern to ALL Minnesotans!

Sincerely,

Patricia Cole

Kay Fuller **Letter 795**

I have switched from regular ultra pasteurized milk to low temp pasteurized milk from small farms. I am opposed to larger and larger dairy farms. It seems like smaller dairy farms could employ as many people and it would be boom to small business. It also seems that raw and low temp pasteurized milk are coming back into favor. Please don't let this large dairy take over more small dairy farms!

Jackie Colesworthy **Letter 796**

I am opposed to this operation for several reasons. Having this many animals on a feedlot is inhumane treatment. The waste from them would be damaging to the environment, and I would never drink an ounce of milk from such an operation. Restorative, regenerative farming is the best way to treat animals and the soil they live on. Please turn this proposal down.

Jennifer Zeltwanger **Letter 797**

Subject: Support for West River Dairy Expansion

My name is Jennifer Zeltwanger and I've lived in Darnen Township, Stevens County for 17 years about two miles from Riverview Dairy. Our home is about eight miles from West River Dairy.

Based on our experience as neighbors, I support the West River Dairy expansion. No EIS is needed as the state environmental review process is rigorous and very sufficient. I reviewed the over 600 pages of documents in the EAW with input from numerous industry professionals and am impressed with the amount of time, effort, energy, and cost that has already gone into the permitting process to get to this point. As a fellow cattle producer, I fear the precedent that could be set by requiring a farm that has clearly already met all the requirements set out by the MPCA to obtain their permit to move into a new level of regulation. I respectfully encourage your support and approval of this important project and believe the expansion will continue to reflect the same level of care and professionalism Riverview has demonstrated time and again.

As very close neighbors to Riverview Dairy, we've been able to see how the dairy is managed and maintained in a clean, professional manner. Our house is across the road from a field farmed by Riverview for cattle feed and is on the harvest truck routes. Truck traffic has been handled responsibly, and local roads are kept in good condition through pre-season application of chloride for dust control and box scraping to remove mud or repairing as needed. This happens around all the sites in our county, including at West River Dairy.

Having the three local Riverview dairies has provided stable employment opportunities in our community for service providers, construction companies and other local businesses. Expansion at West River Dairy builds on this by bringing in additional jobs, families, and opportunities. Small towns like ours need growth to support our schools, businesses, and civic leadership needs so a quality business like Riverview adding additional passionate staff members who participate in the community is a boon for Stevens County.

After living near another of Riverview's dairies in Stevens County for nearly two decades, we have had no negative impacts on our lives (not on our well, our land value, our family, our community). In fact, I would say the opposite is true. Having Riverview's dairies in our area has brought more opportunity and diversity to our community and enriched our experiences living in the Morris area. I urge your support of the approval of the West River Dairy Expansion in Stevens County.

Sincerely,

Jennifer Zeltwanger

Crystal Prom **Letter 798**

To whom it may concern,

I am writing to dissuade the use of an EIS with regards to the expansion of Riverview in Stevens County. I, as an experienced dairy consultant in the Upper Midwest, have visited several Riverview sites and found them to be clean, professional, and committed to producing nutritious milk products while also being good stewards of the land. Going through the EIS process will be an expensive and time-consuming waste of resources and only stand to harm dairy product consumers. From my observations, Riverview is an excellent boon to the rural communities of Minnesota and beyond.

I am asking that you do not proceed down the EIS pathway and instead follow normal environmental assessment processes with regards to dairies.

Sincerely,

Crystal Prom, PhD

Dairy Focus Consultant

Thomas Obar **Letter 799**

I am in favor of the expansion of the dairy.

Ethan Hoffman **Letter 800**

I am in favor of the expansion.

Nick Meierhofer **Letter 801**

I am in favor of this expansion. Great company.

Corey Roberts **Letter 802**

For what reason does Riverview need to keep expanding their dairies? They are already running small farmers out of business. The same small dairies that built communities. The same communities that are becoming ghost towns because places like riverview dairies don't support local infrastructure. Veterinary, construction, etc., are done in house and don't support members of local community. They say they create jobs but bring in more illegal immigrants for cheap labor. They use their size and scale to push others around. Basically taking over AMPI (Associated Milk Producers Inc.) and claiming a $2cwt premium over other producers for a "volume discount". With milk prices already where they are, how can other dairy producers compete? With dairies of such scale comes greater risk of pollution as well. Look at the what has already happened when an upright manure silo exploded at the Meadowstar location in Pennock, Mn. Shrapnel of the silo and hundreds of thousands of gallons of liquid manure littered the ground. Not to mention that anybody nearby when that happened would have been killed. Loss of nitrates from such manure spills end up in our water. This affects wildlife and have the potential to lead to cancerous cases, diminishing the quality of life. How can we let systems like this continue to go into place? Riverview does not support local community infrastructure nor are they good for environment.

Sandra O'Brien **Letter 803**

I am very concerned about the negative impact on the environment if West River Dairy is allowed to expand as requested. It goes against everything I have learned about Minnesota farms working towards sustainability. The extra manure and methane would contribute to climate change, water pollution and air pollution. Can the neighbors enjoy breathing in fresh country air near the dairy as it is now? And the humane treatment of cows would be a great challenge with so many extra livestock. Expansion also jeopardizes the livelihood of smaller dairy farms. There are so many reasons against it. Please do not approve.

Kyle Staebler **Letter 804**

ATTN: Charles Peterson

My name is Kyle Staebler. I am a resident of Swift County, and I farm in Stevens County. I am writing in support of the proposed West River Dairy Expansion.

I grew up on a small neighboring, family dairy farm in Stevens County about four miles from Riverview Dairy. My grandfather milked for forty years and later chose to transition to grain farming. I have seen Riverview's commitment to being a good neighbor to my family, other local farmers, and businesses.

I have worked with Riverview on many occasions at their facilities. Their operations are well kept, organized, and clean; staff consistently conduct themselves with professionalism and an emphasis on safety.

Manure management and water use are highly regulated in Minnesota, and Riverview has demonstrated attentiveness to those regulations and to nutrient management. There are clear benefits to the responsible use of manure on farmland to improve the soil health, organic matter, and reduce erosion to support long-term agricultural sustainability.

Riverview is diligent with soil testing and manure application, ensuring they meet or exceed required standards.

Based on the available data, existing regulations, and Riverview's proven track record, I am confident this project can continue to operate responsibly. I believe the current review process is sufficient and that additional regulatory burdens, including an EIS, are unnecessary.

I respectfully encourage the appropriate agencies to approve the West River Dairy

Expansion.

Respectfully,

Kyle Staebler

Kelsey VanOverbeke **Letter 805**

My name is Kelsey VanOverbeke and I would like to not only express my support for the expansion project at West River Dairy, but also give my personal & professional experiences interacting with Riverview directly & indirectly. I grew up on a farm near Campbell, MN which some of our family land is near the Campbell Dairy location. I have worked in the local agriculture industry in MN, ND & SD mainly within the counties of Wilkin, Traverse, Grant, Ottertail, Big Stone & Stevens in MN; Richland, Sargeant, Barnes in ND & Roberts in SD for 20 years as a professional agronomist with a B.S. degree in Agriculture Economics & also Crop & Weed Science from NDSU, Certified Crop Advisor including credential of certification to work with large dairy operations, Technical Service Provider for the NRCS including 590 & 595 mainly for Nutrient Mgt & IPM. I work with 32 farms that account for about 285,000 acres of farmland mainly in an 80 m radius of Fairmount, ND.

My first experience with Riverview was when the Campbell Dairy was proposed. From a farm girl perspective of it being my hometown, you always wonder who is this "new business" that is moving in and change is hard for anyone to accept. However, the way Riverview was honest & transparent with their intentions as well as the legal steps they had to take to even have the project considered, let alone a permit approved, exceeded the expectations of myself and so many others that I heard from in the community and through the daily conversations of my job. As they always say, "Good intentions are overrated. Good actions is where the proof of character exists." Riverview showed our community of Campbell MN the proof of their character as a business and as people; not just in the business interactions but also their support for the community and working with neighbors both farmer neighbors and non.

Fast forward to current interactions with Riverview management, local dairy location management and staff in the Red River locations & Stevens locations, farm operations management and staff as well as

their agronomists, contracted operators, etc; my impression of Riverview as a dairy operation, farm operation & the people in general keeps exceeding my expectations with every interaction I have with them. Again, as an agronomist I interact with many farm managers, operators, staff, etc on a daily basis & what I can confidently say about Riverview Personnel is that they carry themselves in a professional, ethical manner in which they always are more than happy to hear any questions, concerns, recommendations, etc anyone has to offer. They follow their legal & moral duties without wavering. I cannot say that about too many businesses otherwise that go to the extent that they do. They have a large business to run, but unlike most people I see with that much responsibility, they always seem to make time to spend time in their community, with local growers & neighbors, youth, etc whether it be in a community parade event to show support or a winter meeting providing an educational presentation and open discussion with their very knowledgeable Master Agronomist whom I have a great deal of respect for.

Knowing the massive amount of agronomic benefits having manure in your crop rotation can provide in various ways as well as the diversity of the alfalfa in crop rotations and silage as an option as well; the Riverview Dairy locations in our Red River Valley area have provided intangible benefits & measurable returns to the local farmers who participate in a relationship with Riverview. I know through direct conversations with growers in that area that tell me if Riverview had not been approved to set up their dairy location in our local home area of Campbell & Nashua (Campbell Dairy & North Ottawa Dairy); there would have been some tough decisions to make on some farms to either rent out or sell in some cases. However, because Riverview set up a dairy and offered silage & haylage acres including the option of manure, those farms are still in operation today and thankful the opportunity was there for them to diversify their operations and their source of nutrients to help with the biology of their soil as well as the organic matter & water holding capacity that had been struggling in recent years. I have seen this first hand in fields I work with directly that there are many agronomic advantages to the soil health & biology mainly through carbon sequestration that the alfalfa provides, improvements in Organic Matter & C:N balance in creating a balanced soil biology for microbes to excel in creating better soil health and mineralization, etc. I walk alfalfa fields weekly and am so thankful that we are able to grow it in the Valley where it typically would not have any reason to be grown otherwise. Many alfalfa crops that come out of rotation also allow for us to not have to apply as much nitrogen for a crop year or two as the residual N is consistently sufficient as a large percentage of the next year's corn crop needs.

This is extremely important in times like we are in now with extremely high fertilizer prices to be able to have growers access alfalfa acres and manure. The growers that I work with that have the least cost of production per bu produced are ¾ of the time a grower that works with one of the Riverview Dairy locations to grow silage, haylage and access manure. This is the kind of options we need in agriculture for these local farms to survive and leave their legacy for the next generation.

Growers (and I) rest assured that the recommendations of the manure management team have been intensively reviewed to be in compliance with the BMP's each location & field has to follow in order to be in compliance. I have no doubt that the West River Dairy location follows & will continue to follow the same strict protocol that all the other locations know to follow as well. Their team, from upper management to field applicators all keep in communication on compliance along with rigid record keeping and submitting documentation to the proper entities. I know, because I have been a part of the process of these steps and their professionalism exceeds my expectations every interaction where we work together to make plans for a grower.

They don't take the requirements of any of the permitting process lightly and anyone who wants to work with them in executing the agronomic needs at hand, also knows that they are to follow the guidelines. Even their haylage & silage operations are run extremely safely & efficiently so that there is

very little room for error or injury or damage otherwise. My brother runs a cart for an operation that carts for silage at one of the locations and he said that safety, efficiency, cleanliness & communication are all keys to a successful season that Riverview stresses. If you've ever toured any of their facilities in the RRV, Steven's, Swift, etc you already know they run a clean, organized & first class operation in the care they take with their animals, the cleanliness of the facilities inside and out and also by the way everyone carries themselves in a kind & professional manner.

The obvious characteristics of Riverview is that if you know how this all works; you know they they or any other operation for that matter cannot set up an operation like the West River Dairy without following ALL of the proper protocols and procedures legally. The key thing that most people overlook, assume or just flat out do not have experience with is the fact that they also prove to me and others that they not only follow their legal obligations but they follow their moral obligations to the environment, the local communities, their personnel, their farming neighbors & to the generations yet to come. I believe that is just as important to know about them that I hope more people get to experience and know about the Riverview people. Thank you for your consideration of supporting & approving the West River Dairy. Kelsey VanOverbeke

Tyler Young **Letter 806**

Growth is necessary as demand rises

Sheyla Ramirez **Letter 807**

To whom it may concern.

I want to express my support to the West River Dairy Expansion project; I have known about Riverview for over 8 years. This includes touring their farms in different states.

This opportunity has given me an insight of Riverview, the more I know about who Riverview really is, the more I realized it is something good and not only for the employees or vendors who work directly but also for the communities, townships and counties where Riverview operates.

No matter the circumstances Riverview sites comply with the regulations, laws and even go beyond, sites are clean, organized, with minimal flies, minimal odor even during manure pumping season in the fall.

I have friends, family and people impacted by the opportunities.

Thanks,

Sheyla J Ramirez

Brian Eisenschenk **Letter 808**

I've been working in the dairy industry for 25 years, Riverview is a top notch company. Expansion is necessary to keep up with the demands of the industry. I'm in favor of their expansion!

Carolyn Anderson **Letter 809**

This proposal is harmful to man and beast. We all need clean water and air. Please do not permit this.

Mary Jo Forbord **Letter 810**

Dear MPCA,

I am writing to formally request that the MPCA mandate a full Environmental Impact Statement (EIS) for the proposed West River Dairy expansion. As the largest livestock operation in Minnesota's history, the cumulative environmental risks—specifically regarding Contaminants of Emerging Concern (CECs)—far exceed the scope of the current Environmental Assessment Worksheet (EAW).

The Minnesota Department of Health (MDH) and the MPCA classify hormones as CECs. MDH data indicates that these substances already affect 90% of tested Minnesota lakes, and a U.S. Geological Survey study found the Mississippi River in Minnesota has the highest rate of "feminized" fish--male fish that develop female characteristics, such as eggs in their testes. The cause is attributed to endocrine-disrupting chemicals (EDCs) that act as estrogens, causing sexual disruption.

The scale of the West River Dairy expansion poses the following significant risks:

- Hormone Output: Pregnant and lactating cows produce large amounts of estrogen and related hormones. An 18,000-cow herd produces approximately 15 pounds of estrogen daily. Hormones are potent in very small concentrations. In addition, large dairies routinely use synthetic hormones to maximize lactation and control the cows' reproductive cycles, which further increases this biological load.

- Environmental Persistence: Estrogens in dairy wastewater are notably persistent and often fail to biodegrade under the anaerobic conditions found in manure storage lagoons.

- Public Health Implications: These hormones bioaccumulate in the food chain. Human exposure through contaminated drinking water is linked to impaired fertility, developmental malformations, and hormone-sensitive cancers.

- Private Wells: Rural residents relying on private wells are particularly vulnerable. No one monitors our wells for safety, so the full financial and health burden of testing and harm falls directly on us. Most municipal systems are incapable of filtering out these contaminants, so well owners are particularly disadvantaged by lack of regulatory oversight to keep our water safe. We deserve better. Our state prides itself on its water, pure water at that. If our water is no longer drinkable because others have profited from making it so, regulation and justice must prevail.

Having grown up along Shakopee Creek in the adjacent watershed to the proposed expansion, I have witnessed the degradation of local watersheds firsthand; the Shakopee is now a designated critical nutrient hotspot. Nearby is Dublin Dairy, one of Riverview LLP's 8000 cow dairies. Do we have CEC data for Shakopee Creek? A blueprint for protecting our water and preventing contamination may become apparent if we choose to look. Perhaps we have hardly begun to accurately assess the environmental impact of dairies of this size, placing them ahead of CEC data collection and the safety of our drinking water.

If this expansion is green-lighted, hormones and endocrine disruptors will enter our water system at an unprecedented scale, affecting us all. Along with raising already elevated levels of nitrogen, phosphorus, and E. coli, the West River Dairy expansion represents a permanent threat to regional water security. I urge the MPCA to require a comprehensive EIS to study these cumulative impacts.

Sincerely,

Mary Jo Forbord

Prairie Horizons Farm LLC

John Kopp **Letter 811**

I have been working alongside Riverview as a vendor for many years. They take care of everything the right way and have a very clean way of doing it. I support this expansion because it is good to see dairy growing in our community's. They also provide back to local farmers in many ways. Until you get the chance to work alongside the employees and see how well it is ran, I think it is best to keep positive attitudes towards expansions in the dairy industry.

John Kopp

Judy Gregg **Letter 812**

The damage that this facility would do to the environment...especially to the water quality should be enough to deny a permit to this organization. The unnatural environment created for these animals to live in sounds like an animal concentration camp. Our state should not be condoning this kind of treatment. Please deny this request for expansion.

Isidro Granados **Letter 813**

MPCA,

I have been working with Riverview for more than 16 years, as a First Generation American, this kind of projects have provided an unvaluable opportunity for my daughter who is studying college at SDSU, my two boys who are also Americans and one is working, and another one is studying here in the USA and my wife also who works here.

The sites I have work at through the years are clean, organized, with minimal flies and odor, the integrity and ethic is part of part DNA, also we care about the land, water and future for all Americans.

I support the expansion

Isidro Granados

Erika Gilsdorf **Letter 814**

Hello,

I find it interesting that you write 'we value your comments'. I have been attending numerous county meeting, shared videos about public comments against CAFOs, attended numerous meeting and discussions and the opinion of people don't reach the decision makers interested in purely money and profit. I find it disgusting and appalling that treating livestock in these manners of concentrated animal feeding operations where animals are trapped inside, the manure is collected below them because they never leave and their conditions are horrific. But, why should we care about animals? It's about money, right? Profit, right? What about the environment? Why should we care about that? It's about money, right? Profit, right? Do we need to care that the animal waste has to go somewhere and that regulations of how that is handled safely without impacts to pollution, harm to our rivers, lakes and groundwater is not even close to being safe and regulated? What about setting a precedent for this area that prioritizes care of animals, care of our waters, care of our communities...does that matter? Or, is it profit and greed all put under the nice umbrella of 'economic growth' and 'feeding the people'. There are better ways that don't harm animals, land, water, and yes...people. These large operations are overtaking small family farms, bringing traffic, pollution, roads and extra impact to local community structures. Is that what you want? It seems so. The voice of a CAFO owner, seems to continually outweigh the voice of many. And, animals don't have a voice so it is as if they don't count. It's disgusting. It's time that MPCA takes a stand on stopping the pollution. What?! Stopping pollution? That's crazy. It seems like you're

open to discussing pollution and degradation of our natural systems and the animals that we live and rely on for a company's growth and expansion. This is not just one decision but the tipping point of many more to follow. It's like an open door saying, hey, all you CAFO's, come on over to West Central Minnesota. They don't have the courage to stand up and demand something different. A better way. It's a free for all to use and abuse and when we've used it up, maybe we'll move up to Canada? I mean, Iowa is already taking it in the shorts with their CAFO's. I'm fairly confident no one has read this. But, if you have, seriously, do not let this expansion happen. It's disgusting, appalling, and needs to be rejected. Please, please, stand up for what is right and just to our animals, our communities, and our lakes, rivers and natural world. There is no turning back from this decision.

Yaasika Quist **Letter 815**

In 1995, Minnesota had 9,000 dairy farms. By 2025, that number has fallen to 1,605. As farms have grown larger, many small family dairies have disappeared, and our rural communities feel that loss in real ways.

Among the organic farms, only two remain, and both are struggling.

Riverview says this 18,500 cow facility would create 40 jobs. Yet the same number of cows could support around 70 conventional family farms. Those are families who hire local help, support small businesses, build relationships, and keep small towns alive.

I do have concerns about the environmental impact of concentrating so many animals in one place. But I am also concerned about what is lost when family farms disappear. There is something so good about families caring for animals, tending the land, and working together with purpose. Family economies grow strong families and strong communities.

Please consider supporting family farms over corporate agriculture.

Thank you!

Carla Anderson **Letter 816**

I encourage the MPCA to complete an Environmental Impact Statement (EIS) for the West River Dairy Expansion. I was born in Morris (Stevens County) and lived there until I was 20. I have visited the area most months of my life to see family and friends.

I am concerned how such a large concentration of animals will impact water (groundwater impacts from greatly expanded pumping and surface water impacts from manure),quality of life in the area (e.g., increased truck/heavy equipment traffic, air quality, noise), and pressure on smaller on farms.

Randi Wingert **Letter 817**

To whom it may concern:

I am a small family dairy farm owner in MN. I am writing to hopefully make someone understand that expansions like River View should NEVER be allowed. River View is not a family farm they are a factory. They pollute and destroy the water supply at that capacity, they destroy farm land with no care, they destroy roads, they do not supply local revenue or employ locals. They push cows to unnecessary limits with no care to their well being.

Farms of this magnitude are ridiculous and reckless. They put real families, with real farming abilities and ties out of business. We do not need factory farms we need real dairy farmers, real families, real

caring, hardworking dedicated small town farmers who are dedicated to their families and their communities.

This is the time to stop all this before its too late, you want to see the real impacts of this talk to the real farmers, it's time to end factoryfarming.

Patricia Bouta **Letter 818**

I think an Environmental Impact Statement needs to be required for the West River Dairy Expansion so that everyone would know the impact to the water, land, neighbors, and other dairy farmers.

That large of an operation would change the land and the water. The large amount of manure it would produce and being used as fertilizer could lead to nitrates leaking into groundwater.

There are several rivers and other waters in the area.

There would be risks of manure spills and there have been manure spills at other operations. There would be excessive smell (stink) and it would lower the land values in the area for miles around.

Riverview has enough dairy operations in Minnesota already. It is already difficult enough for farmers to compete and this would make it worse, and be a detriment to the land and water.

Guido Niederoest **Letter 819**

There is no reason why this mega project should be allowed without an independently performed Environmental Impact Statement. There are a number of rivers and waters in the area that would be negatively impacted by a manure spill as has happened in other operations of this size. The local population in the area would be impacted by the excessive smells on a regular basis with these smells drifting to heavily populated areas as well. Property values would also be impacted negatively. This large of an operation would also make it more difficult for local farmers to compete being that it will have such a large number of dairy cattle.

Rodrigo Machemehl **Letter 820**

I've worked with Riverview, know their expansion projects, and I really could saw the commitment and how serious the project is. Critical backbone of our community, generating jobs, and helping the economy!

Sonja Trom Eayrs **Letter 821**

Dear Mr. Peterson and Members of the MPCA:

I submit the following comments in support of an environmental impact statement (EIS) for expansion and future development of large animal projects, such as the one proposed by Riverview Dairy.

I grew up on our family farm in Dodge County, Minnesota. I am an attorney in Minneapolis and am actively involved in the day-to-day operation of our family farm. My family has been on the frontlines for years fighting corporate agriculture and installation of industrial factory farms.

Today, our family farm is surrounded by 12 swine Confined Animal Feeding Operations (CAFOs), aka factory farms, housing an estimated 30,000 hogs in a 3-mile radius. These industrial factory farms collectively house an estimated 12,000 animal units. See, attached Animals to Animal Units Conversion, Iowa DNR 01/2021 (Number of head (30,000) times equivalency factor (.4) equals animal units (12,000)). Although area factory farms in a 3-mile radius collectively exceed 12,000 animal units, every industrial

operation cleverly escaped environmental review. Every factory farm houses animals just shy of one thousand animal units-the threshold for even minimal environmental review.

My family has had a front row seat to the corporate takeover of rural America. Our story is captured in my book, Dodge County, Incorporated: Big Ag and the Undoing of Rural America (Univ. of Nebraska Press, Nov. 2024). See, https://sonjatromeayrs.com/ My book weaves together my family's struggles with the larger realities of corporate livestock production in the United States: the pollution, the waste, the metamorphosis of thriving, verdant countryside into bleak commercial zones.

In the comments below, I briefly address three topics, including: (1) Dangerous nitrate levels; (2) Corporate consolidation and the decline of rural America; and (3) Harassment on the prairie faced by my family and other frontline families fighting corporate agriculture.

Please incorporate my comments and the noted attachment in the public record.

Dangerous Nitrate Levels

According to EPA records, "The drinking water of millions of Americans living in or near farming communities across the country is contaminated by dangerous amounts of nitrates and coliform bacteria from fertilizer and manure widely used in agriculture." Private wells in farming communities are routinely found to have nitrate levels above the municipal drinking water safety threshold of ten parts per million. This high bar is based on when levels become potentially fatal to infants, but drinking water at even half this limit increases the risk for colon, kidney, ovarian, and bladder cancers; miscarriages; thyroid disease; and neural tube birth defects.

A 2017 report showed that samplings of private wells in Dodge County between 1995 and 2016 found that 21 percent of private wells contained nitrate "above background concentrations," and 7 percent contained nitrate above the legal drinking water limit of ten parts per million. The county acknowledged that contamination was more prevalent in areas of Dodge "with shallow soils over limestone and over sand aquifers." I'm baffled that even with this contamination data, the county continues to permit feedlots over karst. Residents of Berne in northern Dodge, where karst topography dominates, fought hard against the first large swine CAFO in 2006. The community lost that battle.

In the years that followed, my late husband's mother, Ruth, along with other Berne residents, watched as the nitrate levels in her private well shot up. Ruth encouraged family members to drink only bottled water at the farm. In the fall of 2013, she succumbed to cancer. For years, my husband's family participated in the state's nitrate-monitoring program and dutifully submitted water samples to the local environmental ser vices office in the spring and fall. The results were damning: nitrate levels regularly came back between twenty and twenty-seven milligrams per liter, or three times the municipal drinking limit. My husband's family spent several thousand dollars to install a reverse osmosis system that removes contaminants from the water.

While pigs in the Berne area's factory farms drink pristine water drawn from a well drilled 480 feet down through multiple layers of porous limestone to the Prairie du Chien aquifer, residents drink water filled with nitrate from the pigs' manure. Today, locals refer to County Road 8, the main thoroughfare north of my husband's family farm, as "Cancer Road."

County Road B garnered international media attention following a 2023 news report that highlighted the nitrate contamination found in area water supplies. The reporter, Keith Schneider, spoke with four families who shared stories of twelve cancer cases and seven deaths concentrated along a short stretch of this single rural road. "Though the causes of the cancers are not proven, a key suspected culprit is

believed to be the elevated levels of nitrates that have contaminated the drinking water for County Road B families," Schneider wrote.

Contaminants deriving from livestock manure are also found in public water systems. A 2020 study found that the drinking water of an estimated half million Minnesotans is drawn from groundwater with elevated nitrate levels, citing "fertilizer and manure that runs off from farm fields and seeps into groundwater" as the primary contamination source. In this and other ways, feedlot pollution is both a localized and a dispersed problem. Groundwater leaching impacts public water supplies in neighboring towns and cities, and pollution in local rivers and streams is an uncontained hazard.

Data from the EPA shows that as of 2018-19, 42 percent of the length of lakes and streams in the United States had elevated phosphorous levels, and 44 percent have elevated levels of nitrogen. The EPA attributes these elevated levels primarily to fertilizer and manure runoff. In Iowa, where hogs outnumber people by seven to one, well over half of all waterways are impaired. The widespread degradation of waterways not only impacts people's health, well-being, and leisure activities but also causes massive fish kills and contaminates the fish that we eat. This is, of course, only a broad summary of the impacts of concentrated livestock agriculture on wildlife and the health of ecological systems.

In 2019 the Minnesota Pollution Control Agency issued a report about pollution in the Minnesota River, which eventually flows to the Mississippi. The report identified livestock manure runoff as a primary culprit behind an emerging environmental emergency that, per local press coverage of the report, is "degrading our superstar Minnesota River to sewer status." Worryingly, while the report indicated that the area of southern Minnesota included in the study contains 135 federally defined CAFOs (those holding a thousand-plus AUs), it did not specify the locations or the sizes of these feedlots-information that the public deserves to know. It also acknowledged that "while a full accounting of the fate and transport of manure was not conducted for this project, it is clear that a large portion of it is ultimately applied to the land surface and therefore, this source is of significant concern." So the MPCA can identify the pollution and deduce that much of it derives from factory farm manure, but lacking oversight capabilities, the agency is unable to pinpoint the most serious offenders or hold them accountable if identified.

Another MPCA study concluded that in Minnesotan regions dominated by agricultural land, "just half or fewer" of the area lakes "do not fully support swimming" due to excessive phosphorous levels, which are likewise caused in part by manure runoff. Our beloved Minnesota, the "Land of 10,000 Lakes," has become the land of 4,600 impaired waterways. The meatpacking and dairy industries use local rivers and streams as their own personal toilet.

Corporate Consolidation and the Decline of Rural America

The proliferation of industrialized livestock operations has significantly impacted rural farm communities in several states during the first decades of the twenty-first century, including Minnesota. The raw data tells the story well.

The EPA estimates there were more than 17,000 large CAFOs (buildings holding more than a thousand AUs) in 2012 compared to 6,600 in 1995. That's nearly a threefold increase in less than seventeen years. Looking at hogs specifically, the data coming from Iowa, the top hog-producing state, is alarming: CAFOs increased fivefold between 1990 and 2019, with 94 percent of this growth attributable to hog barns.

The straight line between this corporate consolidation and the extinction of independent farmers is easy to follow. Since the mid-1990s, 70 percent of hog farmers have gone out of business. The meatpacking conglomerates seized near-total market control, while their loyal contract farmers have captured an ever-dwindling proportion of profits. In the mid-1980s, thirty-seven cents of every dollar that Americans

spent on food went back to farmers, but by 2019 that had decreased to fifteen cents of every dollar. More than half of all farmers have lost money every year since 2013.

Meanwhile, the corporate meatpackers enjoy profits of a previously unimagined scale. Smithfield Foods saw sales increase tenfold between 1990 and 2005 thanks largely to its corporate strategy of buying up competitors and then maneuvering to fix prices and cut off access to a competitive marketplace. In 2013, in what was the largest-ever Chinese acquisition of a U.S. company, the Chinese company WH Group gained control of Smithfield.

Looking at the bigger picture, consolidation is the norm across major agricultural commodity groups. Dairy, soybean seed, and corn seed are other commodities that swiftly consolidated during a similar time frame. Between the years 2005 and 2010, eighty thousand independent farms in the United States disappeared. Then between 2011 and 2018, an additional hundred thousand farms in the United States were lost. In 2019 a feature article in Time about that year's farm bankruptcy crisis put forth a chilling proposition: "Farmers have always talked of looming disaster, but the duration and severity of the current crisis suggests an alarming and once unthinkable possibility-that independent farming is no longer a viable livelihood."

What's so worrying about today's corporate ag economy is that as profits soar and corporations boast to shareholders about outputs and efficiencies, the entire system is a house of cards. The droughts and severe weather associated with climate change have pummeled crops. Trade wars and unstable commodity prices continually stress the system. Thanks to short-sighted federal policies promulgated under pressure from Big Ag corporations, large farmers rely heavily on subsidies. During the agriculture crisis that former president Donald Trump's trade wars played a role in triggering, $16 billion in aid went to farmers, and 40 percent of farm income in 2018 derived from federal aid and insurance.

Farm subsidies have always been an important governmental tool for protecting producers and consumers from the inherent unpredictability of seasonal yields. Yet when subsidies are overused and funneled primarily to the wealthiest farm operations, the result is a highly unstable, top-heavy system that has no incentive to solve the pressing problems-such as climate change-that cause low and unpredictable yields.

As small farmers left the industry en masse, what has been the impact on rural communities and economies? One of the best efforts to probe this issue is Food & Water Watch's 2022 study of counties in Iowa that compares rural counties with high CAFO density to rural counties with both low CAFO density and more small farmers. The results show that between 1982 and 2017, personal income rose significantly in Iowa; even in the average rural county, income rose 41 percent. But in the top hog-producing counties, personal income fell by 8 percent. The report also found that while retail businesses in Iowa declined by a modest average of 2 percent across the state, counties with the highest CAFO concentration saw a decline of 33 percent.

Meanwhile, the study found that small, independent farms have the opposite impact: counties in Iowa with the highest proportion of small farmers actually experienced retail business growth, beating the state average. (The economic vitality of small farms reminds me that hogs used to be called "mortgage lifters" because raising a small number of hogs on a diversified farming operation brought in some extra cash.)

CAFO approval in Iowa is all but assured by a combination of lax regulatory procedures, county-level industry infiltration, and state and national lobbying efforts. In this system, 97 percent of requested CAFO permits in Iowa are approved. This overt friendliness to CAFOs is a main reason why Iowa produces more pork than any other state, surpassing Minnesota and North Carolina, which both have

more regulations on the books. That's good for the meatpacking conglomerates but bad for the people of Iowa. In 2019 a senior official at the Iowa Farm Bureau predicted to ag journalist Austin Frerick that "most rural communities will soon disappear." Frerick observed that the official seemed "accepting of this fate, even a bit happy about it."

CAFO proliferation has disproportionally impacted communities of color and marginalized communities. African American, Hispanic, and Native American people are significantly more likely to live within three miles of a hog CAFO in North Carolina-a pattern that likely exists in other states as well. Writing for the Sustainable Development Law and Policy journal, attorney Christine Ball-Blakely showed that communities lacking political power, resources, and education are targeted as sites for CAFO development. Targeted communities "lack the resources to leave compromised areas, where they are trapped by decreasing property values and a plummeting quality of life," Ball- Blakely wrote.

A CAFO's impact on property values depends on the size of the CAFO and whether the impacted property is downwind or upwind from the operation. The larger trend, however, is clear: factory farms cause surrounding property values to decline. A 2015 analysis of appraisal values estimated that properties within three miles of a CAFO lose 26 percent of their assessed value, and properties that are very close to a CAFO-within a quarter mile-lose as much as 88 percent of their value.

This impact has a devastating ripple effect in rural communities, where many farm families are asset rich but income poor. The notion of losing a home's value is so frightening that families are forced to choose between taking a "wait and see" approach or being proactive by selling their properties and moving away before a CAFO goes up. I've seen this happen time and again. I'm reminded of a small farmer and self-employed business owner in Goodhue County, Minnesota, whom I will call "Jack." I've contacted Jack several times regarding his community's resistance to area factory farms. Jack asked me to use a pseudonym, as he fears retaliation against his family and small business.

In 2015 he and his wife purchased a rural home on a few acres in Goodhue, an ag county adjacent to Dodge. Ten months after moving into the home with their children, they observed a hog CAFO going up nearby. They soon learned that while they were negotiating the purchase of their home, the Big Ag-friendly Goodhue County Planning Commission had approved the adjacent factory farm by a unanimous vote.

Jack also discovered that the previous owners, who had lived there for many years, were aware of the planned development. No law requires sellers to notify potential home buyers that a feedlot has been proposed or approved in the immediate area. The decision to cut and run before a CAFO is built and to not disclose such information-shuffling the property off to unwitting buyers-is yet another aspect of the factory farm takeover that corrodes social and community relationships.

After the facility went up and additional CAFO applications were submitted in Goodhue County, Jack joined with other neighbors to monitor the air quality near the border of the feedlot's property. The results showed concentrations of hydrogen sulfide far above state safety standards in the area near Jack's home. He is concerned for his kids, who frequently play outside.

Jack's family has been living in Goodhue County since the late 1800s. His father owns a small dairy operation nearby, but he's facing the decision to shut down. The operation is now surrounded by CAFOs, and the nitrate levels in his well have steadily increased. Soon he may be unable to give the water to his cattle.

The story of Jack's family is typical. In CAFO country, a small handful of feedlot operators profit, while their operations are under no legal obligation to abstain from rendering neighboring small farms

inoperable and neighboring residences unlivable. Reflecting recently on his family's experience, Jack said, "The industry divides communities and divides families.

Harassment on the Prairie

My family has paid a significant price for speaking out against industrial agriculture-facing years of harassment and intimidation. Fresh bullet holes riddled the stop sign just a few feet from where my brother and I had been picking weeds. Constant garbage left in the roadside near our driveway, harassing phone calls, and nighttime intrusions remained a regular occurrence. False telephone calls to the Dodge County Sheriff's Office, not to report some infraction, but to put the heat on me personally and get me to shut up.

These are just a few examples among hundreds, perhaps thousands, of harassment, intimidation, and outright threats and violence among neighbors that have become all too common in farm country today. The vast majority of these incidents go unreported because the threats are effective. People decide to stay quiet when they realize that speaking against factory farms will put their jobs, businesses, and families at risk. Livestock operators make it very clear that one's position on the latest factory farm development is a purity test that measures the loyalty of the locals.

Dead animals left in mailboxes and on front stoops; death threats, raised rents, social ostracization; fires set in front yards; threats to local businesses; getting fired from your job-these experiences are common among rural residents who speak out against new CAFOs or proposed feedlot expansions. When choosing a site for a new CAFO, the industry targets remote rural areas often inhabited by poor or undereducated residents who are likely to either drink the industry Kool-Aid or lack the resources to effectively fight back. In an industry game of Whac-a-Mole, these isolated battles-strategically targeted in remote or impoverished locales-are part of a systematic strategy to permanently anchor the corporate Big Ag factory farm economy.

We need immediate action in Minnesota to address corporate livestock production and the resulting pollution and waste. It is incumbent upon the Minnesota Legislature to halt corporate consolidation and further decline of rural Minnesota. We also need stronger laws in place to address and punish violators for intimidating and harassing frontline families fighting corporate agriculture, like mine.

Requiring an EIS for large animal projects, such as the proposed expansion of Riverview Dairy, is a start in the right direction. An EIS will limit the proliferation of large Confined Animal Feeding Operations (CAFOs), restrict further corporate consolidation, and prevent further decline in rural Minnesota.

Very truly yours,

Sonja Trom Eayrs

Laura Thielke **Letter 822**

Please require a full Environmental Impact Statement for the proposed West River Dairy Expansion. The thought of over 20,000 animal units in one location is blowing my mind. I have several concerns. Will that many animals in one place require more vaccines, antibiotics, and disinfectants per animal compared to an average herd? Will the cows consume so much water that the aquifer that feeds the well for my residence will dry up? I can't afford to pay for a new, deep well. How likely is manure spillage and contamination of streams and rivers and other people's drinking water? Can the dairy be held liable for other people's contaminated or dry wells? How far will the wind carry the manure smell and feed dust generated at the dairy? When the owners of nearby farm sites want to sell their property, will they have trouble finding buyers? Will local property values decline? Will the additional truck traffic to haul in

haylage, silage, and other feeds and to haul out milk and waste damage the nearby roads, increasing the property tax burden of Stevens County residents and nearby townships' residents? Will local farmers haul more grain to the dairy, so ethanol plants will have to buy corn from farther away, increasing the need to repair roads in the region? Will small family dairy farms all go broke? Since this livestock operation would be nearly double the size of the next largest livestock operation in Minnesota and huge compared to an average Minnesota dairy, please give this permit lots of scrutiny.

Kim Larson **Letter 823**

ATTN: Charles Peterson

My name is Kim Larson and I am a farmer in Kandiyohi County, MN. My full background is not only an agricultural producer but the experience as an agricultural regulator, as well. In the early 2000's I was selected to develop, and carry out the duties as the initial Delegated Feedlot Officer for Kandiyohi County. Over the three years that I devoted to the position, I developed a unique perspective of both sides of the process, and I believe that experience benefits my assessments in this discussion.

In preparation, I committed myself to reviewing the entire Environmental Assessment Worksheet (EAW). Beyond the 72 pages posted online, are the 26 categories of Attachments totaling hundreds of pages.

Associated Agency Reviews Confirm No Significant Concerns

The State Historic Preservation Office found no properties listed on the National or State Registers and no known archaeological resources that would be affected by this project. The DNR Natural Heritage Review found no ecologically significant areas along with no State-listed endangered or threatened species on the project site. The review within the route of the water pipeline returned with *"No Further Review Required"* across all categories. In response to Agency comments from MPCA and the State Archaeologist, Riverview voluntarily removed certain manure application fields from the manure plan, demonstrating responsiveness.

Water Utilization

The EAW is explicit in backgrounding the fact that the well that will supply the West River expansion originally received permitting for 452 million gal/yr. Riverview is reducing that initially granted appropriation to 226 million gal/yr. It would be hard to ignore the extraordinary effort that Riverview put forth in being creative enough through this expansion to significantly reduce the total permitted water appropriation capacity in this aquifer. If a 452 million gal/yr appropriation was initially found to be sustainable in this location, an appropriation of half that amount cannot logically constitute a significant environmental impact, especially considering the on-going regulatory measures incorporated into the DNR's permit.

DNR Comment Letter (March 17, 2026) Inaccuracies

It is puzzling to understand the DNR's statements that the EAW had not considered any impacts on the Pomme de Terre River. EAW Section 12.B.3 (pg 34-37) specifically discusses impacts to the Pomme de Terre, including detailed pumping restrictions based on stream flows (Tables 16 & 17). Included under Section 12.B.g.4 are multiple points addressing pumping restrictions applied to avoid indirect impacts. The letter further indicates that groundwater is *"limited"* in the project area. However, this would be in conflict with their previously detailed review of the aquifer in this location where the DNR found water usage, twice the currently proposed appropriation, to be fully sustainable.

EAW is Comprehensive and Complete

This EAW is far beyond a typical livestock EAW review. As I pointed out initially, there are literally several hundred pages of technical analysis covering ground water, surface water, air quality, natural resources, and cumulative effects. Under Minnesota law, an EAW is intended to be a *"brief document"* designed to set out *"basic facts"* about a project. I believe that it is self-evident that this EAW published by MPCA, greatly exceeds that standard in advance, as it appears that the MPCA has already produced an EIS level of information with respect to this project.

Furthermore, under Minnesota law (Minn. R. 4410), an EIS is required only when there is potential for *"significant environmental effects".* It does not reference any prerequisite for an EIS determined on the basis of an animal unit (A.U.) threshold. As Minnesota AgriGrowth noted in their comments, the purpose of an EIS is to assess environmental impacts, not create public policy on the appropriate size of dairy farms in Minnesota, as that should obviously remain with the representation of elected legislators. Finally, under Minnesota Rules, an RGU must consider *"the extent to which the environmental effects are subject to mitigation by the ongoing public regulatory authority."* Within this EAW, multiple layers of ongoing regulatory …. DNR water appropriation permitting, MPCA individual feedlot permitting, and NPDES zero-discharge requirements …. all serve as specific, targeted mitigation measures that Minnesota courts have recognized as sufficient enough to validate the findings for potential environmental effects.

Consideration of an Individual Permit

The development of an individual permit for this project further shows that the Agency has all of the protections and tools in place to ensure this project is fully protective of the environment, and that no potential for significant environmental effects could be found. As a former County Feedlot Officer, I recall the numerous times in our County's permitting process that when a specific item of concern was identified, we did our best to prevent *"regulation overreach"* by targeting those items with *focused mitigating conditions* that would provide the *specific protection* that is sought.

Conclusion

Upon thorough review, I would encourage a decision by the agencies involved to approve the West River Dairy expansion. With the rigorous safeguards for environmental security well documented in this EAW, the request for an EIS would be considered overreach. And finally, it would be regrettably unfortunate if the process of environmental review for livestock proposals morphed into …. *an act of prohibition.* Respectfully,

Kim Larson

Kandiyohi County

Paul Kostboth, A1 Development Solutions — Letter 824

Dear Mr. Peterson,

My name is Paul Kostboth, and I am the Founding Partner of A1 Development Solutions, a firm serving agricultural operations in Minnesota, including Riverview. I am writing to express my support for the proposed West River Dairy expansion in Stevens County.

Through our work in the agricultural sector, we rely on a strong and stable livestock industry. Operations such as Riverview play a critical role in generating consistent economic activity, supporting local employment, encouraging investment, and enabling businesses like ours to grow and reinvest in the communities we serve.

The proposed expansion represents a meaningful economic opportunity for the region. It will increase demand for local vendors, support both construction-related and long-term employment, and contribute to the continued vitality of rural communities that depend on agriculture.

Based on our direct experience, Riverview is a professional and reliable partner that makes positive contributions to the communities in which it operates. Their presence strengthens the local economy and supports a broad network of agricultural and service-related businesses.

Projects of this nature are essential to maintaining a competitive and sustainable rural economy in Minnesota. Continued investment in agriculture ensures that local businesses can provide jobs, services, and long-term economic stability.

Given the rigor and thoroughness of the state's environmental review process, we believe that an Environmental Impact Statement (EIS) is not necessary for this project. I respectfully encourage your support and approval of this important expansion.

Sincerely,

Paul Kostboth

Founding Partner

A1 Development Solutions

Terry VanDerPol **Letter 825**

I believe this expansion to the largest livestock operation in the state warrants an Environmental Impact Study to ensure a robust examination of all the impacts on the land, water and community.

1. Water use. 226 million gallons per year is huge. Can the acquifer sustain that draw without negatively impacting other users? Will Riverview's draw and the accessibility of water for others be monitored? What are the likely impacts of accelerated climate change? Can Riverview count on the capture part of their projected water supply and do they have a plan B as rainfall becomes more and more variable?

2. Projected amounts of liquid manure will require 13,200 acres of land. That's going to require substantial distances for the manure to travel especially in an area with quite a few CAFOs already. And, the proximity to numerous Waterfowl Areas is concerning.

3. On the socioeconomic impacts there are concerns including and beyond driving family dairy farms out of business. In this time of accelerating climate change we are seeing increased transport of viruses from far flung places, new to this area. Covid should have taught us lessons about the dangers to our food supply concentration of production and processing present. Avian flu has already shown it has capacity to jump from birds to dairy cattle to humans. Caution ought to be the coin of the realm regarding increasing animal concentration.

This expansion needs the robust review and Environmental Impact Study can provide.

Sam Cnossen **Letter 826**

Good morning—

I haven't read every comment that has been written here, but I wanted to share a few thoughts based on my own experience. I'm 63 years old, and I've had my share of failures along with some real blessings. I have a wife, children, and friends in this community, and I respect the people who live and work here. I am grateful to have this opportunity.

I've been involved in the dairy industry my entire life—my dad was a dairyman. Over the years, I've owned my own dairy, worked for other dairymen, and spent time with a company that helped dairies around the world manage operations using computers and software. Today I'm an owner and partner in Riverview, using what I've learned to support the people I work alongside every day.

My failures have helped shape me, and being part of Riverview has helped me grow as well. We are a large operation, and I understand how easy it can be to see things as "them" and "us." But please know this: we are a group of owners and partners, and each of us is a person with a family.

We come to work every day thinking about our families and our coworkers—how we can help one another inside the company, and how we can do right by our neighbors outside of it.

Every one of us has triumphs, failures, and family. We work hard to maintain a culture of safety—not just for compliance, but because it is what is best for our people. Our core values—strong work ethic, spirit of humility, keep it simple, integrity, and candor—are displayed on our common walls as a reminder of who we strive to be.

When we build a new facility, we do it to provide for our families and to create opportunities for others as well. We design our sites with safety, comfort, and care in mind—for our people, for the animals, and for the environment. We follow environmental guidelines and regulations closely, and we use best practices to carry out this work responsibly.

This project is an opportunity to create more good jobs in a place where people can build a stable life and raise their families. Some of those employees may be coming from other countries, and I'm proud our community can be part of giving them that chance. I also want to invite you to meet us personally, take a tour, and see for yourself what we do. And if you see us around town, please feel free to stop and visit—we are always willing to talk.

If you would like to hear directly from us about what is being proposed at West River Dairy, I would like to personally invite you to our informational open house. It is an opportunity to visit face-to-face, learn more about the project, and ask any questions you may have—including the difficult ones.

If you have concerns, please bring them. If you are supportive, I appreciate that as well. Either way, I'm asking you to come learn more about the project and have your questions answered. One thing that I know for sure is every single person that is doing any of the jobs that y'all have concerns about. They enjoy their job and will be doing that job to the best of their ability. This is a come-and-go open house—please stop in when it works for you:

Informational Open House — West River Dairy

April 9, 2026

5:00 PM–7:00 PM

Morris Armory

722 Iowa Ave.

Morris, MN 56267

Thank you for taking the time to read this. I hope you'll stop in, introduce yourself, and give us the chance to talk.

Thank you for listening.

Sam Cnossen

Lauren Blauch **Letter 827**

The current process that is outlined for permitting a dairy facility of this size in Minnesota is already one of the exhaustive and comprehensive processes in the entire nation to ensure our natural resources and our local communities are protected. Riverview has extensively shown to be an exemplary operator with respect for the processes that in place to ensure the rigorous Minnesota standards are met. Demanding an EIS would not only cause undue burden, but also set a terrible example that good dairy operators are now punished for growing and expanding their businesses when there is already an extensive process that needs to be followed and the EAW is a great tool that is nation-leading in its robustness as is.

Rinse Elsinga, Numidia Inc. **Letter 828**

Numidia has a strong and valued commercial relationship with Riverview. We work with Riverview as a trusted, professional partner and greatly value their long-term vision, operational standards, and commitment to responsible agricultural development.

We believe Riverview plays a pivotal role in the increased supply of high quality dairy, intended for both the U.S. domestic market and a range of export markets, strengthening reliable supply chains and supporting growing global demand for high-quality dairy ingredients.

From our perspective, the planned investment represents a positive and forward-looking development for production agriculture. It supports continued innovation, job creation, and economic activity, while enabling long-term partnerships across the value chain. Based on our cooperation to date, we have confidence in Riverview's ability to develop and operate this facility in a responsible manner, and we believe the project will make a meaningful contribution to the future of the dairy sector and the communities it serves.

Melanie Steele **Letter 829**

I am opposed to factory farming and request that you not allow this factory farm to move forward. In addition to the suffering Of animals, factory farms cause environmental harm and damage.

Corey Rost **Letter 830**

To Whom it may concern,

I have had the pleasure of working with Riverview Farms for the past six years, and during that time I have consistently been impressed by the professionalism, organization, and high standards maintained across their operations.

The Riverview Dairy organization is one of the most professional organizations I have ever worked with. Each dairy is consistently clean, well maintained, and operated with a clear commitment to quality and efficiency. This level of consistency reflects strong leadership and well trained staff throughout the organization.

Equally impressive are the employees of Riverview Farms, who have always demonstrated courtesy, professionalism, and a strong commitment to excellence. Their attention to detail and respect for best practices contribute significantly to the organization's outstanding reputation within the industry.

Based on my experience, they are a reliable, professional, highly capable organization that cares about their employees, the environment and communities around them.

Regards,

Corey Rost

Mitchell Coulter **Letter 831**

Dear Charles Peterson

My name is Mitch Coulter. I have worked in Minnesota agriculture my entire life. I grew up in west central Minnesota and I am very familiar with Riverview Dairy LLP. They care deeply about animal welfare and take the very best care of their animals. They educate the general public about their dairy operation. In my professional work representing the farming community they have always provided an open door policy providing tours for all sorts of public groups. They treat their employees with the utmost respect and they provide a positive opportunity for rural Minnesota.

I encourage the agency to support the growth of animal agriculture in the state and support the farming community. Rural Minnesota deserves a chance for opportunity! I strongly support the expansion of West River Dairy!

Sincerely,

Mitch Coulter

Annicka Westrich **Letter 832**

Due to the overwhelming amount of water and land that would be needed for this expansion and the amount of manure that would be created by this expansion, I'm strongly against it. Also, this expansion would push out even more small dairy farmers.

Ginny Halloran **Letter 833**

This is exactly the opposite of what should be happening with our farming operations. Bigger is not necessarily better, money/profit should not be the determining factor in advocating for the common good. We live in a democracy and it's about time we started acting like it. The Riverview expansion needs a environmental review taking into consideration humans are not the only sentient beings on the planet.

Todd Novy **Letter 834**

Knowing the Pomme de Terre river, its watershed and the surrounding communities I can only believe that expanding this business would be reckless and enormously detrimental (if not catastrophic) to both the environment and resources of the area. This proposal must not go forward.

Scott Herrly **Letter 835**

As a Minnesota resident I oppose factory farms. They are highly inhumane, a source of pollution, and put family owned farms at risk.

Dylan Reese **Letter 836**

ATTN: Charles Peterson

My name is Dylan Reese, and I am an employee of Riverview, LLP. I am writing in strong support of the proposed West River Dairy expansion in Stevens County — not just as someone who works in this industry, but as someone who grew up in this community and has seen firsthand the difference operations like Riverview make in people's lives.

I was raised in Hancock and have deep roots in this region. Growing up here, I watched agriculture shape nearly every aspect of life — the local economy, the schools, and the neighbors who stayed. It is a community I love, and one I hope to call home again. My goal is to move back to the Morris area and raise a family here, but that dream depends on whether places like this continue to offer the jobs, stability, and investment that make rural life viable.

I am also a proud former recipient of the Riverview, LLP scholarship, which made a profound difference in my college career. In addition to the scholarship, I was very active in 4H in my youth. Through 4H, I both witnessed and personally benefited from Riverview's generous support of the livestock auction and their donations to improve the fairgrounds.

Riverview's investment in local students and 4H is a reflection of the kind of company that truly invests in the people and places around them and one that genuinely gives back to the communities where they operate.

The proposed expansion represents a meaningful economic benefit to the region. It will generate demand for local vendors, support both construction and long-term employment, and contribute to the vitality of rural communities that depend on agriculture to survive and thrive. In addition to the local economic benefits, I along with many other coworkers are active in our rural churches, local charities, and school programs and events. Without an employer like Riverview, that encourages community involvement, I know I personally wouldn't be able to serve those organizations as I likely would not be in this small local community.

Projects like this are essential to maintaining a competitive and sustainable rural economy in Minnesota. For people like me who want to come home, expansions like this one signal that there is a future here worth coming back to. Continued investment in agriculture ensures that local businesses can provide jobs, services, and economic stability close to home — and that the next generation doesn't have to leave to find opportunity.

Based on my experience with this company and this community, I am confident that no EIS is needed, as the state environmental review process is rigorous and very sufficient. I respectfully encourage your support and approval of this important project.

Sincerely,

Dylan Reese

Earth day **Letter 837**

To whom this may concern.

I'm writing in opposition of this expansion at this site and all other sites owned by Riverview.

To be fair to everyone I think EIS needs to be done there and at all their other sites. If riverview is the company they say they are and many of their supporters claim they are. They should have no problem doing EIS.

Riverview is a huge environmental concern and a huge concern to our local communities.

Riverview is like a locust if they can't expand at west river they will move onto a different site they own.

I have saw comments from school boards saying they are welcoming this west river expansion. Ok so question here what do all these H2A/ people here on a work visa actually do for the schools and local communities and economy? Besides absolutely nothing!

It's the process of limitation when 1 of these riverview dairy sites is built in an area. Riverview doesn't wanna work with a bunch of smaller farmers. They wanna work with 1-2 farming operations that control the vast majority of the acres in that area. So begins the decline to our schools, our small towns and small town businesses and our rural area in a 5-7 mile radius of that site. When 1 of these sites is built in an area it's pretty much the death of that area because nobody wants to live to close to them sites and hardly no one can farm in that area in anymore but 1-2 guys who will over pay to buy and rent any amount of ground from 80 acres to 800 acres to have sowed up for the dairy. There is several farming operations in them areas that would love to grow their farming operations and bring in the next generation but can't compete land wise anymore against the guys that are heavily involved with the riverview dairy sites.

Just think if it wasn't for them riverview dairy's and their need to have all this ground for they dairy and their need to have all this foreign labor weather working at the dairy or all this foreign labor need for the guys that are heavily involved in the dairy's to farm all them acres. There could be a lot more local guys that are from generational farms that would be able to farm more or able to farm full time and our communities would be a lot better off instead of having 1-2 individuals and all their foreign labor trying to control it all.

Let that sink in!

I have noticed the area west of Willmar, MN has become a hotspot for riverview. There is 6 of them in 25 mile and east and west stretch and 6 miles north and south. That area was once really lively and peaceful but has become very stagnant because of riverview. Any ground that moves in that area that wasn't associated with the dairy's there as far as being used to grow feed on or put manure on will be and it's all going to select few individuals who are heavily involved with riverview. They have done absolutely nothing for that area but make a select few guys extremely big acre wise and drive out a lot of younger people and generational farms. Pretty soon that area will be a huge environmental risk if it is not already a huge environmental risk.

They had a manure spill at one of them sites in that area in the fall of 2024 that they cleaned up before they reported it to the Mpca. They claim it was 50,000 gallons of mainly water. 50,000 gallons of mainly doesn't cover an area of 60 plus acres and crust 1.5ft deep in a field and go into 2 separate drainage ditches a quarter mile apart.

For all the riverview employees and guys that are heavily involved in riverview(sold them land to build sites, manure pumping, grow a lot feed and very involved with the chopping) your comments should have little credit to them. What is good for you guys has been never been good for the neighborhood, neighbors and communities. It's only been good for your bottom line and your checkbook.

I have saw comments from people that it gives a younger person a chance come back home and farm. On what? Driving truck for someone with no advancement ever besides being a truck driver or a farm hand. People that wanna farm they would rather own and rent land themselves instead of being a truck driver and chopper operator for the extremely big riverview farmer. Pretty much death of a dream when one of these dairy sites is built to any younger people and generational farmers.

If riverview can keep expanding at an alarming rate there will nothing left to our rural areas and our natural resources will be gone and same with our communities.

I think it's time to put a stop them before it's all to late.

If they are the company they say they are and same with all their supporters they should have no problem doing an EIS. I think it would be ill fated if an EIS is not done.

It seems if you speak out against Riverview and their supporters you get a target put on your back and a bounty on your farming operation and all sorts other non stop harassment from riverview and their supporters.

Shelley Kremer **Letter 838**

Due to the scale of this project I believe a full environmental review is paramount. My dad grew up on Barrett Lake and my family has a home there now. We have seen the water decline over time and want to make sure this project doesn't cause the decline to escalate. A full and thorough review is needed before something of this scale is approved. The town needs 100% transparency before moving forward.

Diane Baum **Letter 839**

This expanision comes at a cost to our other smaller dairy farms in and around Morris, as well as sustainability of the aquifer to provide enough water for our future. Groundwater contamination is also a huge concern- I do not feel that this project is what is in the best interests of Morris and our surrounding communities.

Owen Anderson **Letter 840**

My name is Owen Anderson. I am writing in support of Riverview's proposed West River Dairy expansion in Steven's County. I have had the privilege of working with Riverview over the past two summers, most recently going through the intern program. The internship has provided me with a deeper appreciation of how much Riverview invests in the people and the local communities.

Growing up in Morris, I always knew that Riverview was important to the local economy, but working with Riverview showed me the behind the scenes of what it takes to provide that support.

A project like this will create new opportunities for people who are wanting to build their careers close to home.

Tim Trotter, Edge Dairy Farmer Cooperative **Letter 841**

To Whom It May Concern:

On behalf of Edge Dairy Farmer Cooperative and the dairy farm families we serve across the upper Midwest, I write to express our full support for the expansion of Riverview's West River Dairy in Stevens County, Minnesota.

Riverview is exactly the kind of operation that strengthens Minnesota's dairy industry. They are well-managed, community-oriented, and environmentally responsible. Their track record speaks for itself: innovative water conservation practices, industry-leading manure management plans, and an ongoing commitment to working with neighboring farms and local communities. These are not just good practices — they are the hallmarks of a company with a genuine and deep-rooted commitment to environmental stewardship.

Today's dairy producers operate in a vastly different landscape than previous generations. Advances in precision feeding, nutrient management, manure handling technology, and environmental monitoring have transformed what is possible on modern dairy farms. Riverview has embraced these advances fully. Their expansion, which has undergone thorough environmental review, reflects confidence in both science-based regulation and the capacity of modern dairy producers to exceed environmental standards.

I also want to speak to what Riverview means for its communities. Large-scale dairy operations like West River Dairy do not exist in isolation — they are woven into the fabric of local economies. Riverview creates meaningful opportunities for neighboring farmers through manure application partnerships, supports local businesses and service providers, and contributes to employment and long-term economic stability in the region. Their model of community engagement is a template for responsible agricultural growth.

Edge Dairy Farmer Cooperative trusts the existing regulatory process in Minnesota. The MPCA has the tools, expertise, and authority to evaluate this expansion thoroughly and to impose conditions that protect Minnesota's waters. We do not believe additional environmental review is necessary and would discourage any effort to weaponize the environmental permitting process to address unrelated economic policy concerns. The integrity of Minnesota's regulatory framework depends on it being applied for its intended purpose.

We urge the MPCA to move forward with confidence, grounded in science and data, and to support Riverview's expansion as a model of responsible dairy growth in Minnesota.

Sincerely,

Tim Trotter

Chief Executive Officer

Edge Dairy Farmer Cooperative

Tim Baumgartner, Edge Dairy Farmer Cooperative **Letter 842**

To Whom It May Concern:

I am writing in strong support of the proposed expansion of Riverview's West River Dairy in Stevens County, Minnesota. As someone who works with helping dairy farmers access and maintain proper permits for their farms, I am encouraged about the future of Minnesota's dairy sector and want to see growth in the industry occur responsibly, transparently, and in alignment with sound science-based regulation.

From a financial and regulatory standpoint, I believe the existing permitting framework administered by the Minnesota Pollution Control Agency (MPCA) is well-equipped to evaluate this project. The regulatory process in Minnesota is robust, and I trust it to appropriately assess environmental considerations and impose any necessary conditions. I do not believe additional environmental review beyond what is already underway is warranted.

Riverview has demonstrated the financial discipline and regulatory acumen of a well-managed enterprise. Their investment in advanced manure management infrastructure, water-recapture systems, and nutrient management planning reflects not only sound environmental practice but also strong business judgment. These are not afterthoughts — they are core to how Riverview operates. Their approach to reducing reliance on synthetic fertilizers through responsible organic nutrient cycling represents a meaningful benefit to surrounding farmland and demonstrates the kind of integrated thinking we want to see in Minnesota agriculture.

I am also aware that some comments have called for an Environmental Impact Statement based on economic concerns about competition within Minnesota's dairy industry. To be direct: environmental review a tool for evaluating environmental impacts, not for adjudicating market dynamics or farm size policy. Using the environmental review process to address broader economic policy questions would be

a misuse of that process and would undermine the credibility of Minnesota's regulatory framework. Legislation and rulemaking are the appropriate venues for those discussions.

Riverview's expansion represents a sound investment in Minnesota's dairy future. I encourage the MPCA to apply the science and data before it, use the full range of tools at its disposal to protect Minnesota waters, and proceed with confidence in the existing process.

Sincerely,

Tim Baumgartner

Chief Financial and Regulatory Officer

Edge Dairy Farmer Cooperative

Karalyn Indrelie **Letter 843**

Concentrated Animal Feeding Operations (CAFOs) are degrading Minnesota's air and water, while disproportionately harming rural and low-income communities through chronic public health impacts such as respiratory illness, contaminated drinking water, and reduced quality of life. These operations externalize their true costs onto the public, while the ecological damage continues to compound year after year.

Minnesota has an opportunity and responsibility to move in a different direction. Restoring native prairies and oak savannahs would rebuild soil health, protect waterways, sequester carbon, and provide critical habitat for pollinators that our food system depends on. These ecosystems once defined the region and can again serve as a foundation for sustainable land stewardship rather than industrial exploitation.

Meanwhile, the conventional dairy industry has been in structural decline for decades, surviving largely through repeated government bailouts rather than long-term economic viability. Propping up a failing model only delays the transition to more resilient, diversified, and farmer-centered agricultural systems.

If current trends continue—prioritizing short-term production over ecological limits—we risk accelerating soil loss, biodiversity collapse, and climate instability. The long-term consequence is a global food system increasingly vulnerable to failure. Allowing extractive industries to continue degrading land and water is not just environmentally reckless; it is a threat to future food security. Protecting our ecosystems today is inseparable from preventing hunger and catastrophe tomorrow.

Javier Garcia **Letter 844**

I agree to built this expansion because Riverview have really good core values and help our community in many ways like give job opportunity, buy locols supplies and help people from the towns also. In my opinion is gonna be help for everyone in many ways. Thanks.

Mike DeRosier, Interstates **Letter 845**

Dear Mr. Peterson,

My name is Mike DeRosier, Regional Manager of the Interstates Brainerd, MN. Interstates has had the opportunity to work with Riverview on electrical contractor services over the past several months, and I am writing in support of Riverview’s proposed West River Dairy expansion in Stevens County.

Through our experience, Riverview has been a professional and kind partner. They value their people and approach their work relationships with trust, respect, and good communication.

Projects like this can help support continued investment in rural Minnesota and contribute to the long-term strength of the agricultural economy. Responsible growth in production agriculture creates opportunities for local businesses, trades, and communities that depend on stable economic activity.

I respectfully encourage the Minnesota Pollution Control Agency to consider the value of this project and Riverview's role as a long-standing agricultural business in Minnesota.

Sincerely,

Mike DeRosier

Regional Manager

Interstates Brainerd

Levi Strahm **Letter 846**

The expansion of West River dairy would boost our local economy. It would provide more farmers in the area with the opertunity for manure.

Kevin Meixel **Letter 847**

We here at Meixel Farms, and Meixel Truck sales support the west river dairy expansion. They always have practical logistics planning, and clear milestones to help scale production smoothly. We enjoy doing business with them because of their commitment to quality, transparency, and collaboration—the kind of partnership that values open communication and mutual success. Their expansion creates many local jobs, from farming and harvesting to processing, packaging, and distribution, which strengthens the local economy and builds a more resilient community. By investing in local talent and infrastructure, they not only boost employment but also foster entrepreneurial spirit, support small businesses, and contribute to steady, inclusive growth that benefits families and neighborhoods alike.

It's important for those who oppose the dairy expansion to consider the broader implications of their stance. By resisting this growth, they may be overlooking the significant benefits it can bring to the local community and economy. The expansion is not just about increased production; it represents a vision for the future, one that fosters job creation and stimulates local businesses.

Without embracing such opportunities, there is a risk of stagnation, both economically and socially. It's essential to look beyond immediate concerns and recognize that progress often requires bold steps forward. Engaging with the expansion can provide a pathway to innovation, sustainability, and a thriving community that benefits everyone in the long run.

Ivan Regalado **Letter 848**

Riverview is a great company, I'm excited hearing this because I know will be many families benefits from this project, I have the opportunity to work with Riverview for more than 15 years, and this company has everything that a family needs to grow, full job (stable job) good benefits,Healt insurance,Dental insurance,HSA, 401K.

Joni Heins **Letter 849**

ATTN: Charles Peterson

Subject: Public Comment in Support of the West River Dairy Expansion

My name is Joni Heins, and I have lived in Stevens County for the past 15 years. I am writing in support of the proposed West River Dairy expansion.

Having grown up in the dairy industry, I understand firsthand the level of care, responsibility, and management required to run a quality operation. From what I have observed, the existing farm is clean, well maintained, and professionally managed. That is important to those of us who live nearby.

I also appreciate the positive role Riverview has played in our community over the years. Their support of programs like 4-H and FFA, along with providing scholarships, jobs, and learning opportunities for local students, has made a meaningful impact in rural areas like ours, including for my own children.

I understand the project is currently undergoing environmental review by the state, and I value that these processes are in place. In my experience, the existing review and permitting system is thorough and appropriate, and I believe it provides sufficient oversight for this project.

Beyond that, the dairy contributes to the local economy by supporting farmers, creating jobs, and partnering with local businesses - something that is vital to communities like ours.

For these reasons, I support the proposed expansion.

Sincerely,

Joni Heins

Nic McPhee **Letter 850**

To the Minnesota Pollution Control Agency,

I am writing to express my **serious concerns regarding the proposed West River Dairy expansion in Stevens County**. As this project would create a facility twice the size of any existing livestock operation in Minnesota, I strongly urge the MPCA to require a full Environmental Impact Statement (EIS) before proceeding with any permitting.

An operation of this magnitude—reaching over 26,000 animal units—is far outside the state's historical "envelope of experience." Proceeding with such an unprecedented expansion without the most rigorous level of review is a significant risk to our region.

My specific concerns include:

● **Scale and Precedent**: This facility would be nearly double the size of the next largest CAFO in Minnesota and 60 times the size of the average Minnesota dairy. This is a fundamentally new type of industrial operation that requires industrial-scale scrutiny.

● **Water Usage and Quality**: The proposal to pump 226 million gallons of water annually—nearly reaching the consumption levels of the entire City of Morris—poses a major threat to our local aquifers. Furthermore, the proximity to the Pomme de Terre River watershed and several protected wildlife areas makes the potential for pollution from the 250 million gallons of stored manure a critical concern.

● **Socio-Economic Impact**: Riverview already accounts for approximately one-third of the dairy cows in Minnesota. Allowing further consolidation at this scale is unhealthy for market competition and directly threatens the viability of small, family-run farms that are the backbone of our rural economy and culture.

Given the scale of this project and the potential for irreversible environmental and economic harm, a standard Environmental Assessment Worksheet (EAW) is insufficient. We must understand the full impact through an EIS before moving forward.

Thank you for your careful consideration of these comments.

Sincerely,

Nicholas Freitag McPhee

Kaleb Heins **Letter 851**

ATTN: Charles Peterson

Subject: Public Comment in Support of the West River Dairy Expansion

My name is Kaleb Heins, and I have lived in Stevens County for the past 15 years. I am writing in support of the proposed West River Dairy expansion.

Over the years, I have had the opportunity to engage with Riverview in several meaningful ways that have shaped both my personal and professional growth. Through completing an internship with Riverview, I gained valuable hands-on experience and a deeper understanding of the agricultural industry. Additionally, I was fortunate to receive a scholarship from Riverview that helped fund my college education - support that made a lasting difference for me and my family.

Riverview's impact extends beyond education and into youth development in our community. Through their dairy calf lease program, I was able to participate in the Stevens County 4-H dairy program, an experience that taught responsibility, work ethic, and leadership. Their involvement in helping build the new dairy barn on the Stevens County Fairgrounds has further strengthened opportunities for young people to learn and grow in agriculture.

From what I have observed, the existing dairy operation is clean, well-maintained, and professionally managed. These qualities matter to those of us who live and work in the area, and they reflect the standards Riverview upholds.

I also understand that the project is currently undergoing environmental review by the state. I value that these processes are in place, and I believe the current review and permitting system provides appropriate and thorough oversight.

Beyond its operations, the dairy plays an important role in supporting the local economy by creating jobs, partnering with local businesses, and contributing to the agricultural community. These benefits are vital to rural areas like Stevens County.

For these reasons, and based on my personal experience, I support the proposed expansion.

Sincerely,

Kaleb Heins

Vick Konkin **Letter 852**

its important to support the livestock industry in our state. Its vital for food security, providing essential nutrition to millions in our and neighboring states. these farms also provide the jobs needed for the rural communities and economies. i do not want EIS.

Todd Klein **Letter 853**

ATTN: Charles Peterson

My name is Todd Klein, and I am a farmer in Wilkin County, I am writing in support of the proposed West River Dairy Expansion.

Based on my experience and observations, Riverview Dairy operates with professionalism, integrity, and environmental responsibility. Their facilities are well-maintained, clean, and organized, and their teams are committed to doing things the right way.

As someone familiar with agriculture in this region, I reco□Jnize that manure management and water use are highly regulated in Minnesota. Riverview strives to follow these regulations, including nutrient management planning, soil testing, proper application rates, and timing based on field conditions. From what I have seen, their mindset is to meet and exceed these standards to ensure responsible stewardship.

The use of manure as a nutrient source has clear benefits for local farms, including improved soil health, increased organic matter and reduced erosion. This supports long-term agricultural sustainability.

Riverview has also been a strong community partner, supporting farmers, creating jobs, maintaining roads, and investing in schools and local programs. Their communication with neighbors and officials reflects their commitment to being a good neighbor.

I understand that this project is undergoing environmental review through the state's established process- one of the most rigorous in the region- and provides adequate oversight for this project. Based on the available data, existing regulations, and Riverview's proven track record, I am confident this project can continue to operate responsibly. I believe the current review process is sufficient and that additional regulatory burdens are unnecessary.

In closing, I respectfully encourage the appropriate agencies to approve the West River Dairy Expansion. This project supports local agriculture, strengthens rural communities, and reflects a responsible approach to environmental stewardship. I also believe that an EIS is not necessary.

Sincerely,

Todd Klein

Christopher Westerman **Letter 854**

We love our Riverview LLP neighbors! Not only do they bring a necessary economic driver to our small community (which as a small business owner helps support myself, employees, and family) but they are also great at keeping the countryside beautiful! They way they care for the land and keep their equipment/ facilities clean is rivaled by not many other farmers around. When they are working in fields close to our home we notice they take extra time to come back to clear mud from the roads and re grade them. Their ability to go above and beyond what is required to work and live in harmony with surrounding neighbors and communities is clear to see in the way they operate. Very thankful for their dedication to producing high quality dairy products right here in our backyard!

Chenoa Marks **Letter 855**

I am writing as a resident and student in Morris with concerns regarding the proposed Riverview West River Dairy expansion in Stevens County.

Given the scale of this project, I believe that a full Environmental Impact Statement must be conducted before any approval is considered. The potential long-term environmental impacts on groundwater, surface water, and the overall health of our local ecosystem, are too significant to be addressed through

a limited review process alone. There is much we don't know about our water systems, and they are already vulnerable as is.

In addition to environmental concerns, there are also broader implications for local agriculture. Expanding an operation of this size has the potential to change the local dairy market, placing increased pressure on small and mid-sized farms that are already facing economic challenges. The long-term sustainability of our local agricultural community should be prioritized, and not on economic gains.

As someone who lives, studies, and participates in this community, it is my hope that the decision makers take a precautionary and thorough approach to preserve our water systems and for the wellbeing of the community.

-Chenoa Marks

Anthony Vannelli **Letter 856**

I am writing in support of the West River Dairy expansion. They are on the modern edge of technology in their industry and provide well-paying skilled jobs. The idea that they are willing to re-invest into the state of Minnesota is a positive rather than the alternative of exiting, which would just be another negative impact on our local economies.

Regards

Gretchen Tuck **Letter 857**

We need to support our small family farms for so very may reasons!

In 1995, Minnesota had 9,000 dairy farms. By 2025, that number has fallen to 1,605. As farms have grown larger, many small family dairies have disappeared, and our rural communities feel that loss in real ways.

Riverview says this 18,500 cow facility would create 40 jobs. Yet the same number of cows could support around 70 conventional family farms (or 3,000 micro raw milk dairies like us!!!). Those are families who hire local help, support small businesses, build relationships, and keep small towns alive.

Please do Not allow this proposal to happen. It would devastate our small towns and all of us who live and work together. It would have a huge impact on the people the land the environment as a whole. Please we do not want this.

Liza Eng **Letter 858**

I am deeply concerned over the proposed expansion of West River Dairy operations. I respectfully ask that you preform an Environmental Impact Statement on this dairy expansion. The dairy expansion is massive and that alone should trigger an EIS. The location of this dairy operation needs to be studied. It is within a short distance from several important protected waterfowl areas.

Also, a river is also close to the expansion site. What will happen to those places if a leak from the ponds holding cattle waste would occur? Those stated areas will be ruined. There will be tremendous amounts of water used by this operation and all of our small town farmers will suffer from this huge dairy farm.

Carol Pietrick **Letter 859**

I cannot believe this expansion is even being considered! A feedlot of 18,855 cows is the population of a city. An 11,000-cow dairy is a city. How many small farmers will be put out of business because of this

expansion? The lives of these cows don't mean a thing. The cows are not widgets, they are sentient creatures. A feedlot is not a farm, it is a concentration camp. Do these cows pasture, see the light of day? I don't think so. I know a little something about cows as I grew up on a dairy farm in Morrison County. Please do not allow this expansion. For the sake of small dairy farmers, the environment & the cows themselves, please do not allow this expansion. I recommend you watch Cow, a 2021 British documentary film by Andrea Arnold, revolving around the life of a dairy cow. It's not pleasant.

Matt Sattler **Letter 860**

I support Riverview's West River Dairy expansion project. Additional comments and background in the attached letter. Thank you.

Dear Mr. Peterson

My name is Matt Sattler and I have been involved in the dairy business my entire life. Born and raised on a family dairy in eastern Wisconsin and have worked with dairy business owners my entire life. I am writing in support of Riverview and their proposed West River Dairy expansion in Stevens County.

I have worked with large dairy operations across the entire United States and across those experiences Riverview is the entity that I compare all those other dairies to. The Riverview organization is first class in all they do –

- Creating opportunities for jobs and personal development within the organization
- Environmental stewardship and maintaining clean, attractive tour-ready facilities
- Animal husbandry and their care for their cows
- Organizational culture and community involvement

From my experience working with Riverview, they are strong business partner that cares about where their expense dollars are spent and how that multiples across the local community. Riverview's presence and investments they have made have helped to maintain a vibrant agricultural economic engine and supports a broad base of business from agriculture, construction, and service related business that support the dairies.

The proposed expansion at West River represents a meaningful economic benefit to the area. It will help to maintain the financial viability of the dairy and the direct/indirect local jobs that the dairy supports.

To maintain a sustainable and competitive rural economy and communities across western Minnesota, we need projects like this and companies like Riverview that are willing to make those investments.

Riverview has an exceptionally strong track record with regards to environmental stewardship and protecting the natural resources we all value in Minnesota. The existing state environmental review process through MPCA is rigorous and sufficient and with that in mind, I believe an EIS is not necessary. I respectfully encourage your support and approval of this important project.

Sincerely,

Matt Sattler

Kurt Grimm, NutraDrip **Letter 861**

Riverview continues to be a champion of workplace safety, environmental stewardship, efficiency and an economic development workhorse. Our company offers solutions that allow dairies to apply manure in a way that is more environmentally friendly. Many dairies cannot or will not invest in this technology.

Riverview on the other hand is leading the way in using and implementing this system. Their attention to detail at every level is unprecedented. We work with diaries from CA to NY and I always know when I step on a Riverview site it will be clean, well maintained, and operated at the highest level of professionalism. I can personally attest to their commitment to operate dairies in way that will benefit their neighbors, community and state. And their manure management application is always done in a way that responsibly stewards the environment. I give my support to Riverview expanding their site at West River. And I would welcome the opportunity to share my personal experience with Riverview and how they handle manure and water.

Dennis Cuchna **Letter 862**

I am completely opposed to this expansion.

The actual and potential hazards are massive.

The increased traffic and manure handling are mind boggling.

Thank you

Emily Bruce **Letter 863**

I'm deeply concerned about the unprecedented scale of this proposal, as well as the company's track record with damaging water resources in the southwestern US. This project must be required to undergo a full Environmental Impact Statement (EIS). Please take the potential implications seriously for the sake of all our community's health and wellbeing.

Bonnie Nelson **Letter 864**

I am totally against this expansion.

Cows are not 'units'. They are living creatures that feel pain and mental stress. Confining cows the way Riverview does is not only immoral, but also a very sad reflection on how our species disregards basic compassion towards other living creatures that we share this planet with.

It is impossible to operate a CAFO like this and not be environmentally destructive which is what your agency is supposed to prevent.

Sonja Trom Eayrs **Letter 865**

According to Farm Action, dairy farms have grown increasingly consolidated with a small percentage of large operations producing the majority of the milk supply.

2.5% of dairies (the 834 dairy operations with more than 2,500 cows) produce nearly 45% of American raw milk annually.

Dairy Farmers of America (DFA) aggregates and markets around 30% of the country's raw milk from over 14,000 dairies.

The eight largest milk cooperatives together account for more than 54% of annual milk production.

Domestic Milk Processors CR4: 39-41%
DFA: 15%
Land O'Lakes: 10-12%
Saputo Inc.: 7%
Nestle: 7%

Fluid Milk Sales CR3: 83%
DFA: 39.1%
Land O'Lakes: 35.2%
California Dairies: 8.8%

Further concentration in the dairy industry threatens smaller dairy operations. Further placing control of our food and dairy supply in the hands of a few corporate operators threatens our food supply and our national security.

Sonja Trom Eayrs

Holly Windle **Letter 866**

No, this is just too big a dairy for a responsible operation. This is a profit-driven proposal for concentration of cows that would make it unlikely that considerations about manure run-off or healthy animals would be part of the operation. Well-managed dairies know the value of animals fed on grass, not grain. and they know how to incorporate the potentially-valuable manure into land-enriching compost. This expansion does not seem to fit that possibility.

Minnesota should be encouraging farmers who want to provide a healthy product to us consumers by way of responsible land stewardship and animal management--not jsut looking to make more money by increasing their economy-of-scale.

Dana Jackson **Letter 867**

The Riverview dairy cattle expansion should not even be considered unless the business prepares a full environmental impact statement. This is not just a dairy expansion proposed, it is a huge animal factory expansion with a potential for disastrous impacts on groundwater for a large geographic area. The environmental impacts could be widespread in the soil and the air, as well as the surface and the groundwater. We have evidence of environmental damage done by largescale livestock facilities all over the nation, so why would we want to risk Minnesota's natural resources by allowing this gigantic animal factory. The Minnesota Pollution Control Agency should stop this now instead of working to control the pollution it will undoubtedly cause down the road.

Barbara Hyk-Zimmer **Letter 868**

I have been a STRONG opponent to factory farms. They are BAD for the environment, BAD for the cows (if unhealthy for cows... unhealthy for humans) As a society we are very unhealthy and THIS is one of the causes. Another is GMO's, as well as chemicals in farming instead of organic/sustainable farming practices. I'm a kidney cancer survivor caused by TCE in my drinking water. My only child died at 9 mo 26 days old is saving our place at Ft Snelling National Cemetery because of it. I get sick if I don't focus on organic foods or at least non GMO. In the past we have grown our own veggies and we only did organic farming.

DO NOT APPROVE OF THIS HORRIBLE PROJECT!!!

Mary Polta **Letter 869**

I am so opposed to the West River Dairy Expansion. What an eyesore and a problem of smells, water use, inhumane animal care and environmental pollution. Minnesota is a better state than polluting land.

Roslyn Hjermstad **Letter 870**

Thank you for taking comments about the proposed Riverview Dairy expansion project. The gigantic scale of the proposal rings alarm bells for me, so I am vehemently opposed. As a good first step, there must be a full and rigorous Environmental Impact investigation and report. That EIS should assess the effects of thousands of dairy cows on the environment, both locally and regionally. There are also economic impacts, because this is a corporate entity that will control markets and squeeze out smaller family operations with its sheer size. To approve of the Riverview Dairy project without a thorough evaluation of all consequences is not recommended. I am not a close neighbor of the site, but if approved it would set a precedent for similar factory farms in my area, the SE Minnesota karst geology (driftless) region. PLEASE deny any new permits for Riverview Dairy.

Leona Hanson **Letter 871**

Huge animal confinement of any kind has gotten way out of control. It's unhealthy for the animals, the enviroment and humans. The stench in the air most days is unbearable if you live within a short distance of these farms or buildings. It's disgusting and should have never been allowed in the 1st place. We also need to get rid of all farmers on country boards. I've found from experience that they don't care about the enviroment period. They don't even follow their own rules. It's all about money. As long as they don't have to put up with the smell or the destruction of the enviroment next to them they give the permit to the mega farmer. I'm sick of it.

Kay Drache **Letter 872**

I grew up on what was then considered a large beef operation of around 1000 head of cattle. The very idea of a confined operation of the size proposed by Riverview is appalling. Please do not let this expansion go forward.

Thank you for your attention and consideration of all the implications of this dairy proposal for people and the environment.

Pat Peschman **Letter 873**

I am writing to encourage you to deny the permit for the West River Dairy Expansion, a proposed massive operation. The environmental impacts of CAFO's is well known and cannot be denied. Negative impacts to water quality, increased greenhouse gas emissions, increased antibiotic resistance, and nutrient pollution to land from the massive waste are not what the community or the state of Mn need. I urge you to deny this permit.

George Pliml **Letter 874**

The United States continues to experience business consolidation within the agriculture sector. An example is that only four companies control 100% of the beef processing industry. This does not help the family farm at all, in fact it puts additional strain upon the farms existence. We cannot let further consolidation happen within our states dairy industry. Our county, the largest in Minnesota, now has only two or three dairy operations. These small family operations contribute so much to our local economies. So to allow an expansion of the West River facility is another nail in the coffin in our states and local small family dairy operations. I say no to the permit!

Sandra Sheets **Letter 875**

I live in Stevens county. I grew up here and live in the farm my grandfather grew up on in this county. Our farm is near an existing riverside operation just across the border into Traverse County and we have

learned that Riverview is also trying to expand another operation by our farm in addition to this one. I am concerned about how this operation will impact our water in this community, both quality and quantity. We have already had to start testing our water on our farm because the well that I drank from as a kid is now contaminated. The information presented in this EAW does not reassure me that Riverview will do what it needs to do to protect our water in Stevens county. The information provided in the EAW about water, even after the aquifer test that was initially left out was adde, is outdated and insufficient. An EIS must be required. It is the only way to get the information that my self and my community need to feel this project can go forward safely.

Kathy Herron **Letter 876**

Factory farms are a danger to our farmland, our animals, and our people. The concentration of animals and their waste is not manageable in the magnitude proposed. Please stop this.

Susan Scherer **Letter 877**

Having lived in rural areas for much of my life, small businesses, whether they are agricultural, recreational, or anything that offers a comfortable livelihood, a safe place to live and raise a family, is an essential choice for any person. Increasing the size of farms/dairies is a distressing indication that the values of rural individuals are being dismissed, in favor of corporations that make profit the sole reason for existing. What that consolidation means is that communities lose their residents who are no longer able to make a living.

Small, rural communities have been a safe, affordable choice for people who want to know their neighbors, to be there to help when needed, to enjoy each other's presence, and to raise children in an environment that values the land they thrive on, rather than the need to be bigger and richer. Allowing a massive dairy to become even bigger is a move that nullifies those values, and it contributes to the destruction of the very land we treasure.

Elizabeth Reach **Letter 878**

i am disgusted. too many cows. not enough work for workers, family farmers. again, disgusted. The environmental impact of this would be devastating. this is the largest cafo i have ever heard of. inhumane. makes me want to give up all hope. do not bow down to this corporation. deny their giant cafo please for the love of nature.

Devin Hammer **Letter 879**

My name is Devin, and I have worked for Summerville Electric for 16 years and have collaborated with Riverview on three previous new projects, in addition to providing ongoing service work at their sites. From what I have observed, the existing facility is clean and well maintained. Operations appear organized and professionally managed. That matters to those of who live nearby. I understand the project is undergoing environmental review by the state. I appreciate that these projects are subject to oversight and permitting before moving forward. In my experience, Riverview has operated responsibly in the community.

Furthermore, the dairy provides significant support to local farmers, employment, and businesses. These partnerships are vital to the economic health of our rural area.

For these reasons, I support the expansion.

Sincerely,

Devin

Shane Reynolds **Letter 880**

I am writing in support of Riverview's dairy expansion at West River Dairy and to oppose the imposition of an Environmental Impact Statement (EIS) in this case.

The existing Environmental Assessment Worksheet process, combined with the Minnesota DNR's separate aquifer review, represents a thorough and appropriate level of environmental scrutiny for a dairy operation of this kind. The current process is extensive, well-established, and sufficient. Requiring an EIS would set a damaging regulatory precedent for dairy agriculture across Minnesota and the Upper Midwest.

Beyond the regulatory question, it's worth acknowledging what an operation like Riverview's expansion means for the surrounding community. Dairy farms of this scale are economic anchors for rural Minnesota — they create direct jobs on the farm and ripple through dozens of supporting businesses, from equipment and feed suppliers to veterinary services and local contractors. Critically, they create a reliable, local demand source for the crops that Minnesota's grain farmers produce, strengthening the agricultural economy as a whole. Opposing this expansion doesn't just affect Riverview — it affects an entire ecosystem of rural livelihoods that depend on a thriving dairy industry.

I have extensive professional experience working with large dairy operations across the country, and Riverview ranks among the highest-standards operators I have encountered. Their commitment to infrastructure quality, animal welfare, and responsible land and water stewardship gives me real confidence that this expansion will be executed with the care the community deserves.

The current review process is sufficient. I urge the MPCA to approve this project without an EIS requirement.

Shane Reynolds

Kelly Fredrickson **Letter 881**

I vehemently oppose this expansion. It will be an environmental hazard that poisons our communities. I cannot articulate how much damage this will do!

Jim VanderGiessen, PRO Refrigeration, Inc. **Letter 882**

ATTN: Charles Peterson

My name is Jim VanderGiessen, and I am the CEO of PRO Refrigeration, Inc., a family-owned refrigeration equipment manufacturer serving agricultural operations in Minnesota like Riverview. I am writing in support of their proposed West River Dairy expansion in Stevens County.

Through our work in the agricultural sector, we depend on a strong and stable livestock industry. Operations like Riverview's create consistent economic activity that supports local jobs, drives investment, and allows businesses like ours to grow and reinvest in our communities.

The proposed expansion represents a meaningful economic benefit to the region. It will generate demand for local vendors, support both construction and long-term employment, and contribute to the vitality of rural communities that rely on agriculture.

From our direct experience, Riverview is a professional and reliable partner that contributes positively to the communities where it operates. Their presence strengthens the local economy and supports a broad

network of agricultural and service-related businesses. Riverview is genuinely focused on the future - they have taken some of the biggest steps in their industry toward efficient and environmentally responsible cooling solutions, helping demonstrate to the broader dairy sector what smart, forward looking investment looks like. We will work directly with multiple local and regional supply and service companies to maintain and support the systems we are providing them.

We are confident that Minnesota's environmental review process is thorough and well-equipped to evaluate projects like this one, and we fully support that process moving forward. Projects of this scale are essential to maintaining a competitive and sustainable rural economy, and continued investment in agriculture ensures that local businesses can provide jobs, services, and economic stability close to home.

I respectfully encourage your support and approval of this important project.

Sincerely,

Jim VanderGiessen, CEO

PRO Refrigeration, Inc.

Kim and Deborah K. Larson **Letter 883**

ATTN: Charles Peterson

We find it disheartening that unjustified negative labeling in agriculture continues to be an applied tactic in the ongoing small vs big agricultural operations. Many of the comments written in opposition to this project are typical examples of trying to proclaim this farmer and employee owned dairy (no East/West Coast investments or Hedge funds whatsoever) as a *"factory farm"*. Furthermore, just because this dairy is larger than most, many want to automatically label it …. bad - in all categories.

Statistics indicate the current average dairy herd farm in Minnesota is inventoried at 275 milking cows. When our grandparents milked their typical 16 dairy cows in the 1940's, alarmist of the day may have perceived dairy farms of 270+ cows with the following conjecturing *"…. just seems unreasonably too large"*, and "…. couldn't possibly be safe for the environment", and "…. would most certainly cross the line for animal welfare", and "…. we just don't need any more cows", and finally "…. A dairy farm of 270+ cows can only be defined as a … factory farm." All of these misconceptions about dairy herd size, whether 65 yrs ago or today, couldn't be further from the truth.

What is true, is that Minnesota's dairy farmers of today have more on the line than most, in making sure the environment around their farm is secure and protected, and the welfare of their cows is as humane and ethical as possible. Farmers and their families live in the immediate area of their farms. Nothing is more paramount to any farmer than a safe, abundant supply of water, as their families drink the water from the aquifers right beneath the land they farm. Equally, the welfare of their livestock is of principal importance to the security of their business. They know from experience that the best care they can provide to their livestock has proven to provide the best return to their family's livelihood.

What is also true, is that everything constantly evolves. No more so than in all areas of production agriculture. *"Economies of scale"* is the term used to describe the most efficient size a business needs to reach for maximum competitiveness, in what-ever segment they're competing in. It is most definitely played out in the following examples. The average MN farm acres in crop production in 1940 was 160 acres. The MN average today is 400+ and expected to double by 2040. Likewise, the increase in the average dairy herd size by 2040 will most definitely be bigger than the average of today, because

nothing can be expected to stay constant. But, it would be unjustifiable to formulate a knee-jerk reaction that …. bigger is automatically bad.

There is no disputing the fact that questions rightfully can, and should be asked, in the focus of science. The current EAW review would be absolutely thorough enough to answer all realistic questions enough to support the project. The level of inquiries needed to initiate an EIS would rise to the review level required for a Boundary Waters copper mine or a mid-Minnesota nuclear power plant …. not a livestock farm producing milk.

Respectfully,

Kim and Deborah K. Larson

Beth Stanford **Letter 884**

To whom it may concern: this expansion concerns every person in our state. Please do not approve this extensive expansion. When is large enough enough? If approved this time, others will push for theirs. We're fighting data centers which are destructors of the environment. Agrobusiness is too much for the environment to handle.

Mike Quale **Letter 885**

My name is Mike Quale; I want to express my support for their operation and their proposed expansion in Stevens County.

Riverview runs a top tier operation. Their facilities are clean, they care for the land, they support local communities, and they provide excellent care for their livestock. From what I have observed, they follow a long list of rules and regulations and consistently demonstrate that they are committed to doing things the right way.

Operations like Riverview bring significant value to the local agricultural community. For example:

1. They provide manure for fertilizer, reducing dependence on foreign produced fertilizers that are often controlled by a small number of global suppliers.

2. They give local farmers an additional market for their crops, increasing demand and strengthening local basis levels. This adds value to all producers in the area, regardless of their stance on this specific project.

Projects like this contribute meaningfully to rural America by supporting agricultural sustainability, economic opportunity, and community vitality. Based on my experience as a nearby resident, I fully support Riverview Dairy's expansion project in Stevens County.

Sincerely,

Mike Quale

Brady Koehl **Letter 886**

To Whom it My Concern,

First off, I wanted to introduce myself. My name is Brady Koehl, & I have now lived in Stevens County for 32 years & counting (with a brief hiatus to attend college in Marshall, MN). I am a resident of Hancock, MN – I am a father, husband, farmer, accountant, city council member, & community volunteer. This

isn't really my cup of tea to make a public comment, but the more I thought about it, the more I thought there were some things I needed to say on this matter.

I do want to start off by saying, I understand & acknowledge the environmental concerns. As farmers in greater MN, this is something that we are conscious of every day. As everything scales, & the size of the equipment, livestock herds, & everything in between grows larger – this can seem very intimidating & can be perceived in a negative way by many. I am here to tell you we are hyper aware of this. However, I take comfort in knowing that an operation like Riverview has already done more than their share of due diligence on a project of this nature, including the necessary research in the background, permitting, etc. to make sure that this is done in the correct way. This type of operation already operates under strict regulatory oversight, & the systems are in place to meet MPCA requirements.

Further, I wanted to dig a little bit into some of the specific concerns. I have heard comments about the size of the dairy, & the emissions from the animals., etc. Keep in mind – this dairy will be large, but half of the dairy is already in existence! Yes, the dairy that will be operating after the expansion will be the largest in MN. But it is not all new construction – half is already operating smoothly today. On top of this, I would encourage you to explore some of the positive things that Riverview is already doing to offset many of these concerns. From ensuring the operation is energy efficient as possible – this is something that is done in the name of cost – to capturing the methane gas & re-purposing this in an environmentally friendly way, the operation is only helped by reducing these things.

I have also heard concerns with the manure that will be a biproduct of this increased herd. As a farmer that has used this bi-product, the misconceptions of this being a negative for the land & water are often mis-cast. Regardless of the form, farmers need fertilizer as part of their crop plan. The larger percentage that comes from organic matter sources, the more positive of an impact there is the potential for on the land. Also – as a farmer that is in the business of organic production, this manure becomes a necessity & helps drive the growth in that area of our business.

Finally, the water. This is a concern, & I know this is something that has been seen around the nation. However, in a highly rural area like Stevens County, the water issues that are often tied to overuse or strain on local water systems in more densely populated or drought-prone areas have not come to light. As we become more efficient with our water use, more intentional with our practices, & are conscious of the numerous issues with water around the nation, & around the world – this is being considered, measured, studied, & remedied wherever possible. On top of this – Riverview has a plan in place to re-use much of the water that is in the end-product that is a key cog of this expansion plan. I would encourage you to ask their representatives about this, as it is a very cool concept.

Finally, to anyone reading this that is not familiar with Stevens County, I would encourage you to come & pay us a visit. This area is special & is uniquely positioned to pursue this kind of opportunity. We tend to join as one in support of projects of this nature, & we recognize the many benefits that Riverview has brought to our community, our families, & to the many individuals that are involved with the economics of the area. On top of that, on the drive west past the existing west-river dairy, I am reminded of the beauty of the countryside that we are lucky enough to live in.

When you drive past, yes, you will note the operation. But I would encourage you to reach out & ask for a tour & explore more before you develop an opinion. If you would like to talk about this – feel free to reach out to me – I am happy to discuss both sides of the arguments for & against this expansion. I am always open to more information.

Sincerely,

Brady Koehl

Anonymous **Letter 887**

I am a citizen of the state for 40 years and I wish to register my opposition to the RiverviewLLC cowfarm proposal. This proposed increase would have a severe effect upon the state, causing for example overloading of manure in water and alga blooms, risks to humans from possible health issues, greenhouse gas issues, etc. Please vote AGAINST this proposal when it comes up. THANK YOU!!!

Michael Crinion **Letter 888**

To Whom It May Concern:

I am writing to you as a dairy farmer in Minnesota. I want to express my personal support for the expansion of Riverview's West River Dairy in Stevens County.

I have watched the dairy industry evolve dramatically over the years. The farms we operate today bear little resemblance to those of a generation ago — not just in size, but in how carefully and thoughtfully we manage land, water, and nutrients. The tools available to us now, from precision nutrient management to advanced manure handling to real-time environmental monitoring, have made it possible to grow dairy production while improving our environmental outcomes. Riverview is a leader in putting those tools to work.

I have personally visited Riverview's farms and have seen firsthand how they manage their farms with a high level of professionalism and care for their employees, their animals and the environment. They set the standard for others in how to run dairy farms with consistent, responsible and ethical standards.

Riverview also brings jobs and opportunities to their communities. They partner with neighboring farmers on manure application programs that reduce the need for synthetic fertilizers and improve soil health across thousands of acres. They support local businesses. They show up.

Riverview has also earned its reputation for environmental stewardship. Their investments in water conservation — including water-recapture basins that reduce dependence on a single water source — and their proactive approach to manure management are evidence of a company that takes its responsibilities seriously. This is not compliance for its own sake; it reflects genuine values.

As an Edge board member, I want to be clear that Edge Dairy Farmer Cooperative has full confidence in Minnesota's existing environmental review process. The MPCA is experienced and well-equipped to evaluate this expansion and to use the tools at its disposal — including individual permit conditions where warranted — to protect our state's waters. We do not believe an Environmental Impact Statement or additional review layers are necessary or appropriate here.

I have heard concerns raised about the economic impact of this expansion on other dairy farms. I understand those concerns — competition is real and farming is hard. But the environmental permitting process is not the right place to resolve questions about dairy industry structure or farm size. Those are conversations for the legislature. Using environmental review to block or delay a project that has met the applicable standards would set a troubling precedent and undermine a process that all of us in agriculture depend on.

Riverview has done the work. They have earned this permit. I encourage the MPCA to proceed based on the science, trust the process, and support the kind of responsible dairy growth that keeps Minnesota competitive and keeps farm families on the land.

Sincerely,

Michael Crinion

Ash Grove Dairy

Mary Steinbicker **Letter 889**

The Riverview Dairy expansion requires, at a minimum, an environmental review. Coming from a farm community, I cannot conceive of what it will take to safely remove manure for that many animals. And the cruelty of confinement is inhumane.

Micky McGilligan **Letter 890**

In Minnesota and across the country, increasing attention is being drawn to the animal agriculture industry and the anti-competitive practices that are being used to benefit a small minority of parties along the food supply chain. From lower milk check amounts and issues related to accessing processing at a fair price, to higher prices at the grocery store, everyone — farmers, the communities they are a part of, and eaters — is being negatively affected by this.

Tom Beer **Letter 891**

The fact that we don't know the likely impacts of the West River Dairy expansion on air quality, soil pollution and water quality begs the necessity of a full, objective and timely environmental analysis. I urge the MPCA to allow this. Thank you, Tom Beer

Donna Wermus **Letter 892**

Riverview has a recent history of manure spills in western Minnesota. In Arizona, the company recently agreed to pay $11 million to residents affected by the over pumping of the dairy operation. The proposed Stevens County site sits within five miles of eight different protected waterfowl and wildlife production areas and is part of the Pomme de Terre River watershed, just 25 miles from its confluence with the Minnesota River. A facility of this scale located in such a vulnerable area calls for a thorough environmental review.

Amy Nankivil **Letter 893**

The Riverview CAFO Proposal Needs an EIS prior to building the first livestock operation in the state to hold over 20,000 animal units.

This operation, which is proposed for Stevens County, would be nearly double the size of the next largest livestock operation in the state in terms of animal units. This makes it a fundamentally new and particularly powerful threat to Minnesota farmers, the water, and rural communities.

The Minnesota Pollution Control Agency (MPCA), the agency that issues feedlot permits, must recognize the fundamentally new nature of this threat and give this permit greater scrutiny than it has to previous proposals. In short, this proposal must be required to undergo a full environmental impact statement process.

Martha Krikava **Letter 894**

Riverview, based out of Morris, Minn., is one of the largest milk producers in the country. The firm now owns 16 permitted dairy CAFOs in Minnesota alone, and these facilities house a total of more than 135,000 cows, according to the Star Tribune. That accounts for nearly a third of the state's entire dairy herd. Riverview also has a major presence in North Dakota, South Dakota, Nebraska, New Mexico, and Arizona.

An EIS will allow the proposal's negative impacts on water quality and quantity, local roads, and existing independent family dairy farms to be fully analyzed before the project is allowed to seek a permit.

According to the documents filed by Riverview, the proposed operation would:

Be allowed to pump up to 226 million gallons of water per year from an off-site well. For reference, the City of Morris, which is home to over 5,000 people, is permitted to pump up to 300 million gallons of water a year.

Have liquid manure storage encompassing 250 million gallons of waste. Require 13,200 acres of farmland for manure application.

This project must not go forward without an Environmental Impact Statement and review. Riverview has a recent history of manure spills in western Minnesota. In Arizona, the company recently agreed to pay $11 million to residents affected by the dairy's overpumping. The proposed Stevens County site sits within five miles of eight different protected waterfowl and wildlife production areas and is part of the Pomme de Terre River watershed, just 25 miles from its confluence with the Minnesota River. A facility of this scale located in such a vulnerable area calls for a thorough environmental review.

Just as importantly, an EIS of the West River Dairy Expansion proposal would address socio-economic impacts. Minnesota is already losing dozens of dairy farms annually due to inconsistent and often below cost-of-production milk prices. Massive dairy operations, like the one Riverview is proposing to build, have glutted the market and tightened Big Milk's stranglehold on the industry, allowing them to push small and medium-sized family farms out of business and off the land. This operation would only exacerbate the situation and accelerate the loss of dairy farms in our state, decimating Main Street economies in the process.

In Minnesota and across the country, increasing attention is being drawn to the animal agriculture industry and the anti-competitive practices that are being used to benefit a small minority of parties along the food supply chain. From lower milk check amounts and issues related to accessing processing at a fair price, to higher prices at the grocery store, everyone — farmers, the communities they are a part of, and eaters — is being negatively affected by this.

Thank you for your consideration of my concern and request.

Susan Darley-Hill **Letter 895**

This project begs extreme scrutiny for the potential of many and varied negative impacts it will most certainly have on traditional, smaller scale farming operations, on appropriate land use, on water supply (sucking up a staggering volume) and pollution from soil runoff and massively excessive manure handling and spreading/disposal of giant amounts of waste. This is not the kind of industrial farming that benefits anyone other than the corporation that reaps profits at the expense of everyone who seeks a safe water supply, healthy soil, an environment undiminished by overuse, pollution, and a safe food supply. Allowing this kind of operation exhibits an utter disregard for families seeking a fair shake in the agricultural economy.

Martha Archer **Letter 896**

This proposal by Riverview must be required to undergo a full environmental impact statement (EIS). This expanded Riverview facility would be more than 60 times the size of the average Minnesota dairy. This makes it a fundamentally new and particularly powerful threat to Minnesota farmers and rural communities. The health of our ag land and wellness of our communities is at risk with this expansion.

This project must go thru industrial scale review to ensure compliance, transparency and communication.

Katharine Winston **Letter 897**

This is a HUGE undertaking - DON'T MESS IT UP! Protect your citizens, communities, and rural lands: In Minnesota and across the country, increasing attention is being drawn to the animal agriculture industry and the anti-competitive practices that are being used to benefit a small minority of parties along the food supply chain. From lower milk check amounts and issues related to accessing processing at a fair price, to higher prices at the grocery store, everyone — farmers, the communities they are a part of, and eaters — is being negatively affected by this.

Amy Cordry **Letter 898**

If built, the facility will hold 18,855 dairy cattle, bringing the total animal units to 26,397 in one place. This proposed expansion would be nearly double the size of the next largest livestock operation in our state in terms of animal units. This expanded Riverview facility would be more than 60 times the size of the average Minnesota dairy, which had fewer than 280 cows in 2025. This makes it a fundamentally new and particularly powerful threat to Minnesota farmers and rural communities.

Riverview, based out of Morris, Minn., is one of the largest milk producers in the country. The firm now owns 16 permitted dairy CAFOs in Minnesota alone, and these facilities house a total of more than 135,000 cows, according to the Star Tribune. That accounts for nearly a third of the state's entire dairy herd. Riverview also has a major presence in North Dakota, South Dakota, Nebraska, New Mexico, and Arizona.

The Minnesota Pollution Control Agency (MPCA), which is the agency that issues Minnesota's feedlot permits, must recognize the fundamentally new nature of this threat and give this permit greater scrutiny than it ever has to previous proposals. This proposal by Riverview must be required to undergo a full environmental impact statement (EIS).

Mark Muller **Letter 899**

Large CAFOs are an affront to family farmers and our soil and water. Riverview represents the wrong direction for Minnesota agriculture. Please require the CAFO to go through a full environmental impact process.

Chloe Stotler **Letter 900**

This expansion is enormous and needs to be reviewed in depth before proceeding. The proposal should undergo a full Environmental Impact Statement (EIS).

Dorothy Dolezal **Letter 901**

I strongly disapprove the use of CAFO facilities, as they are cruel to the animals and harmful to our environment. There is nothing that could convince me that this is an appropriate way to farm.

William Gorman, Pro Refrigeration **Letter 902**

Dear Mr. Peterson,

My name is William Gorman, and I serve as Vice President of Sales for Pro Refrigeration, supporting dairy operations across the United States, including partners like Riverview.

I am writing to express our strong support for Riverview's proposed West River Dairy expansion in Stevens County.

Through our work in the dairy industry, we see firsthand the importance of stable, wellmanaged livestock operations. Businesses like Riverview play a critical role in sustaining rural economies by creating jobs, driving local investment, and supporting a broad network of suppliers and service providers.

I have personally visited Riverview's farms and have seen firsthand how they operate with a high level of professionalism and care for their employees, their animals, and the environment. They set the standard for how modern dairy farms should be run—with consistent, responsible, and ethical practices.

This proposed expansion represents a meaningful economic opportunity for the region. It will increase demand for local vendors, support both construction and long-term employment, and strengthen the surrounding agricultural community.

From our experience, Riverview is a dependable and well-run organization whose continued growth benefits not only their business, but also companies like ours and many others that rely on a strong dairy industry.

Based on our understanding of the state's environmental review process, it is both rigorous and appropriate. We do not believe an Environmental Impact Statement (EIS) is necessary in this case.

I respectfully encourage your support and approval of this important project.

Sincerely,

William Gorman

Vice President of Sales

Pro Refrigeration

Sarah Johnson **Letter 903**

I strongly encourage the MPCA to conduct a very thorough environmental review for this gigantic operation. I think we need to be more supportive of smaller, family farms frankly. But at least please don't rubber stamp this factory farm. Thank you!!

Jason Henrich, Flat Rate Inc. **Letter 904**

ATTN: Charles Peterson

My name is Jason Henrich, and I am the General Manager of Flat Rate Inc., a company specializing in concrete placement and aggregate hauling throughout Minnesota and the Dakotas, servicing agricultural operations like Riverview LLP.

I am writing to offer my support for Riverview's proposed West River Dairy expansion in Stevens County. Based on our firsthand experience of working on projects with Riverview over the last fifteen years, we can confidently say that Riverview operates with professionalism and reliability. Their projects contribute positively to the areas in which they are located, strengthening the broader network of agricultural producers and service providers.

Agricultural operations like Riverview's play a key role in sustaining the economic health of rural communities that depend heavily on agriculture. They drive economic activity by creating jobs, encouraging local investment, and supporting local businesses like ours. Supporting growth in this sector

helps ensure that local businesses can continue to operate, expand, and provide valuable employment opportunities within their communities.

Based on our longstanding relationship and firsthand experience, we are confident in Riverview's ability to meet all applicable environmental regulations and operate responsibly within the community. I respectfully encourage you to approve and support the West River Dairy expansion.

Thank you,

Jason Henrich

General Manager

Flat Rate, Inc.

Jeanne Landkamer **Letter 905**

Dear MPCA,

I am very concerned about the expansion of CAFOs in Minnesota. They pollute area waters and make large areas unlivable because of the toxic air quality. They put small producers out of business. They have a record of intimidating and harassing farmers that object to these gigantic operations. For a variety of reasons, I think it is imperative that the MPCA require a full environmental impact statement to assess the dangers posed by the proposal to expand the West River Dairy operations.

Thank you,

Jeanne Landkamer

Allison Greenwald **Letter 906**

Hello,

I have many concerns about this expansion and believe that a full environmental impact report is absolutely necessary.

This expansion would keep cows in total confinement which raises serious animal rights concerns. In addition, increasing livestock production of this scale with generate massive amounts of manure, increasing the risk of water pollution and toxic algae blooms. It will put a strain on already taxed water resources using up to 100-226 million gallons annually. The Minnesota Pollution Control Agency estimates that 56 percent of surface waters do not meet basic water quality standards, and that crop and livestock production contribute to 85 percent of the state's water pollution.

Please do not move forward with this project.

Thank you,

Allison Greenwald

Jessica Renner **Letter 907**

Yes, we need a full environmental impact statement!!

Gwendolyn Fassett **Letter 908**

This CAFO proposal needs an environmental review, a SERIOUS environmental review! Almost twice the number of cows as the current largest operation in the state? As much water as the city of Morris? I

don't know why we're even considering this proposal -- CAFOs are terrible for the animals, terrible for the neighbors, terrible for small farmers, and terrible for the environment. At the very least, this proposal should not move forward without a strict environmental review and regular, thorough inspections to ensure that their 250 million gallon waste storage (!!!) is not leaking. Actually, don't bother with the review -- just do the right thing and deny this proposal!

Thank you.

Tiffany Nesbit **Letter 909**

Please do not expand and please complete a full environmental review.

Ah-li Monahan **Letter 910**

I am very concerned about the proposed dairy in the area near Morris, Minnesota. It is more than double the animal units of the next largest dairy operation in Minnesota. As such, it risks more harm to the area than our current CAFOs. It would be located near several sensitive wildlife areas where manure could do a lot of harm. The company already has a track record of harmful spills in other states. The company is also asking for a permit to use almost as much water as the nearby city.

With such a large operation, Riverview, LLP must be required to submit a full EIS, and the EPA needs to do an in-depth examination before deciding on whether to issue a permit.

Thank you for your consideration.

Laura Cullip **Letter 911**

To Minnesota Pollution Control Agency,

I am writing as a concerned citizen, landowner, and farmer in MN regarding the West River Dairy Expansion. My concerns are environmental, economic, and to the overall health of the MN community. Nationally and in MN, we are in an economic farm crisis with small farms struggling to pay their bills and continue their farming livelihood due to low market prices and high costs of inputs, rental price of land, and difficulty competing against a few larger and larger farm operations. An expansion of this size is not of an economic benefit to MN. It continues a trend of inequality in agriculture with just a few farmers monopolizing the market and animals, while the smaller farms are often kept out of markets, milk trucks won't come to their farm, they can't compete on land rental prices, milk prices plummet, and ultimately smaller farmers can't compete and stay in business. Our land, economy, and communities suffer when family farms go out of business and business is consolidated into a few.

Environmentally, this is altogether too many animals, too much water usage, and too much manure consolidated into one location. It is an outrageous and egregious example of consolidation. This site is within 5 miles of 8 different protected waterfowl and wildlife protection areas. There needs to be a full environmental review in the form of an EIS so that local residents have the opportunity to weigh in on the impacts this project may have on them, their farms, their community, the wildlife, and landscape. If there are no environmental, community or economic issues with having 26,397 animal units in one location, then let the EIS process illustrate that and give citizens an opportunity to weigh in for further review. We need full transparency and accountability in this permitting process. Otherwise it looks like the largest dairy operation in MN gets to leverage their market monopoly, influence, and power to favor their individual business over what is best for the community, environment, and local farming community.

Thank you for considering my comments.

Sincerely,

Laura Cullip

Darlys Vogt **Letter 912**

The SIZE of the Riverview expansion project is OUTRAGIOUS and NOT WANTed in STEVENS COUNTY.

Being a proud area farm resident for most of my 80 years, as well as the generations before me. I VALUE our MANY LAKES and the outcome of the grain and smaller farms we have in the area now and into future.

Also have a HUGE concern for the ODOR, WATER, HEAL TH ISSUES and what about the aquifer in the future.

We need everyone to make up a community, not just the BIG Companies.

Regardless of the outcome of the reports. My answer is NO! NO! NO! To the LARGE EXPANSION.

Respectfully,

Darlys Vogt

PS thanks for your time

Nicole Wenzel **Letter 913**

Hello MPCA,

The MPCA must recognize the fundamentally new nature of the Riverview Dairy Expansion threat to our land and water resources and give this permit greater scrutiny than it ever has to previous proposals. This proposal by Riverview, LLP must be required to undergo a full Environmental Impact Statement (EIS).Riverview has a recent history of manure spills in western Minnesota. In Arizona, the company also recently agreed to pay $11 million to residents affected by the dairy's overpumping. There are 8 different protected waterfowl and wildlife production areas within 5 miles of the new location, and is located as part of the Pomme de Terre River watershed, just 25 miles from its confluence with the Minnesota River. A facility of this scale located in such a vulnerable area calls for a thorough environmental review. Minnesota is already losing dozens of dairy farms annually due to inconsistent and often below cost-of-production milk prices - an EIS would help address the socio-economic impacts of this project. Massive dairy operations, like the one Riverview is proposing to build, have glutted the market and tightened Big Milk's stranglehold on the industry, allowing them to push small and medium-sized family farms out of business and off the land. This operation would only exacerbate the situation and accelerate the loss of dairy farms in our state, decimating local economies in the process.

PLEASE conduct a full EIS - thank you for your time and consideration. We are so lucky to have the natural resources we have in MN and the greater Midwest and need to do all we can to take care of it.

Scott Wirtzfeld **Letter 914**

Dear MPCA,

My name is Scott and have just began working with Riverview on a project unrelated to the expansion of the dairy in question. Up to this point this company has been a class act to work with. They do not cut corners and are constantly trying to help better their employees. They offer a huge economic benefit to

the communities that they are present in. They preach cleanliness and you can certainly see it at the sites they have. I would like to give my support to Riverview LLP, thank you for your time.

Jessie Pinney **Letter 915**

The impact of the amount of water for the 18,000 dairy operation is a major impact. Also, the fact that the manure is spread over such a large area is another reason for environmental impact study. I know this is just looking at the environment, but I would like to know how many farmworkers will be employed and also what they will be paid. Do they have other benefits like health care, vacation, overtime pay, etc. and my last comment is that we are already subsidizing milk because we have a glut of it do we really need more dairy? And if we do, where is the product going, what market will it be in, and how does it affect the existing market now?

Michelle Carroll **Letter 916**

Minnesota's approach to managing water resources is lax, to the detriment of taxpaying citizens. Corporations benefit far more than citizens from our shared resources. Examples: Riverview Dairy. Data centers. Pivot irrigation.

In a recent tour of Riverview's Waubun facility, our group was told that the test for whether the dairy was depleting groundwater was to run the facility at average capacity water usage - not peakand monitor nearby residential wells for 6 days to see if they ran dry. If not, the water use permit would be granted. And while there was ongoing monitoring of water quality on site after operations began, there was no ongoing monitoring of the source water (aquifer) or of surrounding water quality.

Riverview touts the "closed ecosystem" of their facilities - wastewater and solid waste are recycled and pumped underground back to adjacent farms, who serve the dairy. That doesn't support the continuation of the aquifer/water source and landowners that depend on it.

With climate change data the past 30 years we know not expect aquifers to recharge, or for water sources to become more plentiful.

Reduce the amount of water these large facilities are permitted to use. You're supporting big business at the harm of Minnesota's residents.

Chris Sonnek **Letter 917**

Members of MPCA:

I initially wrote this Letter as a response to request from the "Land Stewardship Organization" to fight this dairy expansion. My response also fits the same purpose for public comment for West River Dairy Expansion

I'm truly disappointed in your decision to fight this preliminary permitting process for Riverview LLP or any other Livestock facility for the following thoughts and reasons. -

There are already Strict Federal, State, County, and Township thresholds and regulations put into place to address the multitude of concerns any Livestock operation operates within.

The manure can be handled through digester system and the Methane Gas used to generate electricity to power the operation.

Compost can be made and sold in multiple ways to surrounding farmers or bagged up and sold throughout United States.

Humus can be made from the manure as well and used in the multitude of Biological products in the Fertilizer Industry. (Organics Included)

The remaining liquid still makes an excellent renewable fertilizer option to the area farmers. Who are you (Land Stewardship) to decide as an organization how many animal units are too much?

I had a personal friend that expanded his 70-cow dairy to 500 cows back in the late 90's. I had my own 35 cow herd for 20 years and had considered the same option to expand my herd. Instead, choose to follow the opportunity to be involved in a Sow Coop.

30 years ago, a group of 12 farmers, myself included, established a 2,400 Head Sow unit that was built on my 170 Acre farm.

We all experienced this same outrage that you are promoting yourselves now.

I heard a Quate while attending a MN Pork Producer Seminar that said "In the Lack of Sound Science Based information, Outrage Drives Perception" How True and fitting is that Quate unfolding right now for this proposed Dairy Expansion.

All Livestock operations can create beneficial opportunities to other area farmers and communities.

I've had the privilege to attend a few of your different Seminars and on Farm presentations.

My suggestion for Land Stewardship Organization and yourself, Continue to offer Educational Seminars, Hands on Field Days, Informational communication via email, texting, Facebook, Tic Tok or whatever the upcoming communication tools that develop. We will be able to Learn and see these alternative ways of farming and decide individually whether it warrants the risks, efforts to pursue those new paths forward.

In the end of the day, Economics still play a Huge role in every decision that each and every one of us must do remain viable. Doesn't matter how big or how small, at the end of the month, we all have to pay our bills to remain in agriculture.

Thanks for your time

Chris Sonnek

Samantha Meurett **Letter 918**

This is a horrible, environmentally unfriendly idea. Dairy is becoming less popular, not more.

Karen Locke **Letter 919**

I am against this expansion. In addition to the harms of water usage and potential pollution, it would harm the economy because of the huge scale taking away the ability of smaller farmers to compete.

Please deny their request.

Dave Vipond **Letter920**

Dear MPCA Review Team,

I am writing to express my strong support for Riverview Farms' plans to expand their West River Dairy operation.

I grew up on a small dairy farm and saw firsthand how environmental practices and oversight can vary across operations. Smaller, unregulated dairies are often not held to the same environmental standards,

monitoring, or accountability as modern, permitted operations. That experience has given me a strong appreciation for farms like Riverview that operate transparently under strict regulatory oversight.

Riverview Farms is among the best at what they do. They are highly environmentally conscious and consistently go the extra mile to ensure their operations protect land, water, and surrounding communities. They do not cut corners. Their long-standing commitment to responsible manure management, water protection, and environmental compliance is well documented and proven through their existing operations.

The additional cows proposed as part of this expansion are not introducing anything new or untested. Riverview Farms has extensive experience managing operations of this size safely and responsibly. The current Environmental Assessment Worksheet (EAW) process is doing exactly what it is intended to do—evaluating potential impacts and ensuring environmental protections are in place.

Based on Riverview Farms' proven track record and the safeguards provided through the EAW process, this expansion does not warrant a full Environmental Impact Statement (EIS). The existing environmental review process already provides adequate protection for Minnesota's natural resources while allowing responsible agricultural operations to move forward.

Riverview Farms has shown that agricultural growth and strong environmental stewardship can go hand in hand. I respectfully encourage the MPCA to consider their outstanding environmental record and support the proposed West River Dairy expansion.

Thank you for your time and consideration, and for the important work you do to protect Minnesota's environment.

Sincerely,

Dave Vipond

Jacob Sklar **Letter 921**

To whom it may concern/Dear blank

I am a Rabbinical Kosher Supervisor for the Midwest area that oversees many different facilities involved in kosher production. Part of doing so requires very close involvement in the inner workings of each facility. River View Farms makes kosher supervision a pleasant experience thanks to their professional, cooperative team and well-organized, sanitary facilities, among many other reasons. Their production is done with the highest level of sophistication, from simply being an organized, well-done affair to their highly environmentally conscious policies. They efficiently milk their cows while strictly maintaining very humane conduct, showing their impressive ability to efficiently get a job done with integrity. In a similar vein, River View Farms maintain an impressive level of cleanliness in their buildings, which directly coincides with the absence of the unpleasant odor that is commonly present in milk farms. Simply put, their environmental impact is minimal to practically non-existent. As a kosher supervisor for the entire Midwest, River View Farms is an excellent asset to the farming industry; that only improves that market when expanded.

James Lubenow **Letter 922**

My name is Jamie Lubenow, and I am the owner of Wagner Company, an excavating company that works alongside agricultural operations throughout West Central Minnesota. I am writing in support of the proposed West River Dairy expansion in Stevens County.

Through my work, I have had the opportunity to work with Riverview Dairy and have seen firsthand how they operate. They run a professional, well-managed operation and take their responsibilities seriously, both from a construction standpoint and in how they approach long-term planning and compliance.

Projects of this scale require detailed engineering, careful site preparation, and strict adherence to environmental and construction standards. In my experience, Riverview Dairy has consistently worked with qualified professionals and followed those standards closely. These are not casual projects, and the level of coordination and oversight involved reflects that.

I also want to speak to their environmental approach. Based on my experience working with them, they take environmental responsibility seriously and are continually working to improve their practices and reduce their impact. That commitment shows in how they plan and execute their projects.

This type of expansion also plays an important role in supporting rural economies. It creates steady work for local contractors, suppliers, and service providers, and contributes to the overall stability of communities that rely on agriculture.

I strongly encourage the MPCA to approve this project and allow the expansion to move forward. This is a well-run operation with a proven track record, and this project represents responsible growth that will benefit both the local economy and the broader community.

Thank you for your time and consideration.

Monte Strelow, Strelow Ranch Trucking — Letter 923

ATIN: Charles Peterson

My name is Monte Strelow, and I am an owner of Strelow Ranch Trucking. In my role, I work directly with agricultural operations across Nebraska, including in Riverview, Stevens and I am writing to share my support for the proposed West River Dairy expansion in Stevens County.

Through important my day-to-day work in trucking and agriculture industry, I see firsthand how important strong livestock operations are to keeping rural economies moving. Businesses like Riverview provide steady work not only for producers, but also for those of us in supporting roles such as transportation, feed supply, and other agricultural services.

From my personal experience working with Riverview, they have consistently been professional, organized, and dependable. That level of reliability is critical in this industry, and it has a positive ripple effect on everyone connected their operations.

The proposed expansion will bring real economic opportunities to the area. It will create additional demand for local contractors, support long-term employment, and increase business for companies that serve agriculture. For people like me, it represents continued stability and the ability to support our families through this line of work.

Rural communities depend on continued investment in agriculture to remain strong. Projects like this help ensure those communities can grow, maintain jobs, and support local businesses well into the future.

Based on my experience in the industry and the strength of the state’s environmental review process, I do not believe an Environmental Impact Statement is necessary for this project. I respectfully ask that you support and approve the West River Dairy expansion.

Sincerely,

Monte Strelow

Strelow Ranch Trucking

Linda Olson **Letter 924**

Aside from the obvious pollution issues, mega-dairies like this saturate the market, driving smaller producers out of business. And of course, there's the well-known fact that factory farming is harmful to the animals farmed. They are treated like products, not living beings.

Leah Rogne **Letter 925**

I oppose the approval of a dairy operation of this size in this location. The concentration of animals is unhealthy and the competition with local dairy operations is unacceptable. Any investigation should go beyond an Environmental Assessment Worksheet and should include extensive testing for airborne and water-carried pollution and thorough examination beyond a cursory look at the potential harm.

Robert Rutkowski **Letter 926**

Community members and advocacy organizations have raised questions about whether the impacts of an operation this large can be managed safely, including:

Manure volume:

18,855 cows would produce an estimated 285,000 gallons of manure every day — about 520,000 tons per year — nearly 40% of Morris's daily water use

Groundwater risks:

Potential contamination from manure storage and land application

Drinking water:

Increased nitrate levels that can threaten private wells and public health

Air quality:

Odor and emissions that affect the quality of life for nearby residents

Farm consolidation:

Pressure on small and mid-sized family farms and a continued "get big or get out" model

Cumulative impacts:

Multiple large CAFOs are concentrated in one region, with limited oversight

Market Saturation:

Mega-dairies like Riverview dominate the milk market, and expanding this facility would further flood it, making it even harder for small farms to survive

Ian Vogel **Letter 927**

The idea of putting almost 19,000 cows in one confinement setup seems absurd, but I think it's important to be open to business growth and expansion and to make informed decisions based on data. With that being said, moving forward on a project like this without completing a full EIS is irresponsible and would be a dereliction of duty for state officials overseeing the project if permitted.

We only get one shot at getting this right. Please do the right thing. Complete and EIS so that the decision makers have the best possible data to make the best decision for the people of Stevens County and the citizens of Minnesota.

We love agriculture, but not all ag business models are good for the environment or their neighbors.

Christopher Carlson **Letter 928**

A full Environmental Impact Statement (EIS) is needed, only a more in-depth review can fully assess the unique risks posed by such a massive dairy operation.

Reasons listed below.

Manure volume:

18,855 cows would produce an estimated 285,000 gallons of manure every day — about 520,000 tons per year — nearly 40% of Morris's daily water use

Groundwater risks:

Potential contamination from manure storage and land application

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Steven Vogel **Letter 929**

I was born and raised and educated in neighboring Wisconsin, but have worked and lived in the Washington, DC suburbs since 1977. I am extremely concerned about whether the impacts of an operation this large can be managed safely, including:

1) **Manure volume:**

18,855 cows would produce an estimated 285,000 gallons of manure every day--about 520,000 tons per year--nearly 40% of Morris's daily water use.

2) **Groundwater risks:**

Potential contamination from manure storage and land application.

3) **Drinking water:**

Increased nitrate levels that can threaten private wells and public health.

4) **Air quality:**

Odor and emissions that affect the quality of life for nearby residents.

5) **Farm consolidation:**

Pressure on small and mid-sized family farms (like the ones both of my parents grew up on in southwestern Wisconsin) and a continued "get big or get out" model.

6) **Cumulative impacts:**

Multiple large CAFOs are concentrated in one region, with limited oversight.

7) **Market Saturation:**

Mega-dairies like Riverview dominate the milk market, and expanding this facility would furtherflood it, making it even harder for small farms to survive.

For all of the above solidly fact-based reasons, I respectfully but sincerely urge the MPCA to reject the expansion of this CAFO.

Kally Goschke **Letter 930**

This would be a monopoly that would alter the market and push out smaller dairies.

I request an extensive EIS and animal welfare issues investigation of current operation. It looks like they are not caring for current animals by the look of their calves especially, let alone thousands more!

I don't think we should be bearing the costs of this mega CAFO. Their manure plan is not adequate. I live near Minnesota River and can see the impacts of current nutrient load and hydrology.

Pomme de Terre River watershed.

This watershed already shows documented nutrient stress, including elevated nitrate levels in local surface waters and connected basins. Given these existing conditions, the proposal should be evaluated not in isolation, but in terms of cumulative nutrient loading.

1. Nitrate Loading and Existing Impairment

The addition of manure from a significantly expanded herd, applied across approximately 13,000 acres, will increase total nitrogen inputs in a watershed that is already exhibiting nitrate concerns. Even with best management practices, it is well established that a portion of applied nitrogen is not taken up by crops and is instead transported via leaching and runoff.

I request that MPCA require a quantitative cumulative nitrogen loading analysis demonstrating that this project will not worsen existing nitrate conditions in receiving waters.

2. Tile Drainage and Rapid Transport Pathways

The project area includes extensive subsurface tile drainage, which creates direct hydrologic pathways from fields to ditches and streams. This significantly reduces natural attenuation and increases nitrate delivery to surface waters.

I request that MPCA require specific analysis of tile-drain contributions to nitrate transport, rather than relying solely on general nutrient management assumptions.

3. Groundwater Protection

The region relies heavily on groundwater for drinking water. Land application of manure at this scale presents a risk of nitrate leaching to aquifers, particularly in vulnerable soils.

I request that MPCA require:

* Expanded groundwater monitoring wells in application areas

* A clear nitrate threshold response plan if levels increase

4. Manure Storage Risk and Extreme Weather

While the proposal includes lined manure storage basins, extreme precipitation events are increasing in frequency and intensity. Overflow or application during saturated conditions could result in significant nutrient releases.

I request evaluation of climate-adjusted storage capacity and land application timing safeguards.

5. Water Quantity Impacts

The proposed groundwater appropriation (over 200 million gallons annually) raises concerns about local aquifer drawdown and potential impacts to connected surface waters and wetlands.

I request a cumulative water balance analysis evaluating impacts to nearby water bodies and ecological systems.

6. Anti-Degradation and Downstream Impacts

As the Minnesota River system is already impaired in many reaches, additional upstream nutrient loading may contribute to downstream degradation.

MPCA should evaluate this project under anti-degradation standards, ensuring it does not contribute to further impairment.

Conclusion

Given existing nitrate concerns in this watershed, approval of this expansion without robust, site-specific cumulative impact analysis would pose a significant risk to both surface water and groundwater quality. I urge MPCA to require additional study, monitoring, and enforceable safeguards before considering permit approval.

Manure volume:
18,855 cows would produce an estimated 285,000 gallons of manure every day — about 520,000 tons per year — nearly 40% of Morris's daily water use

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Cynthia Huse **Letter 931**

Riverview Dairy LLC has the right in our capitalistic and democratic society to propose an expansion of operations. This current herd expansion at a single location, however, is extraordinary in the resources required to plan, build and maintain this unprecedented project proposal. The consequences of this project for the wider human and natural community as well as air, water, soil and infrastructure need to be carefully studied in proportion to the proposal. Therefore I urge a full environmental review. Half measures will avail the wider context nothing in the face of this unprecedented request.

Megan O'Hara **Letter 932**

This MEGA dairy operation will seriously impact water quality across the region. Water is a commonly held resource, critical for life and health, and it doesn't respect county or municipal boundaries. Minnesota is made of water and we cannot keep exploiting it. Please respect the rights of other dairy farmers, the health and welfare of children and families and the water quality of Minnesota. Riverview is simply too large an operation for the land and water to support and for the health of residents throughout the state!

Yvonne Weber **Letter 933**

I have concerns about whether the impacts of an operation as large as the West River Dairy Expansion can be managed safely, including:

Manure volume:

18,855 cows would produce an estimated 285,000 gallons of manure every day — about 520,000 tons per year — nearly 40% of Morris's daily water use

Groundwater risks:
Potential contamination from manure storage and land application

Drinking water:
Increased nitrate levels that can threaten private wells and public health

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Mark Roalson **Letter 934**

There are many things to consider on this issue. Large CAFO consolidations threaten small farmers and basically crowd out the small farm enterprise market-share wise and in available land and possibly permitting as well.

Manure is always a logistic issue. How is this (285,00 tons a day) going to be handled and controlled? Is it going to seep through its containment area and get into groundwater? Will nitrates eventually get into local drinking water? What are the preventive measures that will keep groundwater and drinking water free of contaminants? Air quality is a concern for local home-owning residents. People with lung and breathing issues will have a difficult adjustment, and maybe having to move.

I am not against dairy farming, but I know from experience that the bigger the animal agriculture system, the more chance there is not only of pollution, but the likelihood of disease increases and the need for more antibiotics arises. That is why we have the high antibiotic resistance factor of bacteria and in other human pathogens today. Creating more opportunity for pathogens to become resistant to antibiotic chemicals is a bad idea. Show me a CAFO that does not use large quantities of preventive anti-pathogenic chemicals today. There are none.

Melissa Heinen **Letter 935**

Concerned about the expansion of the West River Dairy and what it could mean for our water, air, and soil. Please be sure to carefully understand the possible long-term impacts on our environment and communities.

Roger Wacek **Letter 936**

Several years ago I listened to a SWCD (Soil & Water Conservation) official talk about measured nitrate contamination of aquifers in the Karst Region of SE Minnesota; Lets get SWCD comments on an EAW (Environmental Assessment Worksheet).

Jan Joannides **Letter 937**

This type of consolidation in agriculture is not good for our environment, rural communities, water quality (and availability), or animal welfare. I oppose the expansion.

Nathan Collins **Letter 938**

c/o Charles Peterson

I support the expansion of Riverviews West River site.

I have farmed around and worked with Rivrview for 25 years, have seen the benefits to the community and surrounding farms, helping keep both vibrant and alive.

This process is to be fact and performance based and not emotional, and if this process does not remain as such, it will have a devastating impact on dairy's of all size in Minnesota! And the entire state will feel the repercussions.

Therefore, I believe the current review process is sufficient and that additional regulatory steps, such as a requirement for an environmental impact statement (EIS), are unnecessary.

Thank you

Nathan Collins

Linda Herron **Letter 939**

With such a large cow population (11,000), the need for a complete Environmental Impact Statement(EIS) is obvious. Such an immense feedlot has a strong potential for water pollution(including groundwater) as well as land (where manure wastes are stored) and air pollution (methane gas).

Considering past applications of the environmental laws in Minnesota, enforcement of existing laws has been spotty. As a Minnesota resident and taxpayer, I urge the MPCA to follow best practices and require an EIS before any enlargement of the facility is approved.

Thank you for the opportunity to comment.

Amy Flatten **Letter 940**

Dear Charles Peterson and the Minnesota Pollution Control Agency,

I write to you today to share I do not support the expansion of the West River Dairy CAFO Operation. I am concerned of the irreversible impact huge dairies like this place on our natural resources.

I have worked on a farm, previously lived in a rural town, and have learned about the impact of CAFO's. I have even worked in dairy manufacturing in Wisconsin and understand the importance of the dairy industry, but supporting such huge corporations like this is not beneficial to the local economy or environment in the long-term.

Please do not allow such a big operation to push their weight around and exceed current animal unit limits.

Thank you for considering the implications of a CAFO of this magnitude.

Kindly,

Amy Flatten

Phillip Lermon **Letter 941**

I think this project is about more than Synnes Township. A dairy this size affect the markets for milk in all of Minnesota. Dairy is very important to my area of the state, our rolling pastures and fertile soils make it about perfect for dairy farming. This huge project is detrimental to the milk markets and will drive dairy out of my part of the state. It will without a doubt pollute the shallowest aquifier and surrouding streams. I also have a family member who lives in a valley 3 miles from a 2000 head dairy. There are many days they can't go outside as the stench is so strong, especially in the spring and fall when they apply slurry from the pits. I can't imagine how awful this operation stinks. It stinks this bad because it's completely unnatural way to raise animals. This dairy and it's feed suppliers will use huge farm equipment, which means bigger fields, and more erosion. They will farm more marginal lands intensively not because it makes economic sense, but just because it's more convenient for the larger equipment. That's what is happening around our area. Riverview Farms is not a farm, it is a corporate conglomerate.

Brian Miller **Letter 942**

ATTN: Charles Peterson

My name is Brian Miller, recently retired from Merck Animal Health where I worked as a Dairy Technical Services Veterinarian. In this role, I served dairy producers and practice veterinarians primarily in the upper Midwest including the state of Minnesota. I worked as an industry veterinarian for over twenty

years. Prior to my industry career, I was in private practice as an owner/partner of Whitewater Veterinary Hospital, Whitewater, WI for more than twenty years.

Over the course of my industry career I have witnessed firsthand the growth of the Riverview operation, and I have personally visited many of their sites that are located in multiple states. Riverview is an extremely responsible operation that provides state of the art facilities, nutrition, and management incorporating protocols that maximize the health and wellbeing of the animals under their care. In addition, they possess high standards of land and manure management and have been good stewards of the land and good neighbors to those around them. I am writing in support of their proposed West River Dairy expansion in Stevens County.

American agriculture sector, and the people it feeds, depend on a strong and stable dairy industry. Operations like Riverview are key to this vital process as they provide milk and meat to countless consumers. They also create consistent economic growth that supports local jobs and drives investment and reinvestment in the communities in which their operations are located.

Their proposed expansion represents a meaningful economic benefit to Stevens County. The expansion will generate demand for local vendors, will support construction and long-term employment, which will contribute to the vitality of this rural community that relies on agriculture.

In closing, from direct experience, Riverview is a professional and reliable partner that contributes positively to the communities where their dairy operations are located. Their presence strengthens local economies and supports a broad network of agricultural and service-related businesses. Projects like this are essential to maintaining a competitive and sustainable rural economy in Minnesota. Continued investment in agriculture ensures local businesses will continue to provide jobs, services, and economic stability within a region.

No Environmental Impact Statement is needed as the state environmental review process is rigorous and very sufficient. I respectfully encourage your support and approval of this important expansion project.

Sincerely,

Brian E. Miller, DVM

Sharon Fortunak **Letter 943**

The proposed West River Dairy Expansion should not be approved. In addition to the harmful effects to the environment, it is also animal abuse!! Cows need space for exercise and herd socialization. No one needs a farm that large!! Case closed!!

Laurence Margolis **Letter 944**

Minnesota's largest dairy producer, Riverview LLP, has applied to build the first livestock facility in Minnesota. If built, the facility will hold 18,855 dairy cattle, bringing the total animal units to 26,397 in one place. This proposed expansion would be nearly double the size of the next largest livestock operation in our state in terms of animal units. This expanded Riverview facility would be more than 60 times the size of the average Minnesota dairy, which had fewer than 280 cows in 2025. This makes it a fundamentally new and particularly powerful threat to Minnesota farmers and rural communities.

Riverview, based out of Morris, Minn., is one of the largest milk producers in the country. The firm now owns 16 permitted dairy CAFOs in Minnesota alone, and these facilities house a total of more than 135,000 cows, according to the Star Tribune. That accounts for nearly a third of the state's entire dairy

herd. Riverview also has a major presence in North Dakota, South Dakota, Nebraska, New Mexico, and Arizona.

The Minnesota Pollution Control Agency (MPCA), which is the agency that issues Minnesota's feedlot permits, must recognize the fundamentally new nature of this threat and give this permit greater scrutiny than it ever has to previous proposals. This proposal by Riverview must be required to undergo a full environmental impact statement (EIS). We should be supporting more family run dairy farms.

Mark Hockel **Letter 945**

Dear Mr. Peterson,

I respectfully submit this letter in support of Riverview LLP's proposed expansion of West River Dairy near Morris, Minnesota. I am an agronomist with decades of experience advising producers on crop production, nutrient management, and soil health. I have worked extensively with dairy and livestock operations on manure application planning, soil fertility management, and the agronomic value of organic nutrient sources. In my opinion, based on my review of the EAW and the draft feedlot permit, no EIS is needed.

In my professional experience, properly managed manure application is one of the most effective tools available for building long-term soil health while simultaneously providing crop nutrients that would otherwise need to be supplied by commercial fertilizers. The proposed expansion includes a comprehensive Nutrient Management Plan covering over 16,000 acres of currently tilled cropland identified for manure application. This plan reflects appropriate and careful planning.

The agronomic benefits of manure application are well-documented. Manure supplies nitrogen, phosphorus, and potassium—the three primary macronutrients essential for crop growth—along with secondary nutrients and micronutrients often absent from commercial fertilizer blends. Equally important, manure adds organic matter to the soil, which improves soil structure, water-holding capacity, infiltration rates, and aggregate stability over time. These improvements translate directly into more productive soils that are also more resilient to drought and heavy rainfall events.

From an agronomic and economic standpoint, the availability of manure as a locally produced organic fertilizer represents a significant value to area crop producers. In the current fertilizer market environment, the nutrient value of manure can offset substantial commercial fertilizer costs for participating landowners, while also delivering soil health benefits that commercial fertilizers alone cannot replicate.

Concerns about nutrient runoff from manure application are understandable, but the scientific evidence—including research published by the MPCA itself—demonstrates that when manure is properly incorporated into the soil, it actually reduces the risk of runoff and soil erosion compared to untreated fields.

The MPCA's 2018 literature review, "Runoff Reductions with Incorporated Manure" (wq-f1-08), synthesized the results of multiple peer-reviewed studies conducted across the Midwest, including research conducted in Morris, Minnesota—the same community where West River Dairy is located.

The findings are clear and consistent:

Runoff volume reductions: Fields receiving annual applications of incorporated manure showed runoff reductions compared to fields that did not receive manure.

Soil loss reductions: Fields receiving annual incorporated manure applications showed soil loss reductions compared to fields that did not receive manure. A single application of manure in Morris, Minnesota reduced annual soil loss by 67% in the following year.

Phosphorus management: The research found that injection of liquid manure—the primary method proposed for West River Dairy's liquid manure—results in more-effective phosphorus management when compared to surface-applied manure.

The MPCA's own conclusion from this body of research is significant: all studies reviewed found that, compared to tilled plots that did not receive manure, the incorporation of manure into soil can significantly reduce runoff volume and soil loss and does not increase runoff phosphorus levels on an annual basis. The review further emphasized the importance of incorporating manure through minimum-tillage methods such as knifing or injection—which is precisely how West River Dairy proposes to manage its manure, using knife injection for liquid manure and incorporation within 24 hours for solid manure.

West River Dairy's Nutrient Management Plan reflects the best practices identified in the MPCA's research. Application rates are calculated to match crop nitrogen needs, phosphorus management restrictions are in place to prevent soil phosphorus buildup, and the plan includes best management practices for fall application timing.

From an agronomic perspective, the West River Dairy expansion's manure management plan, supported by the MPCA's own published research, demonstrates that properly incorporated manure is not an environmental liability but an environmental and agronomic asset—one that builds soil health, reduces runoff, and recycles nutrients that would otherwise require energy-intensive commercial fertilizer production. The expansion also represents exactly the kind of investment that rural Minnesota needs—one that supports processing infrastructure, creates jobs, strengthens the local agricultural economy, and provides a market for locally grown crops.

Thank you for the opportunity to provide comment.

Reference:

Minnesota Pollution Control Agency. "Runoff Reductions with Incorporated Manure." May 2018. Publication wq-f1-08. Available at: https://www.pca.state.mn.us/sites/default/files/wq-f1-08.pdf

Steve Albrecht **Letter 946**

I fully support the expansion of West River Dairy. As an employee of nearly 19 years, I can assure you that integrity is one of our core values. Without clean water and healthy soils, our dairies cannot thrive. We do everything we can to maintain this. There are several dairies across the country that are much larger than this proposed one and they have proven that it is very possible and highly likely to operate in a responsible manner. Furthermore, the positive economic impact this will have on a small rural community is very important to me, as I have young children about to enter the workforce and I hope that they can find employment close to home. Thank you for taking the time to review this comment.

Karen Neenan **Letter 947**

I am writing to say that the expansion of Riverview Dairy MUST have an in depth look. An Environmental Impact Statement must be required.

The questions of how to deal with the manure from such an operation cannot be overstated. The water usage is enormous . What will happen to groundwater supplies? The groundwater has not even been mapped in this area.

Minnesotans have been given rich farmland and an abundance of clean water. It is our task to be good stewards of these amazing resources.

Can it be possible to be a good steward and have dairy cows on this scale?

I believe not. I grew up in a dairy farm 60 miles from Morris. I am aware of the constant question "where will all this manure go."? With the incredible scale of this dairy who would believe this manure disposal and water usage will not harm those living nearby and beyond.

Groundwater supplies can be depleted quickly and recover very very slowly.

Smaller farmers are struggling to make a living, therefore smaller communities are struggling to be viable. Riverview can certainly not help either of these.

We need an Environmental Impact Assessment!

Sincerely,

Karen Neenan

Kedron Nohl **Letter 948**

I live in Stevens County and have had the opportunity to observe multiple Riverview sites. From both an operational and environmental standpoint, I have consistently seen a high level of care, cleanliness, and attention to detail in how their facilities are managed and how their cattle are treated.

Riverview partners with local farmers to grow silage, alfalfa, and other crops used to feed their animals, creating valuable opportunities for local agriculture. Their manure management practices also support a sustainable cycle by returning nutrients to the land, which I have seen benefit crop production. Manure application is highly regulated, and Riverview is held to a high standard in how it is stored, handled, and applied. From what I have observed, they take these responsibilities seriously and consistently meet those expectations.

In my experience, Riverview operates in compliance with regulations and is mindful of its impact on neighbors, roads, and the surrounding community. Their sites are well-maintained and reflect a strong commitment to environmental stewardship.

The proposed West River expansion would bring additional jobs and support to local families, schools, and the broader community. Riverview has proven to be a strong partner and a good neighbor, and I believe this project will continue with that positive impact.

For these reasons, I fully and respectfully support the approval of the West River Dairy Expansion and believe the Environmental Assessment Worksheet process has been thorough and sufficient.

Thank you,

Kedron Nohl

Daniel Belgum **Letter 949**

To: MN Pollution Control Agency Officials,

I believe that Riverview Diary is already too big. The addition of some 11,000 head of dairy cows to an existing facility with 7,855 dairy cows at the Riverview West Dairy would create a significant impact not only on the water supply, and water system (Pomme de Terre River and aquifer) but also, the creatures of the area, and the total ecosystem. Where do you put all that manure? How much additional water will be needed? How many small dairy farms will this replace? In addition, this expansion, if allowed, would continue to have a deleterious effect on Minnesota's smaller dairy farmers, the small towns they support economically and socially, and as noted, the ecology of the county. It would also become the largest dairy in Minnesota in one location. I don't think any of that is good.

I encourage the MPCA to conduct an extensive, exhaustive environmental analysis on what the projected impact of this proposed dairy expansion would mean for Stevens County; and the state's small dairy farmers. This proposed dairy expansion is a massive ethical issue with extensive and potentially dangerous ramifications. It also will have, one way or another, a precedent-setting impact. It must be treated as such. The citizens of Minnesota expect the MPCA to do a thorough job of environmental reviewal.

John Pierce **Letter 950**

This Dairy represents a pollution (health) risk at a time of compounding environmental issues to water quality, air quality, and emissions reductions in the state of Minnesota. It does not make sense to expand confined dairy at this location as proposed in the documents.

Joan Meierotto **Letter 951**

It is unconscionable to even contemplate having that many animals confined within this small area.

Daryl Maulfair **Letter 952**

My family and I have lived in Morris for 9.5 years. We moved from Pennsylvania to Morris for the opportunity for me to work at Riverview as an on-staff nutritionist for their cattle. We have owned a home in Morris for that entire 9.5 years, we are parishioners of Assumption Catholic Church and our children attend St. Mary's Catholic School. We have become active members of the Morris Community in many ways. This would have not been possible without the opportunities afforded by Riverview's previous growth and this expansion will provide many more opportunities for people in this community and in the agriculture industry. Please see my attached comments on why the EAW shows that an additional EIS is not needed.

Public Comment in Support of the West River Dairy Expansion

EAW Comment Period: February 10 – May 7, 2026

Submitted to: Charles Peterson, MPCA Resource Management and Assistance Division

I am writing in support of the proposed West River Dairy Expansion in Synnes Township, Stevens County, and to respectfully urge the MPCA Commissioner to issue a negative declaration on the need for an Environmental Impact Statement. Having reviewed the Environmental Assessment Worksheet (EAW), the Notice of Availability, and the supporting attachments, it is clear that the project has been thoughtfully designed, that its potential environmental effects have been carefully studied, and that those effects are localized, controllable, and well within the limits of existing state and federal regulatory programs. The EAW does precisely what the State of Minnesota intends it to do: it lays out the basic facts of the project and demonstrates that an EIS is not warranted.

Why the project should be allowed to proceed

Riverview, LLP proposes to expand the existing 7,855-cow West River Dairy by adding an 11,000-cow facility on adjoining cropland that is already in row-crop production. The site is in the General Agricultural District of Stevens County, with the nearest incorporated city more than five miles away, and it is fully consistent with the Stevens County Comprehensive Plan 2017, which directs feedlots of this size into precisely these kinds of agricultural areas. The project complements, rather than conflicts with, the surrounding land use: local growers will supply corn silage, alfalfa, and other feedstuffs, and the dairy will return a local, organic fertilizer to the same fields that currently rely on synthetic inputs.

The benefits are tangible. The project replaces roughly 1,545 tons per year of anhydrous ammonia with manure-based fertilizer, avoiding an estimated 9,038 tons of CO2e per year associated with synthetic fertilizer manufacture, transport, and storage. Approximately 2,200 acres of row crops will be converted to alfalfa to feed the herd, sequestering an additional 2,662 tons of CO2e per year and reducing tillage on those acres. The expansion creates skilled local employment, on-site housing for staff, sustained demand for area crops, and continued investment in the rural Stevens County economy. Riverview has operated the existing West River Dairy on this site since it received a negative declaration on the need for an EIS in 2003, and has compiled more than two decades of permit compliance, including the addition of an anaerobic digester (2008), dry manure solids storage (2010), and expanded liquid manure storage (2014). That track record matters.

Why this EAW shows that an EIS is not needed

Under Minnesota Rules, an EIS is required only when a project has the potential for significant environmental effects that cannot be adequately anticipated, controlled, or mitigated through ongoing regulatory authority. The EAW demonstrates that, on every resource category it examines, those tests are met.

Air quality and odor. Barr Engineering performed AERMOD dispersion modeling under an MPCA-approved protocol using five years of weather data. With conservative background concentrations added, modeled hydrogen sulfide concentrations at the property line (29.44 ppb) remain below the Minnesota Ambient Air Quality Standard of 30 ppb, ammonia concentrations at neighboring residences (15.11 µg/m³) are well below the 80 µg/m³ chronic inhalation Health Risk Value, and odor at the nearest non-feedlot residence (74 OU) is below the 83-OU faint-odor threshold. Impermeable synthetic covers on the liquid manure storage areas, knife injection of land-applied manure, and on-site good-housekeeping practices all reduce emissions further. (See EAW Item 17 and Attachment 13.)

Water resources. The project actually improves the water situation on this parcel. The site today is pattern-tiled cropland with no retention or treatment. After construction, three permanent stormwater basins, sized more than 20% larger than required for a 25-year, 24-hour storm, will capture runoff before any controlled release. The Engineer's Run-Off Hydrology Report (Attachment 24) shows annual runoff volume dropping from roughly 117 million gallons to 106 million gallons and modeled erosion falling from 0.41 to 0.05 tons per acre per year. There are no wetlands or surface waters on the project site, and the LMSAs use 60-inch compacted clay liners

(well above the required minimum), perimeter drain tile for monitoring, and 14 months of storage capacity rather than the required nine. Groundwater appropriation is governed by DNR Permit #2008-0230, which conditions pumping rates on real-time Pomme de Terre River flow and includes a complete cessation requirement when river flow drops below 15 cfs. (See EAW Items 11, 12, and Attachments 22–26.)

Manure management. Local producers have offered more than 16,500 acres for manure application, while the project and existing facility together require only about 13,200 acres — a buffer of more than 3,000 acres that provides operational flexibility, eliminates pressure to apply on unsuitable fields, and effectively rules out winter application. Manure is knife-injected at agronomic rates per an MPCA-approved Manure Management Plan, sampled annually, and tracked through the MPCA's Nutrient Management Tool. Setbacks meet or exceed state, Stevens County, and Swift County requirements. (See EAW Item 12.B.5 and Attachment 23.)

Wildlife, rare features, and cultural resources. DNR Natural Heritage and U.S. Fish & Wildlife Service IPaC reviews identified no federally or state-listed endangered species at the project site. Where threatened or special-concern species were flagged near manure application areas, the Proposer either removed those parcels or confirmed that the row-cropped fields do not provide suitable habitat. The State Historic Preservation Office, the Office of the State Archaeologist, and a Phase I archaeological assessment by Agassiz Archaeology cleared the project site, the waterline route, and the manure application sites. (See EAW Items 14 and 15, and Attachments 6–7.)

Noise, traffic, and cumulative effects. Modeled noise at the nearest residence is effectively at background. The project would add roughly 45 vehicles per day to County Road 8, an 8.7% increase well below any threshold that would trigger a traffic study. The Proposer also delineated an Environmentally Relevant Area encompassing the project, all manure application acres, and a one-mile buffer around the off-site well, ensuring that no other reasonably foreseeable project overlaps environmentally with this one. (See EAW Items 19–21.)

Regulatory authority is sufficient to anticipate and control the effects

The EAW catalogs an unusually thorough package of overlapping permits and approvals: an MPCA Individual NPDES Feedlot Permit, a Construction Stormwater Permit, two DNR Water Appropriation amendments, a DNR Dam Safety permit, a Utility Crossing License, a Stevens County Conditional Use Permit, and SSTS permits. Each carries enforceable conditions, monitoring obligations, and inspection regimes. This is exactly the framework Minnesota's environmental review program contemplates when it asks whether environmental effects can be adequately addressed through ongoing public regulatory authority. They can be, and they will be.

Conclusion

The West River Dairy Expansion EAW is a complete, well-documented, and conservative environmental review. It identifies the project's potential effects, quantifies them against state standards, and shows that mitigation, project design, and existing permit programs reduce those effects to levels that are not significant. An EIS would not produce materially better information, would delay a project with clear local benefits, and is not justified on this record. I respectfully urge the MPCA to issue a negative declaration on the need for an EIS and to allow the project to proceed under its proposed permit conditions.

Respectfully submitted,

Daryl Maulfair

Jon Nohl — Letter 953

To Whom It May Concern,
I am writing this comment in favor of the West River Dairy Expansion project. As a farmer near multiple Riverview dairy operation's I can say that they are good neighbors. Their dairy's have given us options

for marketing crops and purchasing manure (to replace commercial fertilizer) that have brought additional competitiveness to our family farming operation. They are good stewards of the land and natural resources and are great people to work with. I would encourage the respective governmental agency's to approve the expansion project as I believe current environmental review concerning the project is adequate and the project should be allowed to move forward.
Sincerely,
Jon Nohl
Farmer near Hancock, Minnesota

Kendall Wendling **Letter 954**

We have been working with Riverview for a few years now. They are nice to work with and take good care of those around them.

Lance Lindeman **Letter 955**

My family and I need to have a comprehensive environmental review of this project. As a landowner with a private well in west central Mn, we do not believe there is enough evidence that our groundwater will not be negatively affected by this operation and others like it.
Also the amount of water to be used in the ongoing operation is also detrimental to other private wells with West Dairy's single well drawing down groundwater levels in the area.

Emilie Evink **Letter 956**

The EAW is comprehensive and complete. No EIS is needed.

Christian Cabrera **Letter 957**

I've been living in Morris for 13 years and I support the West River expansion no EIS required.

Luis López **Letter 958**

I support west river expansion. Not EIS required

Jose Castro **Letter 959**

I support the west river expansion, no IES required

Sergio Vazquez **Letter 960**

I support the project of Westriver expansion No EIS is need

Alejandra Vazquez **Letter 961**

I support the proposed expansion of Riverview. This project would bring economic benefits to the community, including jobs and local growth. I believe Riverview can operate responsibly while meeting environmental standards, and I trust that proper regulations will ensure any impacts are managed safely. I encourage approval of this permit so the community can benefit from this opportunity. I don't think EIS is really necessary

Mario Cervantes **Letter 962**

I support the West River expansion, no EIS required!

Ernesto Hernandez montellano **Letter 963**

I support the West Riverview expansion. No EIS required

Juan pablo Brom **Letter 964**

I support the West Riverview expansion. No EIS required

Lizeth Carmona **Letter 965**

I support the project and EIS is not needed.

Diego Gutiérrez **Letter 966**

I support West River/Riverview expansion. No EIS required.

Julio Villagomez **Letter 967**

We support the West River/Riverview expansion. No EIS needed.

Pedro Garcia **Letter 968**

I support West River/ Riverview Expansion. No EIS required

Carlos Daniel Rosiles Gallegos **Letter 969**

I support the west river river view expansion not is requeriet

Jenessa Solvie **Letter 970**

I support the West River Dairy expansion. No EIS required.

Jose Gutierrez **Letter 971**

I support the west river riverview expansión. No EIS required.

Helstrom G Sanchez **Letter 972**

I support the West Riverview expansion, it will create more job opportunities, direct and indirect, and will be beneficial for the region in the long run. No EIS is necessary, the company has show good management of the natural resources.

Yahveh Carrillo **Letter 973**

I support the West River Dairy expansion. No EIS required

Juan Carlos Garnica Montes **Letter 974**

Estamos a favor de west river

William Ojeda **Letter 975**

I support the west River/Riverview expansion. No EIS required.

Librado Ortiz **Letter 976**

"I support the West River/Riverview expansion. No EIS required."

Omar Ali Salinas **Letter 977**

I support the West River/Riverview expansion, No EIS required

Leonel Chavez Salas **Letter 978**

I support the West River expansion. No EIS required.

Tatiana Gutierrez **Letter 979**

I support the West River/Riverview expansion. No EIS required

Carlos Ivan Romero Ramos **Letter 980**

I agree with the expansion; I think it's a great idea and an opportunity for everyone.

Moises Moreno **Letter 981**

I support the West River/Riverview expansion. No EIS required

Antonio Cruz Magdalena **Letter 982**

I support the west river expansion.

Rosa Arenas Benitez **Letter 983**

I support the West Riverview expansion. No EIS required.

Fabian Cruz **Letter 984**

I support west river expansion

Leonel Orozco **Letter 985**

I support west river expansion

Leonel Sanchez Barbosa **Letter 986**

I support the West Riverview expansion. No EIS required.

Orsai Gonzalez Vazquez **Letter 987**

I support west river expansion

Nicolas Vega **Letter 988**

I support the West river/riverview expansion.

Jorge Hernandez Navarrete **Letter 989**

I support the west riverview expansion, no EIS requered.

Ivan Regalado **Letter 990**

I support the West River/Riverview expansion. No EIS required.

Victor Manuel Suarez Zepeda **Letter 991**

I support the West Riverview expansion. No EIS required.

Victor Maldonado **Letter 992**

I support the west riverview expansion. No EIS Required

Juan Avilés **Letter 993**

I support the west riverview expansion. No EIS required.

Mario Mancilla Hetnandez **Letter 994**

I support west river dairy expansion

Salomon Arrieta **Letter 995**

I support the West River/Riverview expansion

Erik Chavez **Letter 996**

I suporte west river/riverview expansión. No eis requiered.

Isaias Martinez Parada **Letter 997**

I support the west river/Riverview expansion

Elias Hernandez **Letter 998**

I support the West River expansion, no EIS required.

Braulio Medina **Letter 999**

I support a west river Dairy

Antonio Capi **Letter 1000**

I believe this will provide new job oportunities for local workers and increase the need of local vendors as well.

Miguel Sanchez **Letter 1001**

I support the West River/Riverview expansion. No EIS required

Jesus Mireles **Letter 1002**

I support the West River/Riverview expansion. No EIS required

Jesus O Gomez **Letter 1003**

I support the proposed West Riverview expansion and believe that an Environmental Impact Statement is unnecessary, given the limited environmental impact anticipated.

Lindsey Lindor **Letter 1004**

I fully support the West River Diary Expansion. No EIS should be needed.

David Diaz **Letter 1005**

I I agree with the expansion of West River Dairy.

Miguel Arreola **Letter 1006**

I support the West River expansion

Alejandra Anguiano **Letter 1007**

I am in favor of the expansion project. EIS is not necessary.

Cristian Castillo **Letter 1008**

I sopport the West River Dairy Expansion. No EIS required

Héctor Rosales **Letter 1009**

I support West River/Riverview expansión. No EIS required

Teague Picht **Letter 1010**

I support the West River Dairy Expansion. No EIS needed.

Blanca Garcia **Letter 1011**

I support the West Riverview Expansion. No EIS required

Eduardo Nochebuena Zaragoza **Letter 1012**

I support west river dairy expansion. No elS required

Antonio Ramos **Letter 1013**

I support West River/Riverview expansión. No EIS required

Hugo Sanchez Arenas **Letter 1014**

I support the west river dairy expansion. No Environmental Assessment needed.

Berenice Huescas **Letter 1015**

I support the West Riverview expansion. No EIS required

Kurtis Wulf **Letter 1016**

My name is Kurt Wulf and I have lived in Stevens County my entire life. As a member of the Morris Area School I have seen the generosity of Riverview first hand. They donate to the school on a regular basis as well as many other community programs such as 4H, FFA and the County fair. When evaluating a project like this dairy, is there any consideration to what Riverview has willingly given back to our community? I

support this dairy project getting built and see no reason to require more study or permitting. Thank you for your work on this permit.

Jesus Galindo Hernandez **Letter 1017**

I support a west river Dairy

Miguel Urrutia Calvo **Letter 1018**

As a member of the Morris Public Schools Board of Education, My comment is to share my strong support for the proposed West River Dairy expansion. In my role on the school board, I focus on what helps our students and community grow and succeed over time. I would also like to note that I am an employee of Riverview LLP.
From what I see in our community, projects like this make a real difference. When there are new opportunities and jobs, more families choose to move to or stay in the area. That leads to higher student enrollment, which is very important for our schools. Strong enrollment helps us keep and improve programs, support our teachers, and continue offering activities and opportunities that benefit all students.
There is also a clear connection between a growing local economy and stronger support for schools. As communities grow, we tend to see more involvement from families and local businesses; whether through donations, partnerships, or simply being more engaged. That kind of support creates a better environment for our students to learn and succeed.
Most importantly, this kind of growth benefits students directly. It helps create a more stable and vibrant community, gives students access to more opportunities, and strengthens the connection between schools and the real world. These are the kinds of factors that help prepare students for their future and encourage them to stay and invest back into the community. Riverview has shown that it values being part of the communities where it operates, and I believe this project is another step in that direction.
For these reasons, I respectfully encourage the MPCA to consider the positive impact this project can have on our students and community and to move forward with the permitting process in a timely manner. Thank you for your time and consideration

Karen Campos **Letter 1019**

I support expansion of west river

Ramos Jaimez **Letter 1020**

I support the West Riverview expansion. No EIS REQUIRED

Mitch Koehl **Letter 1021**

I support the West River Dairy expansion. I feel the MPCA has done sufficient work with the EAW and no EIS is needed. Riverview has a proven track record of proper manure management. I have lived within less than 1 mile of one of their existing dairies for over 17 years and there has never been any issues causing environmental concerns. Their manure is a preferred source of fertilizer for our crops. They have provided a huge benefit to our region.

Carlos Portillo **Letter 1022**

I support west river dairy expansión no ELS Requierd

José Borjas Gonzales **Letter 1023**

I support west river dairy expansion no els required

Valente Fuentes **Letter 1024**

I support west River expansión.

Miguel Cruz **Letter 1025**

I support west River/Riverview expansion. No EIS required

Kyle Fehr **Letter 1026**

I am in full support of the West River expansion. No EIS needed.

Dylan Reese **Letter 1027**

I am in full support of the West River expansion. No EIS needed.

Oscar Neri **Letter 1028**

I am in full support of the West River expansion. No EIS needed.

Oscar Celaya **Letter 1029**

I agree with with West River expansion, no EIS required

Lucio Santiago **Letter 1030**

I support the West Riverview expansion. No EIS required

Alton Ekren **Letter 1031**

I strongly support this project, an EIS is not needed.

Christofer Ruiz **Letter 1032**

I support the West Riverview expansion. No EIS required

Misael Carrasco **Letter 1033**

I support the West Riverview expansion. No EIS required

Victor Morales **Letter 1034**

I Suppot west river dairy

Carlos Alba Mora **Letter 1035**

I support the west River Dairy expansión. No EIS requiered.

Susana Medrano **Letter 1036**

I agree with West River expansión, no EIS needed

Daniel Camacho Ramírez **Letter 1037**

I support the west Riverview expansion

Fernando Chapa **Letter 1038**

I fully support the west River dairy expansion project *No EIS required

Miguel Rodriguez **Letter 1039**

I support the West Riverview expansion. No EIS required

Heribier Ramos **Letter 1040**

I support the West River dairy expansion and feedlot permit. No EIS irequired.

Hilary Reeves **Letter 1041**

The scale of this expansion calls for an Environmental Impact Statement. The increasing severity of weather events & the already high levels of nitrogen in water already are worrying enough, for families and the health of our communities. An EIS will allow the proposal's negative impacts on water quality and quantity, local roads, and existing independent family dairy farms to be fully analyzed before the project is allowed to seek a permit. Thank you.

Benjamin Juarez Cervantes **Letter 1042**

I support the west river dairy expansion Without EIS

Amber Ramey **Letter 1043**

An expansion of this size needs considerable investigation on the impact to the people of Morris before it is allowed. I am very concerned about the amount of water it will use and pollution it will create. I am also very disappointed in the way Riverview has tired to throw its weight around and silence people living in Morris. They had their employees pack the meeting tonight over an hour before the start time. They want to make sure no one can express concern. It really makes me wonder what else they are hiding or pushing through. This is an over reach of power and deserves to be investigated fully before proceeding.

Robert Valnes **Letter 1044**

No EIS needed for this project.

Dustin Hollermann **Letter 1045**

The proposed West River Dairy Expansion will be a net positive in regards to environmental effects. Air quality, water resources, manure management, and rare species concerns have all been thoroughly evaluated and are adequately addressed through the EAW and ongoing regulatory oversight. An EIS is not necessary and would not result in the discovery of any additional concerns.

Jared Wohlers **Letter 1046**

Minnesota Pollution Control Agency
Attn: Charles Peterson

I am a local resident to the Morris area. I attended the public meeting hosted by the MPCA yesterday evening. I found the process to be informative and thank the MPCA for providing the opportunity to attend. I have reviewed the EAW material and Feedlot application. I found the material to be factually sound and in alignment with the conversations and clarification provided by the MPCA yesterday evening. Based on the facts, understanding the process and the public meeting hosted by the MPCA I am supportive of this project. An EIS is not needed for the proposed West River Dairy Expansion.
Thanks,
Jared Wohlers

Luis C Hernandez Valenzuela **Letter 1047**

My name is Luis C Hernandez and complete support the west river project because it's a big opportunity for the area to going forward on the consolidation of development. Minnesota it's a base on agriculture and this project have all the right to be done on the best way to protect the environment and of course the community

Alberto Ochoa **Letter 1048**

Yes I support west river expansion

Helstrom Sanchez **Letter 1049**

I support the expansion of West River Dairy. I believe that Riverview has gone through potential environmental impacts thoroughly, they have enough experience and expertise, and the expansion will provide a positive benefit for the community. Thus, I believe no EIS is required.

Gordon Dalseide **Letter 1050**

First of all, this is not an expansion of the existing West River Dairy. It is a complete stand-alone new construction that could be built anywhere with little or no additional cost. It appears that very little of the existing infrastructure will be used to support this proposed project. Official Public Notice published in the Stevens County Times January 6, 2026, is misleading indicating that the expansion will take place in the NW 1/4 of section 1 Synnes Township. Are manure management acres secured by written contracts or are they simply "Handshake agreements"?
Water use is a major concern. According to Minnesota Well Index records that I have viewed River View currently has at least eight active wells and has drilled at least 5 additional test holes. Active wells range from 138' to 300' in depth. Test holes range from 302' to 418' deep. Static levels range from 90' to 119'. Pumping levels range from 101' to 200' at the time the wells were drilled. No information relating to recharge rate was found. Bed rock level is approximately 300'. Existing water wells surrounding WRD range from 75' to 340'. The 340' well just happens to be owned by a WRD employee. Looks like the same issue that people in Arizona are facing is happening or about to happen in Stevens County. My own well located 1 1/2 miles north of WRD has dropped in production from and estimated pumping capacity of 150 gallon/min to barely 3 gallon/min currently. Intensive water well testing needs to be done by independent testing company before any permit for WRD is approved.
Damage to County and Township roads during harvest are to the point that they are impassible with anything but a 4-wheel drive pick-up. Roadbeds have been displaced to the point that ditches no longer drain properly, culvert aprons have separated from nearly every culvert along my property and have had to be repaired at county expense.

Manure spills have occurred on several occasions as the result of failure to connect hoses or lack of proper monitoring. Several of these spills have been of a size requiring considerable time to clean up and occurred on public property (county road ditches).
Animal disease should be a major concern to be looked at. New World Screw worm currently less than 100 miles from the US- Mexican border is a devastating disease. Riverview transports animals between Minnesota and Wilcox AZ. almost daily. What is the Minnesota department of animal health emergency management protocol for handling such and outbreaks?
No one has discussed negative economic issues involved with the project. Farmers not participating will likely see lower bids for grain, higher prices for fertilizer and propane due to lower volumes.
Employees will be let go or have time reduced. People will have to leave the area to find full time employment.
There are many more important issues that need to be studied. The fact that the commissioner has not made an independent onsite visit and possibly even with close neighbors that are not part of WRD is a very concerning issue. Boots on the ground, ears open, smell the air, see the situation before you make a final decision. Once the damage is done it cost a lot more to fix. A full and complete study is the only option!

Lucas Anderson **Letter 1051**

I support the West River Dairy Expansion project. I feel an EIS is not necessary.

Ford Thunderbird **Letter 1052**

EIS must be done. Be only fair to everyone. Why are the riverview supporters so afraid of seeing an EIS done?
It's just 1-2 big wigs who wanted these dairies in each area. Vast majority of everyone else living in them areas don't want them to start with.
Riverview is like a mining company. They come into an area and just mine all the resources and once the resources are gone so is riverview. They are off to a new area to mine.
What many people don't know if this goes through this expansion it's just a green light to expand other sites they already own. They want to expand East Dublin dairy south of Murdock to 32,000 cows.
Looks like there is an expansion in the future at the Swenoda site in swift county south of benson with riverview recently purchasing additional 80 acres on the east side of that site close $1,400,000.00 million dollars and this late winter.
Speaking of the swenoda site. Many people well most everyone doesn't know about the huge manure spill there in the fall of 2024 that covered 65-70 acres and went into 2 separate drainage ditches a quarter apart and that manure spill was about 2.5 miles away from the Chippewa river and them drainage ditches feed directly into the Chippewa river. They cleaned it up before they reported it to the MPCA and claim it was mainly 50,000-60,000 gallons of mainly water. Very alarming and very concerning. Very disturbing especially for anyone that lives in a 5-6 mile radius of that manure spill. Probably have high nitrate levels in their drinking water from their wells.
When they manure pumping crews are mainly made up of Hispanics and South Africans who's primary language isn't English it's hard to follow rules and directions. Heaven forbid these big wigs from riverview or who are strongly affiliated with riverview get any manure on their shoes or smell like manure.
What a good show riverview put on the night of April 28th. They use a smaller venue in morris when there are 2-3 other larger venues to use in Morris. They jam it pack with all their supporters and Hispanics who work for them and who are speaking Spanish across the room to each other and one is holding up a sign in Spanish to comment on this site for approval for this expansion. Looks like a 100 plus

comments in a couple hours time last night from riverview employees. All them comments should be disregarded.
Riverview does an extremely good job getting one of their supporters and employees on every local government board possible. From township, planning and zoning,rda and school boards and and everything in between. They make sure riverview is taken care of and rest of us non supporting riverview people they make sure our voice isn't heard at all or our comments and concerns are brushed aside.
They claim they do so much for the communities they are by but yet I don't see any them riverview supporters or Riverview employees on the volunteer fire department or on the EMT. Oh wait they aren't getting paid for that and no need to protect riverview's interest on them rural volunteer positions. It will be a good day in rural Minnesota when riverview and their businesse partners are no longer in business and are broke because that is what they are trying to do everyone else in rural Minnesota now who doesn't want anything to do with them.

David Hauge **Letter 1053**

The list of infractions on the land stewardship site for this dairy shud be more than enuf to deny a permit. Groundwater and air contamination will invariably occur with such a large operation. U wud set a precedent for large dairies in se mn where the ground structure cannot support manure incorporation of such magnitude

Nicole Wagner **Letter 1054**

I think it is worth mentioning that 200+ Riverview employees were at the door two hours early to prevent citizens from being able to enter as the building was at capacity with Riverview staff. Some were able to get in but I have spoken to many people that were not. They should rectify this farce of a public meeting by using the high school which allows for 5 times the attendance.

Laura Lee **Letter 1055**

I am writing to request that the MPCA require a full Environmental Impact Statement(EIS) for the proposed West River Dairy expansion project. A farm of this size is unprecedented. We must protect Minnesota's natural resources and communities.

David Kortan **Letter 1056**

Expansion of this magnitude would be disastrous for the community in terms of the massive amount of water usage, electricity drain on the electrical grid, and massive manure that could effect ground water pollution. Also I would like to know who owns all of their dairy operations and all of the farmland it takes to feed the cows. China? Bottom line is it's not good for the smaller dairies or Morris

Ann Williams **Letter 1057**

As a citizen of Morris, I tried to attend the public meeting this past Tuesday and was denied entry because the space had reached capacity. I am strongly against allowing this expansion. I have read articles about the depleted water wells in other states which allowed dairy expansions. The water use is not sustainable. What happens to all the bull calves born? I have watched video of them being shot dead and dumped like garbage. My husband and I operated a family run dairy in Kandiyohi County in the early 80"s. Cows are not units, but living creatures. Riverview run by Apostolic Christians is run by greed and little regard for nature or other people. Please deny this expansion.

Greg Solberg **Letter 1058**

Hi, I can't even come close to imagining the State would allow this proposal to go through without having an environmental impact statement in place. At what point does health (planet, human, animal, etc) come before profits? At what point does the State mandate corporations own their actions? Meaning, they're on the hook for cleaning up the pollution they create that allows them to earn massive profits - not us taxpayers?

Regards,

Greg Solberg

Carrie Slater Duffy **Letter 1059**

Please do a complete Environmental Impact Statement for Riverview's proposed expansion of West River Dairy. A proposed project of this size (the biggest in Minnesota) demands it. Big Ag can and should be held accountable for impacts on Minnesota's water and climate, which directly effects the health and well-being of Minnesotans.

Rebecca Tryon **Letter 1060**

The West River Dairy Expansion should be required to complete an Environmental Impact Statement prior to being considered for approval. Such an expansion would increase greenhouse gas emission and increase water pollution while we are in the midst of a climate crisis. Such harms should be quantified to weigh against our state's stated emissions and environmental protection goals prior to considering the project for approval. Further, as our state is, in collaboration with neighboring states and nations, the steward of a significant portion of the fresh water available to the world to help weather this expanding environmental crisis, we should not move hastily to approve a massive expansion of animal agriculture without fully considering the ramifications to fresh water in our state.

Tom Rosen, Rosen's Diversified, Inc. **Letter 1061**

c/o Charles Peterson

Rosen's Diversified, Inc. is a Minnesota-based, family-owned agribusiness with operations spanning food processing, livestock procurement, and related agricultural services across Minnesota and the Upper Midwest. We have worked closely with Riverview, LLP and its affiliated operations for many years and submit these comments based on our direct experience with them and Minnesota's broader agricultural economy.

The proposed West River Dairy expansion represents the type of well-planned investment that strengthens Minnesota agriculture and rural communities. Dairy farms like West River Dairy play a critical role in sustaining a broad agricultural ecosystem that includes farmers and ranchers, feed suppliers, and food processors. Expansions of this nature create jobs, support local businesses, and provide dependable demand for crops and livestock grown by Minnesota producers. These investments help anchor economic activity in rural areas and reinforce Minnesota's position as a national leader in agricultural production.

Based on our first-hand experience, West River Dairy is a professionally managed and highly reputable operator. The proposed expansion reflects continued long-term planning and operational discipline that is necessary for agricultural businesses to remain competitive in a challenging economic environment.

Projects like this help maintain a resilient, integrated agricultural supply chain that benefits producers, processors, and communities alike.

We understand that the expansion has been developed within Minnesota's comprehensive environmental and regulatory framework. The project will operate under an Individual NPDES Feedlot Permit, which involves site-specific requirements and enhanced regulatory oversight. The Environmental Assessment Worksheet prepared for the project reflects a thorough review of potential impacts to water, air, land use, and nearby resources, consistent with Minnesota's established environmental review process.

In addition, project materials indicate that the facility incorporates design features intended to manage water responsibly, including capturing and reusing stormwater to reduce groundwater demand. This approach reflects a commitment to environmental stewardship and demonstrates that modern dairy operations can continue to grow while managing resources efficiently.

For these reasons, Rosen's Diversified supports the West River Dairy expansion. We believe the EAW provides a sufficient basis for decision-making and respectfully request that the MPCA conclude the environmental review process and proceed with permitting.

Sincerely,

Tom Rosen

Chair & Chief Executive Officer Rosen's Diversified, Inc.

Nancy Hinrichs **Letter 1062**

This kind of farming is bad for the environment. It is bad for small farms. It is bad for the livestock. It is bad enough this "farm" exists as is. It should not be allowed to increase in size. It should be shut down@

Jerry Nohl **Letter 1063**

I support the West River Dairy Expansion project. I feel an EIS is not needed.

Kayla Parkin **Letter 1064**

I strongly oppose the proposed Riverview Dairy Farm expansion.

This area of Minnesota is where I grew up and many members of my family still live here.

Watching our rural communities be increasingly taken over by large corporate operations with little regard for local residents is deeply disheartening. These decisions are not abstract—they directly affect the health, safety, and quality of life of the people who call this place home.

The scale of this expansion raises serious concerns about pollution, excessive water usage, and long-term damage to the surrounding land, waterways, and ecosystems. These impacts don't disappear once permits are approved, they remain with local communities for generations. Profit should never come at the expense of clean water, clean air, or a healthy environment.

Before any expansion moves forward, there must be comprehensive, independent environmental testing and transparent reporting so the public can clearly see the factual impacts for themselves. Communities deserve real data, not assumptions or reassurances, when the stakes are this high. I urge decision-makers to slow this process down, listen to the people who live here, and reconsider whether this expansion truly aligns with Minnesota's values of environmental stewardship and community

well-being. Please do the right thing...not just for corporate interests, but for the families, land, and future of this area.

Linus Meyer **Letter 1065**

It is not a good idea to concentrate all of these nutrients from mass storage in one location. Sooner or later a huge spillage will occur and pollute an entire watershed. The livestock and manure need to be spread out over numerous counties.

Robert Schlobohm **Letter 1066**

May I suggest that you look at other options for dealing with the waste. I have friends that live in upstate New York and run a dairy farm. They covert all of their waste to methane gas and literally produce all the power that they need to run the operation. That seems to me a better alternative than trying to spread all the waste on adjacent farmland. Maybe a combination of the two options would be better. If you would like the names of my friends in New York I would provide that with their permission.

MNDNR (Nathan Kestner) **Letter 1067**

MN DNR's March 17 comment letter had stated that the EAW did not consider impacts from the potential groundwater appropriation on the Pomme de Terre River. That comment was inaccurate as written - the EAW does describe potential interactions between groundwater appropriation and the Pomme de Terre River in Sections 12.B.3 and 12.B.4, including discussion of pumping restrictions intended to reduce impacts.

MN DNR's March 17 comment was intended to clarify that:

-Available aquifer test data (NRG, 2007) indicate that pumping from well 740629 is hydraulically connected to the Pomme de Terre River, and that a portion of pumped water is derived from induced infiltration or reduced baseflow to the river.

-As a result, groundwater appropriation at this location has the potential to impact river flow, particularly during lower flow conditions, depending on pumping rates and duration.

MN DNR is currently completing an updated evaluation of flow conditions in the Pomme de Terre River. This analysis will inform any permit conditions associated with application 2025-1502.

Consistent with Minnesota Statutes and prior DNR guidance (MN DNR, 2016), any issued permit would include conditions designed to prevent negative impacts to the river, particularly during low-flow periods.

Jill Holslin **Letter 1068**

I'm writing to urge MPCA to conduct a rigorous Environmental Impact Study on the proposed expansion of Riverview in Stevens County, Minnesota. I grew up in Chokio and Morris, and my children (now adults) grew up spending their summers on the family farm north of Alberta. The family is still farming there—the fifth generation to work that land. We love the beauty of the local lakes and sloughs, the natural areas that still remain, and the thrill of seeing pheasants and deer along the road. We do and will always consider Stevens County our home. The expansion of Riverview threatens the local watershed, the wildlife and integrity of this fragile ecosystem. It also threatens to push out local small farmers who are struggling enough as it is. Please protect the integrity of Minnesota's rural communities and study this project before it is too late.

Thank you, Jill Holslin

Sonja Trom Eayrs **Letter 1069**

It's imperative for the MPCA to hold a public meeting that will accommodate all attendees.

I understand that industry boys packed the public meeting on April 28, 2026, while local residents who are impacted by this large operation were turned away at the door and unable to voice their concerns. This is standard protocol for the industry, as the industry historically packs public meetings with industry folks. This is part of the corporate playbook as discussed in my book, Dodge County, Incorporated: Big Ag and the Undoing of Rural America. Https://www.sonjatromeayrs.com/

Nearly 25 years ago, a large dairy operation was proposed just a few miles north of our farm in Dodge County, Minnesota. The dairy operation would've been the largest dairy operation in the State of Minnesota at the time. The fight continued for several years. One evening, the meeting was moved to the old Claremont High School. The township residents showed up at the old high school and were surprised to see nearly 200 folding chairs occupied by corporate executives, including Land O' Lakes, Monsanto, Hormel, Cargill, and other companies. Corporate theatre at its best. There were insufficient chairs for the township residents. Although the township residents were blindsided that evening, they nonetheless remained vigilant and were eventually successful.

Today, rather than send corporate executives to meetings, the industry sends insiders. Several years ago, we went door-to-door in my home Township. We asked residents to sign a petition calling for a special meeting, so we could put local planning and zoning in place and stop the proliferation of factory farms, as our family farm is surrounded by 12 swine factory farms, housing an estimated 30,000 hogs in a 3-mile radius. While dozens of residents signed the petition and called for a special meeting, they were blindsided the night of the special meeting. As local residents showed up at the special meeting, they were surprised that the road grader and other equipment had been backed out of the building. The equipment area was converted to a meeting room, and at least 200 chairs were occupied by members of the hog industry, undoubtedly members of the Minnesota Pork Producers Association (MPPA). A corporate rally.

If the MPCA is going to conduct a public meeting and take public comments from all concerned citizens, the MPCA needs to hold a public meeting in a larger space that will accommodate residents and allow them an opportunity to voice their concerns. It is also essential that the MPCA require that those attending the public meeting sign in to the meeting and provide their contact information.

For more information, see Dodge County, Incorporated: Big Ag and the Undoing of Rural America. https://sonjatromeayrs.com/

Philip Strelow **Letter 1070**

Dear Mr. Peterson,

My name is Philip Strelow, and I am the employee and operator of Strelow Ranch Trucking. Our business works with agricultural operations in Nebraska, including Riverview, and I am writing in support of the proposed West River Dairy expansion in Stevens County.

A strong agricultural economy depends on reliable livestock operations. Companies like Riverview help sustain that strength by creating consistent demand for services, supporting local employment, and contributing to the overall economic health of rural communities.

The proposed expansion will bring clear economic benefits to the region. It will support local vendors and contractors, create both construction and long-term jobs, and reinforce the stability of communities that rely heavily on agriculture.

In our experience, Riverview has proven to be a dependable and professional partner. Their operations contribute positively to the areas where they are located and support a wide network of agricultural and service-related businesses.

Projects like this are vital to maintaining a competitive and sustainable rural economy in Minnesota. Continued investment in agriculture helps ensure that businesses like ours can continue to operate, grow, and provide essential services.

Considering the thorough and rigorous nature of the state's environmental review process, I do not believe an Environmental Impact Statement is necessary for this project. I respectfully encourage your support and approval of this expansion.

Sincerely,

Philip Strelow

John Fisher-Merritt **Letter 1071**

Dear MPCA,

I am a farmer in Wrenshall, MN. I am not a dairy farmer, but my friends who are dairy farmers are struggling to make ends meet. The West River dairy expansion will not only threaten soil and water quality in Stevens County, but will also put downward pressure on the price my neighbors receive for their milk.

John Fisher-Merritt

Ricardo Camargo **Letter 1072**

I support the west river expansion

Jennifer Maleitzke, RDO Equipment Co. **Letter 1073**

Dear Mr. Peterson,

I am writing on behalf of RDO Equipment Co., which supports construction and agricultural operations throughout Minnesota, including dairy producers such as Riverview, LLP. We appreciate the opportunity to comment on the Environmental Assessment Worksheet (EAW) prepared for the proposed West River Dairy expansion in Stevens County.

We have reviewed the EAW and note that it addresses the subject matters required under Minnesota's environmental review statutes and rules, including groundwater and surface water considerations, manure management, air quality, traffic, and other environmental topics within the scope of an EAW. The document also identifies regulatory mechanisms that would apply to the project through existing state and local permitting processes.

At this stage, we believe the information developed through the EAW provides a sufficient foundation for the project to move forward into the permitting phase, where the identified mitigation measures and operational requirements can be fully evaluated, refined, and enforced by the appropriate regulatory agencies. Proceeding through the established permitting process is consistent with state statute and allows for continued agency review, public input, and regulatory oversight.

For these reasons, we respectfully encourage the MPCA to follow the state's existing environmental review and permitting processes and allow the proposed project to proceed through those channels.

Thank you for your consideration.

Jennifer Maleitzke

Director of Communications and External Affairs

R.D. Offutt Company

Cathy Solvie **Letter 1074**

Hello, I think you need to have several more of these conversations with the affected community before an MASSIVE expansion and drain on our water happens. It can't always be about the money. You all have more than enough to get you and generations of your families taken care of. This is all unnecessary. Think about the environment and the people you reside around first please.

Nathan Hrnicek **Letter 1075**

I. Introduction and Basis for Comment

I am submitting these comments in strong support of the proposed West River Dairy Expansion in Stevens County, Minnesota. I offer this testimony as both a longstanding business partner of Riverview, LLP and as a dairy industry professional with extensive firsthand experience in nutrient management, advanced manure separation technology, and precision nutrient application systems across Minnesota and the broader Upper Midwest.

NutraDrip works directly with Riverview's operation as a trusted technology and agronomy partner. That working relationship has given me direct, sustained visibility into how this organization approaches environmental stewardship, nutrient management planning, and responsible growth. I do not submit these comments as a formality. I submit them because I have seen, firsthand, the operational discipline and environmental commitment that Riverview brings to everything they build — and I believe the proposed expansion to a combined 18,855 milking cows (26,397 AU) at West River Dairy represents exactly the kind of modern, accountable agricultural investment that Minnesota should be supporting.

II. The EAW Accurately Reflects a Well-Managed Operation

The Environmental Assessment Worksheet is an information-gathering tool — and the information it should reflect is this: Riverview, LLP has demonstrated, over years of operation, that large-scale dairy farming and responsible environmental stewardship are not in conflict. They are, in Riverview's case, inseparable.

The proposed expansion builds on an existing facility with established infrastructure, permitting history, and nutrient management systems already operating at scale. This is not a greenfield operation with untested management. Decision-makers reviewing this EAW should weigh heavily that the proposer has a proven track record managing one of Minnesota's most significant dairy operations — and has consistently done so in compliance with state environmental requirements.

III. Nutrient Management: Infrastructure and Technology That Match the Scale

The most consequential environmental consideration in any Animal Unit expansion is the management of increased manure volumes and the associated potential impacts on surface water, groundwater, and air quality. Based on my direct knowledge of Riverview's approach and systems, I am confident the

proposed expansion can be managed without significant adverse environmental impact — provided the nutrient management infrastructure in place is accurately represented and enforced through permitting.

I would highlight the following specific strengths:

Advanced Manure Separation Systems

Riverview utilizes manure separation technology that meaningfully reduces the volume of liquid effluent requiring lagoon storage and land application, while concentrating nutrients into manageable solid fractions. At the scale of 26,397 AU, this is not a minor operational detail — it is a foundational risk-mitigation tool. Separation substantially lowers the risk profile for nutrient runoff, lagoon overflow, and excess loading to application fields. It also enables far more precise nutrient application by separating the liquid and solid fractions so each can be managed according to actual crop and soil need.

Precision Nutrient Application

As a partner in subsurface drip fertigation and precision nutrient delivery systems, I can speak directly to the practical and environmental advantage of applying separated manure fractions through controlled, metered application systems. This approach dramatically reduces surface phosphorus and nitrogen loading, minimizes ammonia volatilization losses, and ensures that nutrients are placed where growing crops can utilize them efficiently — keeping them out of drainage tile outlets, ditches, and waterways. These are not theoretical benefits; they are measurable outcomes that distinguish operations like Riverview from legacy dairy operations that opponents of large dairy farms often reference.

Nutrient Management Planning (NMP) at Scale

Operations of this size in Minnesota operate under NPDES/SDS feedlot permits that require rigorous, maintained Nutrient Management Plans. Riverview's operational scale means their NMP is actively managed by professionals — nutrient management specialists, certified planners, and environmental consultants — not simply filed and forgotten. The land base required to support 26,397 AU under Minnesota's nutrient application standards is significant, and Riverview's history demonstrates they have assembled and managed that land base responsibly.

IV. Water Resource Protection

The EAW process rightly scrutinizes potential impacts to both surface water and groundwater resources. I offer the following observations based on industry expertise and operational familiarity:

Manure separation systems reduce hydraulic loading on lagoon infrastructure, lowering overflow risk during high-precipitation events — one of the most common pathways for nutrient impairment of surface water.

Precision subsurface application methods effectively eliminate the surface runoff pathways that would otherwise convey nitrogen and phosphorus to drainage ditches or surface water bodies. Stevens County's agricultural soils and land base, when managed under a properly maintained NMP calibrated to realistic crop uptake and existing soil phosphorus indices, are well-suited to receive the nutrient outputs of an operation at this scale.

The expansion of an existing, permitted facility — rather than establishment of a new operation in an unpermitted location — provides regulators with an established baseline for monitoring, inspection, and enforcement.

I would encourage decision-makers and the RGU to ensure that the EAW reflects the specific separation, storage, and application technologies in use, as these are material factors in assessing actual environmental risk — and they distinguish this project favorably from generic large-feedlot assessments.

V. Economic and Community Context

While the EAW is an environmental review document, the decision-makers who rely on it should understand the full context of what is being proposed. West River Dairy and the Riverview family of operations are not simply large agricultural businesses — they are anchors of the Stevens County rural economy and examples of how agricultural investment, when done responsibly, sustains the communities, supply chains, and skilled workforces that rural Minnesota depends on.

Operations like Riverview create and sustain jobs in veterinary services, equipment, trucking, feed, agronomy, and processing. They support local tax bases. And they demonstrate that Minnesota can remain competitive in dairy production without sacrificing environmental standards — a balance that matters enormously to the long-term viability of agricultural communities across the state.

VI. Conclusion and Recommendation

Based on my direct professional experience with Riverview, LLP's operations and my expertise in nutrient management and the dairy industry, I submit the following conclusions for the record:

The EAW adequately describes a project that can be permitted without significant adverse environmental impact, provided the nutrient management, manure handling, and land application systems described are accurately represented and enforced through the permitting process. A full Environmental Impact Statement (EIS) is not warranted. The proposed expansion builds on an established, permitted, professionally managed facility with documented environmental compliance. The incremental increase in AU, when managed through Riverview's existing infrastructure and nutrient management framework, does not present the level of environmental uncertainty that would require an EIS.

Approval of this expansion supports Minnesota's agricultural economy and demonstrates that responsible large-scale dairy farming is achievable. I encourage the relevant agencies to move this project forward expeditiously.

I appreciate the opportunity to provide comment and am available to discuss any aspect of this letter in greater detail.

Respectfully submitted,

Nathan Hrnicek

Director of Sales

NutraDrip

Reyna Estrada **Letter 1076**

How can there be a guarantee that the cows well being won't be jeopardized for profit? Also,the water amount proposed to be used is extremely high and shouldn't be allowed.

Tyler Bueng **Letter 1077**

I personally live 15 miles away from the Waukon Dairy that Riverview operates in Norman County. Myself and my family have all toured their facility. I also have professionally been out there to work on repairs through my employer. So I've had a large sample size of how Riverview operates during their daily operations! I can say confidently they have the cleanest and most efficient operating dairy around. Not only do they set the standard for an outstanding dairy operation, I'd honestly say they are the standard! I also would like to mention how well they support the local communities that surround their

operations. They make a positive impact from top to bottom within their organization. Riverview is helping keep creamery's in Minnesota full and operational, they create job opportunities, give local farmers another market to sell their commodities to, tax revenue for counties and townships, bringing families to these small communities that boost population and put more kids in our schools, and support local businesses with buying supplies and materials locally. The list goes on and on! I also think if there was an negative environmental impact Riverview would go above and beyond to try and fix the situation and improve going forward. Let them expand and continue being a positive impact on the dairy industry!

Josie Hollermann **Letter 1078**

Hi, my name is Josie Hollermann. I am 15 years old and have lived about 1,000 feet from one of Riverview's dairies, and even closer to the covered manure tank. From my experience living this close, the smell of manure has never been so horrible that I couldn't go outside or enjoy the location I live at. I think projects like these help cultivate future opportunities for kids like me. Expanding Riverview will create more job opportunities for the community.

For these reasons I support this expansion project.

Josie

Suzanne Swanson **Letter 1079**

I am writing with deep concern for the potential establishment by Riverview LLP of the industrial-scale livestock facility near Morris, Minnesota. This project's scale requires that the MCPA give greater scrutiny than it ever has to previous proposals. This proposal by Riverview must be required to undergo a full environmental impact statement (EIS).

No feedlot has ever undergone an environmental impact statement (EIS) process in Minnesota. Each time the MPCA has determined that an operation should undergo one, the operator that requested the permit has withdrawn their application. And all of those operations that were determined to need an EIS were significantly smaller than Riverview's current proposed operation will be.

If built, the Riverview operation would be allowed to pump up to 226 million gallons of water per year from an off-site well. For reference, the City of Morris, which is home to over 5,000 people, is permitted to pump up to 300 million gallons of water a year. Once constructed, the facility would produce 202,744,000 gallons of liquid manure and wastewater a year and 26,400 tons of solid manure a year.

The Pomme de Terre watershed, where this expansion is proposed, is already considered a sensitive watershed. The MPCA already lists the two closest waterways to the facility, the Pomme de Terre River and an unnamed creek, as impaired, and this proposal would only exacerbate the impairment.

I no longer live in Western Minnesota, but I grew up in that part of the state. The small town where I grew up is struggling as small farmers try to deal with the challenges of corporate ag. Minnesota is already losing dozens of dairy farms annually due to inconsistent and often below cost-of-production milk prices. Massive dairy operations, like the one Riverview is proposing to build, have glutted the market and tightened Big Milk's stranglehold on the industry, allowing them to push small and medium-sized family farms out of business and off the land. This operation would only exacerbate the situation and accelerate the loss of dairy farms in our state, decimating Main Street economies in the process.

The MPCA is charged with assessing the environmental impact of proposed projects, protecting the safety of Minnesota residents. Again, this proposal by Riverview must be required to undergo a full environmental impact statement (EIS).

Athena Kildegaard **Letter 1080**

Please consider the following questions regarding the expansion of West River Dairy.

• Has the dairy sufficiently accounted for increasing incidence of 25-year 24-hour precipitation incidents? Has it also adequately accounted for the effects of El Nino and La Nina and the potential consequences for leakage?

• Given that the manure from the cows will be used as fertilizer on fields that will supply alfalfa for the cows, what are the long-term consequences of this closed-circuit consumption? Will the milk degrade in nutritional content? Will the likelihood of health issues increase?

• Furthermore, what will the environmental impact of this alfalfa monoculture be over time on the soil and on the surrounding ecosystem?

• The EAW states that Riverview will "look for signs of discoloration or odor that may indicate an issue with the liner." There appears to be no other method for ascertaining the efficacy of the manure liner. Are "signs of discoloration or odor" sufficient? Are we willing to accept "may" as the terms here? If seams open in the bottom of the liner, will there be surface-level evidence of the leak? If not, how long will it be before anyone notices?

• What will the impact to the public be in more than doubled truck traffic—in road maintenance, traffic noise, CO2 emissions?

• How many family dairy farms will be forced out of business by this expansion?

Peter Dolan **Letter 1081**

My mind would certainly be more at ease about the Riverview dairy expansion if there was an Environmental Impact Statement prepared. I've heard good things about the quality of their dairy farms, but I've also heard bad things about water usage and aquifer depletion. Being locked out of the last public comment session that occurred in Morris, MN because the venue was too small for the public interest definitely made me feel uneasy because it made it seem likely that a representative sampling of concerns and supports couldn't have occurred. To me this reinforces the need for an independent assessment of the potential environmental impacts. I've heard some of the potential benefits for our community from the expansion, but the Pomme de Terre watershed is an important part of our local culture and our local environment, so it only seems fair to have at least a somewhat more comprehensive, independent third-party assessment of the risks.

Mark Satre **Letter 1082**

I live 4 miles as the crow flies, we have noticed our well water smelling due to the saturation of soils with manure. Too many being allowed in Chippewa Co. All our commissioners must think the tax revenue is great, or some under the table deals are being done. Too many in Chippewa Co.

Thanks

Susan Kulberg **Letter 1083**

As Stevens County resident, I believe an EIS is necessary. Without that I am in complete OPPOSITION of the West River expansion

Exal Villalbos **Letter 1084**

I support the West Riverview expansion. No EIS required.

Christian Baez Tellez **Letter 1085**

I support the West Riverview expansion. No EIS required.

Jose A Vasquez **Letter 1086**

I support the project

Victorino Serrato Martinez **Lettter 1087**

I support the West Riverview expansion. No EIS required.

Diego Saldana Morales **Letter 1088**

I like the way they work with the environment; they are very gentle and caring with the animals I support the west Riverview expansion, not EIS required.

J. Cesor Chavez **Letter 1089**

I support the West Riverview expansion, no EIS required.

Luis C. Hernandez **Letter 1090**

I give all my support for the project based on the knowledge and experience of all the people wich is infront No EIS is necessary

Humberto Meyer Fuentes **Letter 1091**

I support the west riverview expansion. No EIS required

Anonymous **Letter 1092**

I support the West Riverview Expansion. No EIS required.

Anonymous **Letter 1093**

I support the West Riverview expansion. No EIS required.

Anonymous **Letter 1094**

I support the West Riverview Expansion

No EIS required.

Marilo Rodriguez **Letter 1095**

I support West River/Riverview expansion

Hugo Gonzalez **Letter 1096**

I support West River/Riverview expansion

No EIS

Jackson Walsh **Letter 1097**

We are a local farm by the swift county dairies

Riverview has been great to work with and I believe their permit should be awarded. They have don good work on following current environmental rules and the eis is not nessecary.

Dustin Walsh **Letter 1098**

My name is Dustin Walsh. I live in Swift County MN. I have been a neighbor to Riverview dairy for over 20 years. I fully support the West River expansion and do not see any need for an EIS to be done.

Jeanne Norrgard **Letter 1099**

West River Dairy wants to more than double its industrial-style dairy operation in Morris, Minnesota, to become the largest indoor dairy feedlot in Minnesota history. West River Dairy has the financial wherewithal for this massive expansion. They have the financial wherewithal to run multiple operation here in Minnesota and in other states. They have the financial wherewithal to complete a thorough Environmental Impact Statement. And yet, West River Dairy doesn't want to complete an Environmental Impact Statement to reassure Minnesotans that this expansion would be safe for our land, our water, our air, our fish and wildlife and our public health. Why not? In the face of that very reticence, the MPCA must stand firm and do the job of pollution control oversight on behalf of the citizens of Minnesota and require West River Dairy to complete a full and thorough Environmental Impact Statement.

Connie Benson **Letter 1100**

My name is Connie Benson. I am a retired teacher living in Wheaton, MN. I am writing this letter in support of Riverview Dairy and I see the benefit this dairy has made in our community. First of all, enrollment in our schools was in decline before the dairy and since the dairy has come to the area it has since stabilized. Now approximately 3-4 students in a class have parents who are employed by the dairy. That alone helps our schools financially and secures employment for our teachers. The employees who have moved into the area very respectful and hard workers. They buy and rent homes, support our businesses, and use our medical facilities. They also support our local churches. They are very much apart of our community.

Riverview has also contributed to several projects in our community. I will list a few:
1.Youth baseball summer field improvements
2.Resurfacing of our high school parking lot
3.Repairs of city duck monument

I'm also friends of a family that lives by the Riverview owned dairy by Dumont, MN. They often remark about how good neighbors the dairy is. In summer when gravel roads are dusty, the keep them watered down to prevent dust, there is little to no oder, and at a good price they can sell their corn and alfalfa to the dairy. They can also provide a good fertilizer for their land if the farmers wish. I'm also a good family friend of a young man employed by Riverview. I have heard many good comments of how well their employees are treated.

So, as I can see, Riverview Dairy is nothing but a win for western Minnesota. Therefore, I am in full support of this Riverview project and no EIS is needed.

Sincerely,
Connie Benson

Marcus Vaqueu **Letter 1101**

We support the expansion for West River. As a worker for a local farm in swift co it serves opportunity myself and others help us to suport our family.

Terri Hawkinson **Letter 1102**

The River View dairy expansion is proposed to be located precisely at the front door of my childhood home. Although we no longer own the farm site, we do own farm land 1 mile south and 3 miles north of the proposed site. My immediate concern was what I considered lack of transparency-it took me multiple inquiries to get an answer on the township and section number for the expansion. Until then, my neighbors and I were thinking: "not in my backyard" therefore doesn't concern me. How wrong were we.

My next thought was a fading memory of "didn't something happen at their Arizona site"? Stevens County Minnesota should not be allowed to be their second disaster case. Lastly my concern is for that possiblity of contamination of the local watershed and drying up underground water sources for my neighbors and possible future residents of our family's land.

Please require all of the appropriate studies of the proposed River View expansion.

Thank you,
Terri Hawkinson

Heriblez n/a **Letter 1103**

I support West River Expansion. No EIS required.

Nathan Compart **Letter 1104**

Minnesota's water goes 3 different dirrections, we are the headwaters for a very large portion of the continent. We NEED to look at regulating CAFO's at smaller numbers than this. It is not up to us to pay the environmental costs as a state so that a few people can use the land to extract wealth. Until we do better with our water No one downstream from us can do better with their's.

Alejandra Anguiano **Letter 1105**

I support the West River Expantion

David Diaz **Letter 1106**

I support the West River Expantion

Adam Koehl **Letter 1107**

I support the West River Dairy expansion.

No EIS is necessary

Ash Rose **Letter 1108**

This operation is a huge threat to our water supply. Unless this dairy can provide sustainable waste product processing, it is an extremely bad idea for Minnesota wildlife and environment.

Kyle Klausing **Letter 1109**

As a former Morris resident, I don't believe this expansion will positively impact local residents or the overall environment of our state. The MPCA should conduct as full a review as possible before moving forward.

Brian Wojtalewicz **Letter 1110**

Fact: some farmers overapply manure, and do not comply with rules on application.

Fact: All manure pits and lagoons leak.

Fact: Local economies get detrimental social and economic results from large livestock concentrations.

Fact: Alleged best management practices of large confinement systems fail, not just in Minnesota but around the USA.

Fact: Manure pits will inevitably overflow, and will be made worse and more frequent with the severe weather events of the climate crisis. Are you unaware of the huge rain event in Stevens county within the last year?

Fact: you would be allowing a huge experiment in aquifer depletion.

Fact: the groundwater in the area would be threatened more than ever before in recorded history.

Fact: even in recorded history, the flooding that can occur is so huge that the waters of both the Pomme de terre and Chippewa rivers united. Ask Mark Seeley, meteorologist.

Fact: huge animal confinement systems in the USA use and misuse antibiotics on a huge scale, three to six times more than European farmers

Fact: you folk reading this and making the decision to allow the equivalent shit of about 250,000 people just upriver of where we live along the southern Pomme de terre river do NOT live there, nor do your children and grandchildren.

Chad Davison **Letter 1111**

My name is Chad Davison and I am a farmer near Riverview's North Ottawa Dairy. I am writing in support of their proposed West River Dairy expansion in Stevens County.

In my experience with Riverview, they are a positive influence within the communities they operate. Their presence opens up new markets and new opportunities to local farmers, which is essential in times when we endure low commodity prices.

No EIS is needed as the state environmental review process is rigorous and very sufficient. I respectfully encourage your support and approval of this important project.

Sincerely,
Chad Davison

Diana Oliwaus **Letter 1112**

I support west river dairy expansion

Lynn Hu **Letter 1113**

I urge Riverview to complete an Environmental Impact Statement before determining whether or not to expand their operations. Citizens have the right to determine the magnitude of how this new feedlot would produce more greenhouse gas emissions, introduce additional water pollutants, and introduce a nuisance onto the land. Agricultural developments should only progress using strong, data-backed evidence that they have measures in place to mitigate these harmful impacts.

Barbara Kill **Letter 1114**

We arrived at the informational meeting last week early, only to be turned away with the explanation that the venue was at capacity. There were many others besides us who were disappointed not to be able to be admitted. We were open to hearing what they had to share, but not being able to hear that only deepens our concerns about this expansion in our community. At the very least, a EAW should be conducted to reassure those who are concerned that everything possible is done to circumvent an environmental disaster that could render the surrounding countryside unusable for years. This is just an enormous amount of animals concentrated in far too small an area. I also am deeply concerned that so many smaller family farms will be driven out of business by the massive corporate farms who control a monopoly on the industry.

Brenda Boever **Letter 1115**

To those who are listening,

Rural communities are struggling and fighting for their lives. It takes all of the individual family farms and those in small towns to work together to create a thriving community. Corporate farms have a different agenda. They hold the money and power and push out those who stand in their way. That's not what a good neighbor looks like.

We lived in Morris for over 4o years until just last year. I've seen the local economy change due to those who have this money and power. Main street Morris doesn't come close to resembling the thriving independent business community that we enjoyed in the 1980's and beyond. This corporate money has changed the local economy and has reduced the business climate to one that responds only to those associated with RiverView Dairy - those who have money and power. Sadly, Morris and Stevens County has become a one-note town. It's the primary reason we moved.

The environmental impact on this project is a potential disaster! The Pomme deTerre river shed isn't healthy now, and one "mishap" could be catastrophic. Please require an environmental impact study. This company has a record of not doing their "homework", then withdrawing projects when they are questioned.

Just because you "can" do something like build a giant dairy, doesn't make it a good idea. There are lots of communities like Morris that are struggling for their economic vitality. Corporations like RiverView are not people and they don't make community. Rural America needs neighbors they can count on.

Please stop this absurd project. Thanks for your consideration, Brenda Boever

Shawna Conroy **Letter 1116**

Please require a full wnvironmental review. It is imperative that Minnesota's groundwater be protected. The high concentration of animals and heavy use will likely draw down the aquifer.

Barbara Hyk-Zimmer **Letter 1117**

Corporate farming is horrible. It's horrible for the animals which in turn means horrible for those drinking and eating dairy. Horrible for the environment. PERIOD! We either pay for healthy cows to supply us with healthy dairy products or we pay at the doctors when we are sick. As a 2x cancer survivor I want sustainable (organic) farming practices, which lead to healthy produce, as well as lifestock. That IS the opposite of Corporate farming.

We need to save the small family farms.

Nelson Jorgenson **Letter 1118**

I attended the Public Meeting held by you last week in Morris, MN. I observed that the cloud was very polite and respectful; I was very pleased by that. The majority of the comments came from what appeared to be a well-organized effort by Riverview to pack the room with employees, and most comments were clearly scripted by Riverview to support the expansion. Those against the expansion, therefore, were outnumbered, and the comments were not scripted. The most meaningful objections concerned the threat to water quality and quantity, and the statement made by former MPCA staff that the existing regulations are not strict enough to protect the environment.

I was too unprepared and nervous about speaking in public that I did not speak. But I would like to emphasize several key problems with the expansion:

1) **As proposed this would be the largest dairy farm ever in the state, which of course should trigger the maximum review available, up to and including an EIS. If you don't use an EIS for the largest farm, you would be negligent in your oversight responsibility.**
2) **Approximately 2/3 of the waters in Minnesota are polluted. Water scarcity and pollution are a huge problem world-wide; and all water everywhere needs to be better-protected as climate change, overpopulation, and higher concentration of industrial scale water use occurs.**
3) **Lastly the scale of this dairy farm means there is a higher risk of disaster, pollution, or diminishment of the water in the county. I beg you to require an EIS for this project.**

Thank you.

Herbert Davis **Letter 1119**

As a rural resident with no connection to dairy producers, I'm offering my opinion as a dairy consumer and a tax payer.

I oppose the ever larger corporate model of dairy farming because it will hurt the environment and reduce rural economies.

Some of the existing dairy operations are already too large from a water pollution perspective.

Stop the ever increasing consolidation, it seems it has gone too far and needs to stop!

Billy X Curmano **Letter 1120**

I do not believe it is in the environment or the Minnesota citizens best interest to allow a mega-dairy operation. It will compete with existing family farms and increase pollution. The only benefit would be to the corporate factory farm.

Kay Slama **Letter 1121**

The West River Dairy Expansion is too risky to approve--risky for our environment, bad for smaller dairy farmers, and likely to give the West River Dairy owners too much control over milk prices. An EAW is not adequate for such a huge expansion--we need an EIS to fully examine it and allow for greater citizen input.

Susan Scherer **Letter 1122**

Having grown up near a central Minnesota town (Long Prairie), which had a creamery, a locker plant, a meat market, supplied by local small dairy and beef farms, I am full of appreciation for those resources. My classmates were from those farms, so " town kids" and "farm kids" knew each other and we all understood the value of our parents' livelihoods, whether they were farmers or community employees. It was a balanced economy with cooperation and understanding of everyone's part in making it successful. We all cared!

Distance and size have removed much of that understanding, and reduced the businesses that made this kind of cooperation successful and gratifying. I believe that those mental and physical health benefits lost of personally knowing and understanding the value of small, caring communities has led to more violence, more mental illness, more isolation, while large corporations have made profit their sole goal, while caring nothing for the community. It does not add to a democratic, caring society, and we're seeing the effects at all levels of government and business.

Thank you Attorney General Ellison for listening to this eloquent plea from a small farm owner.

Sincerely,
Susan Scherer

Diane Baum **Letter 1123**

I am a Morris resident who has been in contact with the residents of Willcox, AZ, home to another Riverview project. They are concerned by Riverview's out of control style of land takeover, of draining their water and more. I feel this is a picture into the future of Morris, MN as well. This MUST be stopped, which is why I am asking for an EIS OR, an outright denial of this planned expansion altogether. As one Dakota Sioux woman said, "water is life, all of nature is life. If we don't preserve it for our next generations, who will?"

Ferolyn Angell **Letter 1124**

My name is Ferolyn Angell, an educator, small business owner and Pomme de Terre Foods board member. I have lived in West Central MN (Pope & Stevens Counties) for the past 42 years.

I have now read through 400 + comments regarding the West River Dairy expansion. While a good many comments are repetitive either in favor of the expansion or against it, the number of comments requesting an EIS, as well as in opposition to CAFOs in general, far out number those in favor of expansion (390 – 83 at last count and yes, I kept a tally of the comments I have read). It is also worth noting that more than half of those in favor of expansion are either employed by or business partners with Riverwood, the parent company.

I found substantial concerns and ideas expressed that I would like to bring to your attention.

The comments submitted by Mr. Kestner from the DNR on 3/17/26 regarding wells, aquifer replenishment, and river flow raise concerns about monitoring of aquifers and the need for benchmarks to be established for water tables and contaminants in the Pomme de Terre river and surrounding watershed.

Sensitive areas (marshlands, creeks, ditches) for water fowl, migratory birds, etc. may be at risk. Depletion and contamination of water resources and habitat is of concern.

Although a good argument is made for decreased use of chemical fertilizers by spreading manure, it seems that the impact of increased methane, ammonia, hydrogen sulfide, the release of anti-pathogenic chemicals (antibiotics, hormones, etc) into the air and ground have been overlooked.

There is also concern about how the guidelines for manure spreading are enforced when it is being done by outside partners on fields that are not controlled by the permit seeker.

The current EAW as it was presented on 3/28/26 does not address the impact of the proposed expansion on the marketing of milk and milk products, price impact and the effects on smaller dairy farmers.

The increased risk of disease transmission among the animals is also a concern expressed by many of the comments. The presence of dust and insect pests (a good way to transmit pathogens) is mentioned by nearby neighbors.

The call for an Environmental Impact Statement was repeated often in the comments because it would address the effects of the proposed expansion beyond the operations of the milking facility. The project has far reaching implications that go beyond the immediate area surrounding the site of the West River Dairy. Some of the comments made by people in other parts of Minnesota and even other states point this out.

Up to this point, MPCA has not required an environmental impact for a 'feed lot' of this type. Since this permit would be for the largest milk production operation housing a herd of previously untried size, environmental impact is extremely broad and a review is vital for future health and safety.

I am personally concerned about the tremendously shortened life span of the cows that are subjected to the milking operations in factory dairy production. The dead or dying cows are either rendered or slaughtered for consumption. In some cases, I believe they are buried in pits.

At the public meeting held by MPCA in Morris on April 28th many local farmers and area residents were turned away at the door because the room was at capacity. Therefore the purpose of the meeting - to provide an opportunity for residents to voice concerns and ask questions - was not achieved. This will require another meeting in a larger capacity venue. It is now planting season so scheduling a time when farmers can participate is crucial.

Given the changes in climate and the growing number of extreme weather events, many are concerned about the prudence of relying on currently available rainfall data. Changes in weather patterns will impact the likelihood of manure spills in the future. Minnesota's stated climate targets must also be kept in mind in reviewing this expansion.

In my estimation, an EIS is the best next step for this proposal. I am happy to share my list of substantive comments pro and con if that would be helpful in wading through the more than 1100 submitted so far.

Em Senten **Letter 1125**

This expanded Riverview facility would be the first of its size in Minnesota, and more than 60 times the size of the average Minnesota dairy (fewer than 280 cows in 2025). This makes it a fundamentally new and particularly powerful threat to Minnesota farmers and rural communities.

The MPCA must recognize the fundamentally new nature of this threat and give this permit greater scrutiny than it ever has to previous proposals. This proposal by Riverview, LLP must be required to undergo a full Environmental Impact Statement.

An EIS will allow the proposal's negative impacts on water quality and quantity, local roads, and existing independent family dairy farms to be fully analyzed before the project is allowed to seek a permit.

Riverview has a recent history of manure spills in western Minnesota. In Arizona, the company recently agreed to pay $11 million to residents affected by the dairy's overpumping. The proposed Stevens County site sits within five miles of eight different protected waterfowl and wildlife production areas and is part of the Pomme de Terre River watershed, just 25 miles from its confluence with the Minnesota River. A facility of this scale located in such a vulnerable area calls for a thorough environmental review.

Just as importantly, an EIS of the West River Dairy Expansion proposal would address socio-economic impacts. Minnesota is already losing dozens of dairy farms annually due to inconsistent and often below cost-of-production milk prices. Massive dairy operations, like the one Riverview is proposing to build, have glutted the market and tightened Big Milk's stranglehold on the industry, allowing them to push small and medium-sized family farms out of business and off the land. This operation would only exacerbate the situation and accelerate the loss of dairy farms in our state, decimating Main Street economies in the process.

An industrial scale project needs industrial scale review. We need to make sure efforts to grow our economy are accountable to and support our farmers, our land, and our communities.

Lori Hinrichsen **Letter 1126**

Water depletion could impact surrounding consumers. The concentration of manure, if not managed properly, could lead to an environmental disaster. Diversification of locations and smaller dairy farms would be the most environmentally sustainable solution.

Tommy Houdek, Wild Rice Electric Cooperative, Inc. **Letter 1127**

ATTN: Charles Peterson

My name is Tommy Houdek, and I am the Director of Member Services & Communications with Wild Rice Electric Cooperative, Inc. I am writing in support of Riverview's proposed West River Dairy expansion in Stevens County.

Our experience working with Riverview Dairy has been overwhelmingly positive. They have proven to be a reliable and professional partner, contributing meaningfully to the communities they operate in. From an economic standpoint, their operations provide stable, long-term benefits by supporting local jobs, driving investment, and creating opportunities for surrounding businesses.

In addition to their economic impact, Riverview represents a consistent and dependable presence from an energy perspective. As a strong and stable electric load, their operations contribute to the overall efficiency and sustainability of the local electric system, which benefits the broader membership and infrastructure.

Riverview has demonstrated a commitment to maintaining strong working relationships and operating responsibly within the communities they serve. Their willingness to collaborate and invest locally makes them a valuable partner and an important contributor to rural vitality.

The proposed expansion will build on these strengths, supporting additional economic activity, creating jobs, and reinforcing the agricultural backbone that so many rural communities depend on.

No EIS is needed as the state environmental review process is rigorous and very sufficient. I respectfully encourage your support and approval of this important project.

I respectfully encourage your support and approval of this project.

Sincerely,
Tommy Houdek
Director of Member Services & Communications
Wild Rice Electric Cooperative, Inc.

Robert Dana **Letter 1128**

I urge you to require a full environmental impact review of this project. There should also be a requirement for a social impact review as well.

Ismad Cruz **Letter 1129**

I support west River Dairy expansion.

No EIS needed.

Jason Yoss **Letter 1130**

ATTN: Charles Peterson

My name is Jason, and I am the owner/operator/employee of YB Truckin, I provide a rendering service to Minnesota farms like Riverview. I am writing in support of their proposed West River Dairy expansion in Stevens County.

Through our work in the agricultural sector, we depend on a strong and stable livestock industry. Operations like Riverview's create consistent economic activity that supports local jobs, drives investment, and allows businesses like ours to grow and reinvest in our communities.

The proposed expansion represents a meaningful economic benefit to the region. It will generate demand for local vendors, support both construction and long-term employment, and contribute to the vitality of rural communities that rely on agriculture.

From our direct experience, Riverview is a professional and reliable partner that contributes positively to the communities where it operates. Their presence strengthens the local economy and supports a broad network of agricultural and service-related businesses.

Projects like this are essential to maintaining a competitive and sustainable rural economy in Minnesota. Continued investment in agriculture ensures that local businesses can continue to provide jobs, services, and economic stability close to home.

No EIS is needed as the state environmental review process is rigorous and very sufficient. I respectfully encourage your support and approval of this important project.

Sincerely,

Jason

Julie Kill **Letter 1131**

While reviewing the documentation for Expansion and permitting, several issues came to mind.

First of all- Why is the data for the pump test almost 20 years old? It seems to me that a new pump test should be completed to ensure that the aquifer in questions can handle the amount of water that the offsite well is supposed to be providing. Normally, a pump test should be required in any circumstance where an increase in water use is requested, would it not? Why is the nearly 20 year old data being allowed?

Second- I know of neighbors who had to have new wells drilled when the first ~7000 cows were permitted.

Has the cone of depression around the Onsite wells even been studied? Has this been completed since the First part of the Dairy began using the water? Have water levels been monitored at all in the neighbors wells? Is there data available for the 8 wells that riverview has on site as well as pump testing for those wells? What about monitoring for water usage?

Adding over 11,000 animals units is not going to help the aquifers where these 8 wells are located either. Have studies been done on the increased water that will be drawn from the on-site wells? Three of the 8 Riverview onsite wells are at between 136(a2) and 141 feet in depth. Well H and Well B are 164,166 feet deep. The other wells onsite are screened at nearly 300 feet. How many different aqufers are involved? What is know about them? To the best of my knowledge the aquifers in this area of Minnesota have not been well studied. If these aquifers are further drawn down with the increase in the number of animals, Where is the water supposed to come from? The Dairy will have a storage tank. What will the neighbors have?

Is the Dairy tapping into the Souix aquifer/ or a section of the Sioux Aquifer (which is the largest aquifer in this region of the United States)? What will happen if it is connected to the Sioux Aquifer? A free for all?

Third: According to the capacity levels for the holding areas the total number of animals on site should be 7856. The actual number of animals onsite is 10995!!!!! According to the NPDES PERMIT. THREE THOUSAND ONE HUNDRED THRITY NINE OVER THE CAPACITY! OVER CAPACITY!!!!! NOW. What is going to Happen if they get the go ahead to expand? 50,000 animals?????? EXPAND ALL OF THE OTHER DAIRYS? This is NOT Acceptable!

Fourth: Using earthen barriers in the holding areas for manure. What will be put into place for monitoring them to make certain that they do not leak, burst, overflow? What is the PROVEN life of holding areas like these?

Fifth- packing the house for the meeting is not acceptable either. Many people were turned away who had questions and concerns and as Minnesotans, We have that right to ask them and to have them answered by the MPCA. I would lke to request another meeting! This is not Just, Moral or fair to all.

People Want an EIS for this site and an EIS Should be required for this site.

Please make your decisions with the future of All of us in mind, and our Children and Their Children. Make Certain. that this area is kept safe and the waters and ecosystems are kept healthy for those coming after us.

Thank you for your time.

Janine Wojtalewicz **Letter 1132**

RE: West River Dairy

Below are several factors that my family, who lives in rural Minnesota near the Pomme de Terre River, is aware of concerning how expansion of the West River Dairy would negatively affect this river and the rural environment surrounding it.

*It is well known that some farmers over apply manure, and do not comply with rules on application.

*All manure pits and lagoons leak.

*Local economies get detrimental social and economic results from large livestock concentrations.

*Our health and the health of area wildlife and creatures living in the river are all impacted, as well as our enjoyment of outdoor activities such as canoeing and kayaking in this river, swimming, fishing and holding family gatherings centered around the beauty of the river.

*Alleged best management practices of large confinement systems fail, not just in Minnesota but around the USA.

*Manure pits will inevitably overflow and will be made worse and more frequent with the severe weather events of the climate crisis.

*This expansion would be allowing a huge experiment in aquifer depletion.

*The groundwater in the area would be threatened more than ever before in recorded history.

*Even in recorded history, the flooding that can occur is so huge that the waters of both the Pomme de Terre and nearby Chippewa rivers united. This has been verified by meteorologist, Mark Seeley.

*Huge animal confinement systems in the USA use and misuse antibiotics on a huge scale, three to six times more than European farmers.

*Those of you reading this and making the decision to allow the equivalent feces of about 250,000 people just upriver of where we live along the southern Pomme de terre river do NOT live there, nor do your children and grandchildren.

Kelly Skaurud **Letter 1133**

The EIS is not necessary for Riverview's West River expansion. MPCA's EAW should be more than sufficient. Thank you

Taylor Gibson **Letter 1134**

I have been working with riverview dairy for about 3 years now. The issues that people are having do not know how the company is. The people not only the hired hands but also the vendors (outside resources that maintain operations) are treated with upmost respect. When an issue is presented the issue is delt with accordingly. The cows are treated very well and are very healthy. Not only the day to day operation is great, look at all the other things the dairy brings to the table. Fertilizer for the fields, for farmers its guaranteed place for silage, wheat, straw. For towns it's more money being spent at gas stations, grocery store. There is very little to no smell. Keep up the great work riverview!

Amanda Holslin, Holslin Family Farms **Letter 1135**

ATTN: Charles Peterson

I am writing this on behalf of my 4-generation small family farm, which is about a mile from the proposed dairy barn, which already has an 8,000 head barn. On a windy day, the smell is unbearable, I can't imagine what it would be like if they added 10,000 more cattle.

I believe that they don't just need an EAW, they should be required to have an EIS done, otherwise you will probably have one in your backyard someday too. If approved, say goodbye to water, roads and fresh air, that is just touching the surface of the problems.

Large facilities like this do not exist in isolation. Increased manure application raises the risk of nitrate contamination in groundwater, something rural families, like ours, rely on for drinking water. Increased truck traffic affects local roads that were never designed for heavy, constant loads. Odor doesn't respect property lines, and wildlife habitat that has existed here for decades is altered or lost entirely. These impacts fall disproportionately on nearby residents who have little choice but to live with the consequences.

I will end with this. Small, family-run farms like ours are not asking to stop progress. We are asking for accountability, transparency, and thoughtful decision-making that values people, land, and long-term sustainability over short-term corporate gain. I am tired of watching rural communities absorb the costs and pains while others reap the benefits. Something needs to change.

Sincerely,
Holslin Family Farms

Jay Sheets **Letter 1136**

As a resident of Stevens county and living within 4 miles of Riverviews Dollymont dariy, I have great concerns over Riverviews proposed feedlot expansion. If I'm not mistaken, Riverview was only permitted to drill one well at Dollymont and limited in their total capacity to 9000 head of cattle. Dollymont dairy currently has 2 wells and are milking around 11,000 head. Of the two wells, both penetrate deep enough to go through the sandstone ledge that protects the larger lower aquafer which lies below mine. My well is 193 feet deep. My wife grew up on the farm we now live on, I'm very familiar with the water on this farm. Of the 40+ years of using the water here; it's only been in the past five to six years I've seen the water go from strictly a rusty iron and sand problem to a heavy manganese problem. Dollymont has drilled not one but TWO wells to the depth of 273 feet. Which can draw water from my shallower aquifer down through the sandstone into the lower aquifer. How are the residents of this county supposed to trust that Riverview wouldn't violate any permit they file, given their history in Dollymont twsp? I propose we need a full EIS to study what effect long term water use of this amount will do to these upper (shallow) aquafers. Also given the effects of what happened down in Arizona and what's happening with the well on my property, only 4 miles from another dairy; that I consider to be in direct violation of the permit initially proposed I'd say it warrants consideration. Thank you for your attention to this matter. Jay M. Sheets (concerned resident)

David Soehren **Letter 1137**

Any project of this magnitude should be required to provide a fuLL Environmental Impact Statement rather than just an EAW. The potential problems of water usage, Manure management, and potential spills can then be properly assessed.

Melissa Bakker Roach **Letter 1138**

This is the worst kind of "farm". This is not good for anything: not people, not farms, not rural communities, not consumers, not cows, not the environment. This is not a good neighbor and puts smaller dairy farms, family farms across the state, in danger. No to River Dairy.

Amy Werk **Letter 1139**

I support Riverview's proposed West River Dairy Expansion. The EAW is completed and adequate. All environmental concerns have been addressed and reasonable effort has been made to reduce or mitigate risks. Riverview is a very important member of Stevens County, the Morris community and the state of Minnesota. They are good stewards of the land and the animals. Riverview goes to great lengths to protect the environment and comply with all regulations. Please allow this project to move forward with the EAW. Thank you.

Jeanne Johnson **Letter 1140**

I and all people who value the land andthe cattle oppose this unconscionable project. I don't need to recount the reasons.

Adam Zelltwanger **Letter 1141**

The environmental review is sufficient, no EIS needed

Landon Koehl **Letter 1142**

I strongly support the project moving forward. NO EIS IS NEEDED!Thank you for your time and effort you have put into this project

landon koehl

Lucas Koehl **Letter 1143**

I strongly support this project moving forward. No EIS necessary!

Thank you MPCA for the work you've put into this permit!

Baldomero Penaloza **Letter 1144**

I support west river expansion.

No EIS reqquired.

Osvaldo Penaloza Gomez **Letter 1145**

I support west river expansion. No EIS required.

Thanks.

Anthony Anker **Letter 1146**

I am writing to support the West River expansion and urge the approval of the permit without the need of the EIS. Riverview consistantly does the right thing in all parts of their operation. They are clean, consistant, careful, and considerate of neighbors. They have proven track record of following the state permits that they already have received. Requiring another study for this permit is unnessecary as they

continue to follow all the rules. I am proud to live near a Riverview site as they make good neighbors and are good for our community.

Tyler Thiel **Letter 1147**

I fully support the West River Dairy Expansion. No EIS should be needed.

Javier P Torillo **Letter 1148**

I support the project

Riverview is good company for me and my family.

Froncisco Guadarrama Capitaine **Letter 1149**

I support West River Expansion

No EIS required

Jodi DeCamp **Letter 1150**

1)Any project of this size should demand that an EIS be done.

2)An EIS was required for a smaller project in Baker Township in Stevens Co. & the Fehr's dropped the project. If these projects are environmentally safe, why would there be opposition to doing the EIS.

3)Have you considered the adverse impacts caused by other dairies owned by the Fehr's in both MN and other states? i.e. drinking water, our spreading of manure, etc.

4)Cropland for upcoming young farmers is unavailable due to the Fehr's outbidding anyone.

5)An EIS would address socio-economic and community concerns.

Cameron Adams **Letter 1151**

I support the West river Expansion. Riverview is a great facility, follows all the rules and sets the standard. I trust the MPCA is very thorough in there analysis. No EIS needed.

Kevin Stallman **Letter 1152**

We support this project

No need for EIS

Dustin Nelson **Letter 1153**

I support the west river expansion. We need businesses in rural MN that care about the community they live in and they've shown that all the time. There dairies are immaculate and the people are top notch. Thank you to the MPCA.

Heidi Wellnitz **Letter 1154**

I fully support this project and do not believe EIS is needed.

Matt Wellnitz **Letter 1155**

I support the West River Dairy Expansion, there is no EIS needed.

Lowell Moser **Letter 1156**

I am Lowell Moser and have lived all 62 years of my life in Stevens County.

I want say thank you to the MPCA for doing such a complete job of working through the EAW on this Riverview Site.

I donot believe that an EIS is necessary. The family that owns & operates Riverview is first rate and top notch when operating their dairies.

Thank you!

Rob Needham **Letter 1157**

Highly recomend the project

No need 4 EIS

Mike Wade, Wild Rice Electric Cooperative **Letter 1158**

We would like to express our support for Riverview Dairy and its planned expansion in Stevens County. As an electric cooperative, we work with Riverview Dairy by providing electric service to one of their facilities in Norman County, Minnesota, and our experience has been extremely positive. Their management staff are professional, easy to work with, and operate their facility based on the highest of standards. They take the time to provide our cooperative with educational tours of their facilities, and we meet with them regularly to discuss ways we can work together on common interests. Riverview Dairy is a strong community partner and helps support jobs and economic growth in a rural Minnesota. Based on our experience with Riverview, I have full confidence that the expansion of the dairy will have a very positive impact on the area.

Felipe Jaimes Aviles **Letter 1159**

I support the West Riverview Expansion. No EIS required.

Sam Bradshaw **Letter 1160**

I fully support the West Riverview Dairy expansion and no EIS required.

Diego Velazquez Sanchez **Letter 1161**

I support the expantion of West R.

No EIS required

Martha Cristina Lopez H **Letter 1162**

I support the West Riverview expansion.

No EIS required.

Paulina Velazquez **Letter 1163**

I support the West Riverview Expansion. No EIS required.

Phillip Earle **Letter 1164**

I support Riverview and there west river expansion. No EIS is needed.

James Morais **Letter 1165**

living in Nashwa Minnesota close to 2 Riverview Dairy's I never have any smells or water problems in fact they as a company always help the community, and with the dairy's there the community thrives. More work opportunity and the community grows.

Diary's have a great way in bring community together and ensuring work opportunity. Over the past few years there was and is still no issues regarding water problems I am all for the dairy's as they are a great construction to the community.

Taylor Flemming **Letter 1166**

I support West River/Riverview expantion.

No EIS rquired

Tony Tillma, Valley Dairy Supply **Letter 1167**

MY NAME IS TONY AND I AM CO-OWNER OF VALLEY DAIRY SUPPLY, BASED IN CORONA SOUTH DAKOTA. I AM WRITING THIS IN SUPPORT OF THE PROPOSED EXPANSION OF WEST RIVER DAIRY IN STEVENS COPUNTY MINNESOTA.

BALLEY DAIRY SUPPLY HAS 21 FULL TIME EMPLOYEES. WE SUPPLY DAIRY FARMS WITH SUPPLIES, CLEANING PRODUCTS, ANDPERFORM MAINTENANCE SERVICE FOR THE DAIRIES

RIVERVIEW AS A WHOLE IS A HUGE PIECE OR OUR BUSINESS. I BELIEVE THE PROPOSED EXPANSION WILL BENEFIT THE LOCAL COMMUNITY AS WELL AS THE DAIRY INDUSTRY. IT ONLY TAKES A DRIVE PAST ANY OF THEIR FARMS TO SEE THAT RIVERVIEW IS A TOP NOTCH PRODUCER.

I RESPECTFULLY ASK THAT YOU SUPPORT THIS EXPANSION.

Gerhard Prinsloo **Letter 1168**

I support the west river expansion. Great company. Always clean, great people. Care about the community. No EIS. Thanks.

Rodrigo n/a **Letter 1169**

I support West River/Riverview expansion

no EIS required

Brett Peterson **Letter 1170**

I am not in support of A EIS they are not needed

SG Prinsloo **Letter 1171**

I work for a farmer that works with the dairy. I run dozer for forage harvest. The site is amazing. The people are great. Why wouldn't you want something this in your area. People are scared of change.

Trust the MPCA. They know what there doing. I support the expansion and NO EIS needed. Start building it.

Nancy Fabiola Acevedo **Letter 1172**

I highly support the West River Dairy expansion! I think there's no EIS required.

Marco Grubinoew **Letter 1173**

I support the expansion. No EIS needed.

Victoria Dalager **Letter 1174**

With the impact on our aquafier and the history of Riverview's treatment of water use needed by anyone but them, please do an evaluation before Stevens County ends up like the Wilcox Basin in Arizona.

Anonymous Anonymous **Letter 1175**

I support the West Riverview expansed

It is a great oportunty for the people of Morris, MN.

Anonymous Anonymous **Letter 1176**

I support the West Riverview expansed

Mathew Miller **Letter 1177**

I support the expansion. No EIS needed. Thank you to the MPCA for doing there work on this. If this review has been multiple years. I don't see any shortcuts being taken. Trust the process. Thank you.

Anonymous Anonymous **Letter 1178**

I support the West Riverview expansion

Anonymous Anonymous **Letter 1179**

I support the West Riverview expansion

Luis Carmona **Letter 1180**

I support the project

No EIS needed

Janet Espinoza **Letter 1181**

My family supports the West River Dairy extension because of the economic oportunities for the communty.

Susana Corona **Letter 1182**

I support the West Riverview expansion.

No EIS Required

Rodney McCollum **Letter 1183**

My name is Rodney McCollum and I am the owner/operator of McCollum Hardware, a retail hardware store serving agricultural operations in Minnesota like Riverview. I am writing in support of their proposed West River Dairy expansion in Stevens County.

Operations like Riverview's create consistent economic activity that supports local jobs, drives investment, and allows businesses like ours to grow and reinvest in our communities.

The proposed expansion represents a meaningful economic benefit to the region. It will generate demand for local vendors, support both construction and long-term employment, and contribute to the vitality of rural communities that rely on agriculture.

From our direct experience, Riverview is a professional and reliable partner that contributes positively to the communities where it operates. Their presence strengthens the local economy and supports a broad network of agricultural and service-related businesses.

Projects like this are essential to maintaining a competitive and sustainable rural economy in Minnesota. Continued investment in agriculture ensures that local businesses can continue to provide jobs, services, and economic stability close to home.

No EIS is needed as the state environmental review process is rigorous and very sufficient. I respectfully encourage your support and approval of this important project.

Sincerely,
Rodney McCollum

Rames Jaimez **Letter 1184**

I support the West Riverview Expansion. No EIS Required

Jose Luis Martinez **Letter 1185**

I support the West Riverview expansion

Filemon Cervantez **Letter 1186**

I support the project.

NO EIS NEEDED!

Anonymous Anonymous **Letter 1187**

I support the Proyect.

NO EIS NEEDED

Ratael Sevilla **Letter 1188**

I support the project

Christian Cabrera **Letter 1189**

I support West River Dairy expansion.

No EIS required

Juan Pablo Alvarez **Letter 1190**

I support the project.

No to the EIS

Don Wienhold **Letter 1191**

Regarding Riverviews expansion I feel they definitely need an EIS or outright denial. My main concern is healthy aquifers for many generations to come, by not over pumping or polluting with high nitrates. We need to look at aquifers as the miracle they are, we can draw water from the ground and it is drinkable and life-sustaining. When an aquifer is over pumped it leads to poor water quality and the possibility of collapse, then it loses storage capacity permanently. If the aquifer is compromised it affects way more people than can be quantified, possibly forever.

I am all for science and research, but there comes a time when you need to put on your common sense hat and look at the massive water usage this operation would have. Anytime you compare the water usage of one operation to an entire city it tells you this cannot be allowed.

What we need in this state is an animal unit cap, because anytime you leave it up to businesses, like Riverview, they push for absolute crazy amounts. Anytime you put the making of money ahead of the environment it is not a good thing.

I hope that people can see a trend here, that Riverview is never happy with their current size, they always want more.

Jorge Mehel **Letter 1192**

I support the project.

No EIS needed

Michael Anderson **Letter 1193**

I would like to take this opportunity to provide comments on the proposed West River Dairy Expansion project. My name is Michael Anderson. I am a farmer and business owner from the Hillsboro, ND area. I have had the opportunity to meet and work with Riverview Dairy in several capacities over the last several years.

One of the most striking things that I have experienced working with this group is the amount of transparency and a willingness to answer concerns and questions. Their model of doing business has been much appreciated in my area and with their numerous other projects. They have taken people's concerns and provided time and resources to answer questions effectively and completely. Their concern for people has been evident in everything they do.

The amount of opportunity provided by their projects has been very impactful. They have demonstrated a willingness and commitment to work with local businesses and vendors as much as possible to provide for their needs. I have witnessed many individuals and businesses having new hope and optimism for their area because of the new opportunities to work with Riverview.

Their facilities and operations that I have seen have all been first class. The sites are operated with pride and concern for the area they are located in. Animals are treated humanely and with detail to maintain

health, comfort, and productivity. I have enjoyed meeting and visiting with a very wide range of employees and staff.

The positives are numerous and wide ranging. The impact of this project will be a blessing for the rural economy and provide opportunities for many to benefit. Your support and approval of this project will have lasting positive outcomes to so many people and the entire area.

Respectfully Submitted,
Michael Anderson

Martin M. Ruano **Letter 1194**

I support the West Riverview. No EIS required

Brian Wojtalewicz **Letter 1195**

Facts: After "hard fought negotiations" this same dairy agreed to pay $11 Million and make long overdue changes on groundwater use in Arizona. See more facts here and at related media articles: https://www.azag.gov/ag-mayes-announces-riverview-settlement

Nancy Malcomson **Letter 1196**

We don't need more consolidated farms in the hands of so few. Is this dairy oligarchy? This expansion will harm our earth in terms of water quality, increased herbicides and pesticides on the lands supporting the cows.

Please DO NOT permit this expansion.

Stuart Knappmiller **Letter 1197**

As a member of the Land Stewardship Project, I'm concerned about the way our dairy industry is being contracted from small dairies and expanded by large dairies with huge numbers of cows.

Large numbers of live stock mean more pollution at a specific site, less crop diversity, lower prices for family farmers and fewer farms to support rural economies. Corporate farms probably don't buy in town or send their children to local schools as we did on our 228 acre 28 cow farm. We always had a job for a live in worker or college student who needed the income and room and board provided. Corporate farms ar driving small farmers out of the business and damaging rual communities. More small, thriving dairies means stronger rural economies and a more resilient food system.

Margaret Kuchenreuther **Letter 1198**

I write to urge the MPCA to require Riverview LLC to complete an Environmental Impact Statement (EIS) before approving their proposed River West Dairy Expansion. This dairy operation, if approved, would be the largest feedlot in Minnesota and 500 times larger than the average dairy farm in Minnesota (Land Stewardship Project 2026). An agricultural operation of this unprecedented size deserves especially careful scrutiny in view of its potential to affect the economic, social and environmental conditions of both our local region, and potentially, the nation. Below are just a few of the reasons I believe an EIS is warranted before this project can move forward:

1.The most important reason to require an EIS is that the Environmental Assessment Worksheet (EAW) filed by Riverview considers only the environmental effects of this proposed dairy expansion. It is not designed to also incorporate analysis of the economic and social effects the expansion is likely to

produce. The Land Stewardship Project (2026) recently produced a white paper that discusses dairy markets and the effects that production consolidation has on small operators. I find their analysis, echoed by a recent story in The New York Times (Saslow 2026), to be very concerning. Our current dairy market system is obviously broken, with production costs often exceeding earnings. Consolidating milk production in the hands of a few huge operators is unlikely help the prospects of small operators. Stressing the economics of small operators throughout Minnesota disrupts the lives of farm families and the economics of small towns, as well as leading to an epidemic of mental health issues and suicides among farmers (Rural Health Information Hub 2026). Only by requiring an EIS can the MPCA thoroughly investigate the important economic and social effects of this project.

2.Riverview's EAW acknowledges that ongoing climate change is expected to increase the frequency of heavy precipitation events, in addition to increasing average annual temperatures. They assert that building stormwater retention ponds that are 20% larger than that required to hold water from a 25-year precipitation event will be enough to reliably handle runoff from their impervious surfaces. However, I am not confident that this assertion is justified. The Minnesota Department of Natural Resources (2024) notes that heavy rainfall events are becoming more frequent in our state, meaning that "25-year" events may occur more often than historically expected. Given the current state of our climate and especially the changes expected in the coming decades (UMN Climate Adaptation Partnership 2026), I believe that, within the context of an EIS, Riverview should be expected to provide modeling of how well projected increases in precipitation (especially heavy rainfall events) would be handled by both their stormwater retention ponds and their manure storage facilities in order to prevent contamination of the Pomme de Terre River and adjacent wetlands.

3.Another important effect of climate change is the way that projected warmer and wetter springs (UMN Climate Adaptation Partnership 2026) will affect nutrient retention in fields after fall manure application. Historically, winters and springs were cold enough to keep most of the nitrogen from fall-applied manure in the soil profile. However, data show that unusually warm February and March temperatures (which are likely to become increasingly common in the future) can cause the loss of nearly all the nitrogen from a fall manure application, even if the manure is injected subsurface and treated with a nitrogen stabilizer (A & L Great Lakes Laboratories. 2026; Bayer Crop Science 2025.) Where will this nitrogen go? Into the Pomme de Terre River, of course, only exacerbated by the ubiquity of pattern-tile drainage of fields in our region. Your own agency has documented that the middle and lower Pomme de Terre has experienced nitrate-nitrogen increases of 11% annually from 2007-20017, resulting in problems with dissolved oxygen and anthropogenic eutrophication (Minnesota Pollution Control Agency. 2024). Manure applications from an operation of this unprecedented size are likely to worsen the condition of the Pomme de Terre, despite the assurances offered in the EAW. And, unfortunately, the negative effects don't stop there. Nutrient pollution in tributaries of the Mississippi River annually causes a dead zone in the Gulf of Mexico (NOAA 2022), adversely affecting biodiversity in the Gulf, as well as the livelihoods of fisherman and those involved in the region's tourism industry. An EIS for this project should explore the likelihood of nitrogen loss from field APPLICATIONS of manure in the face of projected climate change.

Literature Cited

A & L Great Lakes Laboratories. 2026. Fall applied manure. Will the nitrogen still be there? https://algreatlakes.com/blogs/news/fall-applied-manure-will-the-nitrogen-still-be-there-1

Bayer Crop Science. 2025. Manure applications and the potential for nitrogen loss. https://www.cropscience.bayer.us/articles/channel/manure-applications-potential-for-nitrogen-loss

Land Stewardship Project. 2026. Flooding the market how dairy consolidation is drowning Minnesota's farmers & rural communities. https://landstewardshipproject.org/wp-content/uploads/Milk-Flood-C-4-23-26.pdf

Minnesota Department of Natural Resources. 2024. Historic mega-rain events in Minnesota. https://www.dnr.state.mn.us/climate/summaries_and_publications/mega_rain_events.html

Minnesota Pollution Control Agency. 2024. Pomme de Terre River watershed stressor identification update. https://www.pca.state.mn.us/sites/default/files/wq-ws5-07020002b.pdf

National Oceanic and Atmospheric Administration. 2022. Ocean Today: Dead zone in the Gulf of Mexico. https://oceantoday.noaa.gov/deadzonegulf/

Rural Health Information Hub. 2026. Rural response to farmer mental health and suicide prevention. https://www.ruralhealthinfo.org/topics/farmer-mental-health

Saslow, E. 2026. The last days of Butter Ridge. The New York Times. http://www.nytimes.com/2026/05/03/us/dairy-farm-butter-ridge-

pennsylvania.html?smid=nytcore

UMN Climate Adaptation Partnership. 2026. Climate change in West Central Minnesota. https://climate.umn.edu/climate-change-west-central-minnesota

Daniel Cona **Letter 1199**

I support the West Riverview expansion no EIS required

Alberto Garcia **Letter 1200**

I support the project. No EIS needed.

Veronica Bonilla **Letter 1201**

I support the project. No EIS needed.

Cole Watzke **Letter 1202**

As a local truck driver I fully support this project, No EIS needed

Reynaldo Gomez Espinoza **Letter 1203**

I support the West Riverview expansion. No EIS required

Roben Hernandez **Letter 1204**

I support the West Riverview expansion. Noe EIS required

Marcelo R Gonzalez **Letter 1205**

I support the West Riverview expansion. No EIS required.

Hugo Gabriel Ruiz **Letter 1206**

I support the West Riverview expansion. No EIS required.

Angeles Salem Hernandez **Letter 1207**

I support the West Riverview expansion.

Leslie Garrido **Letter 1208**

I support the project. No EIS needed

Sergio Vazquez **Letter 1209**

I support the project of Westriver expansion No EIS is needed

Alejandra Vazquez **Letter 1210**

I 100% support this project. EIS is not needed.

Isa Garrido **Letter 1211**

I support the projec, No EIS Needed

Adrian Garrido **Letter 1212**

I support West River Expantion projec.

No EIS Needed

Mariana Garrido **Letter 1213**

I support the project, no EIS needed.

Josh Hollen **Letter 1214**

Dear Mr. Peterson,

Thank you for the opportunity to comment on the Riverview Dairy expansion project located in Stevens County, MN. Milk trucks drive by our house all the time, one was even gushing milk out a left open valve as it drove by a few years ago.

The MPCA was established in 1967 under Republican Governor Harold LeVander to protect air, water, and the land of MN due to growing environmental concerns. Its focus is to prevent and reduce the pollution of air, water, and land. As stated on the MPCA website, the State of MN appropriated $318 million dollars in 2024-2025 from the Clean Water Fund to various water projects in MN.

I think Attachment 16 MPCA Impaired Waters Map says it all. I see miles and miles of impaired streams, creeks, and rivers downgradient from the designated manure application areas for this project. I see two impaired lakes and two impaired wetlands in this attachment. The approval of this expansion will potentially add such lovely words as E. coli, Cryptosporidium, Eutrophication, and Giardia to this attachment. Do you know how much of the $318 million was spent on investigating and cleaning up the waters of Attachment 16?

The job of the MPCA is to protect the environment so people can live in it. It is not the job of the MPCA to promote big business and agriculture. If the MPCA truly cares about the environment and waters of MN, then prove it. Require the completion of an Environmental Impact Statement for this expansion, the people of Attachment 16 deserve it.

Josh Hollen

Gerardo Catalan **Letter 1215**

I support the West Riverview expansion no eis required

Alejandro Gonzalez **Letter 1216**

I support the West Riverview expansion no EIS required

Eric Joos **Letter 1217**

I support this project and no EIS is needed

Anonymous Anonymous **Letter 1218**

I support the expansion. No EIS needed

Zachary Koehl **Letter 1219**

I support the project. No EIS is needed.

Tyler Reese **Letter 1220**

I am in support of the project, No EIS is needed.

Anonymous Anonymous **Letter 1221**

I support the expansion. No EIS needed

Timoteo Alejandro Mtnez **Letter 1222**

I support the West Riverview expansion No EIS required

Monserat Marquez **Letter 1223**

I support West River Dairy expansion

No EIS required

Eduardo Holhebuena Zaraboza **Letter 1224**

I support West River Dairy expansion

No EIS Required

Jesus Suarez Camucho **Letter 1225**

I support West River Dairy expansion

No ELS required

Chrstina Lanzagorta Silva **Letter 1226**

I'm writing in support of the West River Dairy/feedlot project. As someone with knowledge in animal production, I recognize the importance of responsible livestock operation for local economies and food systems. Modern dairy and feedlot operations are designed with environmental management practices that minimize risks to water, soil, and air quality when properly regulated and monitored. I trust that the Minnesota Pollution Control Agency will ensure that all environmental standards are met.

This project represents an opportunity to strengthen the local economy, create jobs and support agricultural development in the region.

With appropriate oversight, it can operate responsibly and sustainably.

I respectfully support the approval of this project.

No EIS required.

Josue Roberto Moreno Soriano **Letter 1227**

I'm writing in support of the expansion of the West River Dairy/feedlot project. Responsible expansion of livestock operations can be done in livestock operations can be done in a way that protects both the environment and surrounding community when proper management system are in place. Modern manure management systems are specifically designed to prevent contamination for water and air. When handled correctly manure is not waste but a valuable resource that can be safely stored, treated, and applied as fertilizer in accordance with nutrient management plans. These practices help recycle nutrients, reduce reliance on synthetic fertilizers, and protect soil health. Concerns about water and air quality are valid: however, current regulations and monitoring requirements ensure that operations must meet strict environmental standars. With proper oversight, runoff, leaching and emissions can be effectively controlled and minimized. Expansion also brings economic benefits to the region, including job creation, support for local agriculture, and longterm sustainability of farming community. I respectfully support the expansion of this project, as it can operate responsibly, sustainably, and in compliance with environmental regulations. No EIS required.

Cristian n/a **Letter 1228**

I support West River Dairy and I think not necessary EIS

Jose Borjus **Letter 1229**

I support west River Dairy expansion

No EIS required

Casey Thorson **Letter 1230**

I am an owner of Black Diamond Industries. We service multiple Riverview locations for lawncare services and snow removal needs. I suport the expansion of West River. Riverview has been nothing but great to work alongside.

It is great to see them bring employment opportunities to the surrounding communities.

Karen Camos **Letter 1231**

I support West River Dairy expansion

No EIS required

Blanca Garcia **Letter 1232**

I support West Riverview expansion

No EIS required

Carlos Angel Alba Mora **Letter 1233**

I support the West River Dairy expansion

No EIS required.

Andres Barrios Hverra **Letter 1234**

I fully support West River Dairy expansion

Yonatan Ordonez **Letter 1235**

I fully support West River Diary expansion

Evelyn Serna **Letter 1236**

I support the West Riverview expansion

Jason Pielt **Letter 1237**

I support this project. No EIS is needed.

Concerned Citizen **Letter 1238**

How big is too big? Require an EIS. If there truly is no environmental concern a completed EIS will show that, yet the EAW documents are filled with concerns about water allotment, catch basins, and manure proximity to bodies of water. Simply stated the reluctance to do an EIS implies there is negative environmental impact to be found within the scope of the West River expansion. If all the energy that has been put in to avoid an EIS was put towards one, it would be done already. The reputation of Riverview has always been to go above what is "required" in order to do good work, here is the chance to do such a thing and it is being fought, why?

There should be an increased concern for a project of this size within such proximity to impaired waters such as the Pomme de Terre River which continue on into the Minnesota and Mississippi Rivers. As seen with the large manure spill near Pennock a year ago that has gone rather under the radar, accidents can and do happen. What happens when an event of similar scale, 1+ million gallons spills again, but this time into field drainage tiling that goes to county ditches and into the Pomme de Terre? It is the duty of Minnesotans to ensure we are good stewards of waterways that millions of people both in state and downstream count on. These rivers and waterways are crucial to the Midwest in being used to move goods, provide jobs, feed a nation. Causing irreversible damage needs to be avoided. Any action that will cause negative impacts should be explored, alternatives found, and plans changed. An EIS should be required.

The above only touches on the water impacts, there is also road/traffic, site noise, and community impacts that need to truly be evaluated. Please require an EIS before something goes wrong and can't be undone.

Justin Englebert **Letter 1239**

My name is Justin Englebert, and I am the Key Account Manager for Perdue Animal Nutrition, a leading dairy feed supplier serving agricultural operations in Minnesota like Riverview. I am writing in support of their proposed West River Dairy expansion in Stevens County.

Through our work in the agricultural sector, we depend on a strong and stable livestock industry. Operations like Riverview's create consistent economic activity that supports local jobs, drives investment, and allows businesses like ours to grow and reinvest in our communities.

The proposed expansion represents a meaningful economic benefit to the region. It will generate demand for local vendors, support both construction and long-term employment, and contribute to the vitality of rural communities that rely on agriculture.

From our direct experience, Riverview is a professional and reliable partner that contributes positively to the communities where it operates. Their presence strengthens the local economy and supports a broad network of agricultural and service-related businesses.

Projects like this are essential to maintaining a competitive and sustainable rural economy in Minnesota. Continued investment in agriculture ensures that local businesses can continue to provide jobs, services, and economic stability close to home.

No EIS is needed as the state environmental review process is rigorous and very sufficient. I respectfully encourage your support and approval of this important project.

Sincerely,
Justin Englebert

Don B. **Letter 1240**

I support this project Do not need EAF

Yohnny Serna Vite **Letter 1241**

I support the West Riverview expansion

Ricardo Camrgu **Letter 1242**

I support the west River expancion

Joaquin Ortega Rerez **Letter 1243**

I support the West River expansion

Diego Serva **Letter 1244**

I support the West Riverview expansion

Alan Stokke, Prairie Pest Control **Letter 1245**

My name is Alan Stokke, and I am the owner/operator of Prairie Pest Control, a company that provides pest control services to agricultural operations throughout Minnesota, including Riverview.

I am writing in support of Riverview's proposed West River Dairy expansion in Stevens County.

Through our work within the agricultural industry, we understand firsthand how important a strong and stable livestock sector is to rural communities and local businesses. Operations like Riverview create reliable economic activity that supports local jobs, encourages investment, and allows small businesses like ours to continue growing and reinvesting in the communities we serve.

Our company has had direct experience servicing Riverview locations, and we have consistently found their facilities to be extremely well maintained, organized, and professionally operated. Cleanliness and sanitation are clearly a priority within their operations, which is something we see firsthand while performing pest control services at their facilities. Their attention to maintaining high operational

standards reflects positively on both their management and their commitment to responsible agricultural practices.

This proposed expansion represents a significant economic opportunity for the region. It will increase demand for local vendors and service providers, support both construction and long-term employment, and strengthen the rural communities that depend heavily on agriculture.

Based on our direct experience working with Riverview, they have consistently proven to be a professional, responsible, and dependable partner. Their operations contribute positively to the communities where they do business and help support a broad network of agricultural and service-related industries.

Projects like this are essential to maintaining a competitive and sustainable rural economy in Minnesota. Continued investment in agriculture helps ensure that local businesses can continue providing jobs, services, and economic stability close to home.

In my opinion, an Environmental Impact Statement (EIS) is not necessary, as Minnesota's environmental review process is already thorough and rigorous. I respectfully encourage your support and approval of this important project.

Sincerely,
Alan Stokke
Prairie Pest Control

Randy Thymian **Letter 1246**

McGinnis Appliance has been involved in the majority of Riverview's projects from the very beginning. With each project, Riverview has consistently chosen the path of quality and continuous improvement rather than taking the easy way out. Their commitment to asking, "how can we be better?" sets the tone for every collaboration. Working with a partner who values doing things the right way without short cuts-makes our work smoother and more efficient. Riverviews dedication to excellence keeps projects on track and reflects the integrity they bring to our community. Riverview plays a vital role in supporting small businesses throughout west -central Minnesota their long-standing presence and community first mindset makes meaningful difference. At McGinnis Appliance, we PROUDLY SUPPORT this project because Riverview continually demonstrates that they are invested in our region's success and are here for the long haul. Thank you!

No EIS is needed.

Brett Sletta, Prairie Pest Control **Letter 1247**

My name is Brett Sletta, and I am an employee with Prairie Pest Control, where we provide pest management services for agricultural operations across Minnesota, including Riverview Dairy locations.

I wanted to express my support for Riverview's proposed West River Dairy expansion in Stevens County.

As someone who regularly works inside agricultural facilities, I've had the opportunity to see firsthand how Riverview operates on a day-to-day basis. Their locations are consistently clean, organized, and professionally maintained. In our line of work, those things matter, and it's clear that Riverview places a strong emphasis on sanitation, upkeep, and maintaining high standards throughout their operation.

Beyond that, businesses like Riverview play a major role in supporting rural communities and local economies. Expansions like this create opportunities not only for agriculture, but also for many local businesses and service providers that work alongside the industry every day. Projects like this help

support jobs, increase economic activity, and provide long-term stability for communities throughout the area.

From our experience working with Riverview, they have always been professional and easy to work with, and they continue to make a positive impact on the agricultural industry and the surrounding communities they operate in.

Agriculture is a critical part of Minnesota's economy, and continued investment in modern, well-managed operations is important for the future of rural communities. I believe the environmental review process already in place is comprehensive and appropriate, and I do not believe an Environmental Impact Statement is necessary for this project.

I respectfully encourage support and approval of the proposed West River Dairy expansion.

Sincerely,
Brett Sletta
Prairie Pest Control

Dick Metzger **Letter 1248**

I strongly support this project. An EIS is not needed. An EAW with over 900 pages of information is very thorough and ongoing oversight by MPCA is enough regulation to make this projects passage keeps it in compliance with current rules and regulation.

Jordan Staples **Letter 1249**

I support this Riverview Project and no EIS is required. EAW provided should suffice.

Brad Visser **Letter 1250**

As a contractor who has worked with Riverview I have not seen a company more dedicated to the environment than they are. I would strongly encourage permitting to allow for the betterment of rural minnesota. As they are strong members of the community and also a very positive impact to the local and state economy I believe permitting should be granted. Rural minnesota is in economic distress and having such great stewards of the land only makes sense. Thank you for your time.

Marcos Lazarro **Letter 1251**

I support the project, No EIS needed.

Amanda Bilek, Minnesota Corn Growers Association **Letter 1252**

Dear Mr. Peterson,

After reviewing the Environmental Assessment Worksheet (EAW) for the proposed expansion at West River Dairy, the environmental review of the project is comprehensive and complete. Additionally, Riverview has a proven track record of environmental stewardship, including continuous efforts to reduce water use and the construction of innovative water-recapture basins to reduce reliance on a single water source.

Based on the information provided in the EAW, the project includes appropriate design features, regulatory compliance measures, and mitigation practices to minimize environmental effects.

In particular, the EAW demonstrates that:

- Manure management, water quality protection, and land application practices are in accordance with current regulations;
- Air quality, odor management, climate adaptation and resilience have been considered and addressed; and
- Traffic, infrastructure, and surrounding land uses have been evaluated at a level appropriate for the scale of the project.

According to the MPCA's website, "the MPCA uses the EAW process to decide whether the project's potential environmental effects should be studied further through an environmental impact statement (EIS)." The Environmental Assessment Worksheet and full environmental review process assess the risks and conditions outlined for the construction and operation of a feedlot project. Minnesota's extensive environmental review process should remain the guide for the determination of environmental risk. We would encourage the MPCA commissioner to focus on the facts of the project and use objective, scientific judgment in the review process.

Please do not hesitate to contact Amanda Bilek, Senior Public Policy Director, at 952-460- 3604 or abilek@mncorn.org with any questions.

Sincerely,
Wesley Beck
President
Minnesota Corn Growers Association

Amando Chagoua **Letter 1253**

I support the project; no EIS needed

Madeline Maxeiner **Letter 1254**

A proposal of this magnitude, an increase of this size, must be evaluated as carefully as possible. Failing to require an EIS would cut corners and let many legitimate concerns go unaddressed. River View should expect to fulfill the most careful examination....not the least. Please do your job. Just on the basis of the extreme magnitude alone!

Rosalind Alexson **Letter 1255**

I can't believe there is any debate about an environmental assessment with an expansion of this size. That should be standard operating procedure. We shouldn't have to be petitioning for this. Of course we want to know how this will impact us. Our very lives depend on it. .

Brad Lewison **Letter 1256**

Riverview does an A+ job taking care of their Dairies and the cows they have. There is no reason this should be stopped from happening. Just look at the current sites that they have, they operate at the top of the class.

Randal Gorder **Letter 1257**

I have a Riverview Dairy (Waukon Dairy) 2 miles from my home and farm, I am also the Treasure and Clerk for the Waukon Township. I live north of the Dairy and do not smell any bad odors or hear any noise from their site. They have designed an operation with the community first, truck traffic is sent to a state highway, equipment noise is concentrated in between a silage pile and buildings. The cows are

happy and don't make hardly any noise. As a Town Board Member I had the same comment from multiple Waukon residents, "when are they going to bring the cows in" my response was they have been here for a month, 3 months and I even had to say almost a year that's how clean and quiet the Dairy is to live next to. They are always learning how to make it better, like water usage, to controlling dust on the gravel roads during corn and haylage harvest. Riverview has brought more to the community than just cows to milk, they have brought jobs, manure instead of commercial fertilizer and economic benefits that would not have been here without them.

Andrew Israels-Swenson **Letter 1258**

As a resident of Morris for 20+ years I am not here to bash Riverview at all. I think they bring a lot of diversity to our community and for that I am grateful. I do think that we as a diverse community need to gather all of the information on how this proposal will affect us. To do so we need independent environmental and economic impact statements from an outside source that is not Riverview. We all saw what happened with them in Arizona. Please do not put profit above the natural resources in West Central Minnesota.

Anna Kilian **Letter 1259**

Hi I am writing to express my concern with the riverview dairy expansion and request the MPCA do full environmental impact statement.

I was unable to attend the in person meeting due to it being full by the time I arrived before the start. I am disappointed that I was not able to listen in and gain a better understanding of the EAW and ask any questions. Thus I have had to gather information via this internet and the bias that come from those information sources. I witnessed many people not able to attend and gain more information about how the dairy expansion will affect the community both good and bad. Since we (as a community) could not learn I urge the MPCA to do a full environmental impact statement to better protect the residents of Morris and Stevens county. I feel more information is always good and taking precautions always saves time and money in the long run. I have seen this time and time again through my career. Taking time to better prevent an outbreak saves more time and money in the long run.

My specific concerns about the expansion is surface and ground water contamination. The more drainage tile that is put into farm field leads to more flooding as water moves faster than it historically did in the prairie pothole region of MN. I have concerns that the expansion will be part of contributing to this flooding as well as being affected by it. If manure or other contaminants get into the pomme de terre river that not only affects the Morris community but every other community in the watershed south of us. I would like to see Stevens county set a good example and be a good neighbor to those downstream from us. I also have concerns about how riverview will mitigate spills and negative environmental impacts. It's well know that leaks, and contamination will occur, it's more a matter of when not if. If a EIS is not done will this lower the responsibility that riverview will have to claim? I want to make sure that our environment will be cleaned up in the best way possible and responsible parties be held accountable.

Thank you for your time and for reading my concerns. I hope you choose to move forward with a full environmental impact statement.

Gary Dukes **Letter 1260**

To: Minnesota Pollution Control Agency (MPCA)

I am writing to formally express my strong opposition to the proposed expansion of the West River Dairy facility near Morris, MN. This project, which seeks to increase capacity from 7,855 cows to 18,855 (totaling over 26,000 animal units), is unprecedented in the state of Minnesota. Given the massive scale and the history of this specific site, I urge the MPCA to deny the permit or, at minimum, require a comprehensive Environmental Impact Statement (EIS) before further consideration.

1. **Water Quality and Watershed Impairment**

The facility is located within the Pomme de Terre River watershed, a system already listed as impaired for bacteria and nutrients.

- Waste Volume: The expansion would result in approximately 250 million gallons of liquid manure storage. The risk of catastrophic failure or "allowable" seepage from clay-lined basins poses a permanent threat to local groundwater and the Pomme de Terre River, which flows into the Minnesota River.
- Application Risks: In a region prone to heavy spring rains, the saturation of phosphorus and nitrogen in the soil leads to inevitable runoff, worsening toxic algal blooms downstream.

2. **Massive Groundwater Depletion**

Riverview LLP has requested to pump 226 million gallons of water annually. Concentrated pumping of this magnitude threatens the domestic wells of neighbors and the long-term viability of the aquifer for the broader community.

3. **Public Health**

The emission of hydrogen sulfide, ammonia, and nitrous oxide (N2O) from a facility of nearly 19,000 cows is a significant public health hazard.

- Respiratory Impact: Neighbors are subjected to particulate matter and noxious gases that are linked to asthma, bronchitis, and other chronic respiratory conditions.
- Climate Change: N2O is a greenhouse gas roughly 300 times more potent than CO2. Permitting a single facility to emit such a concentrated volume contradicts Minnesota's stated climate goals.

4. **Social Justice and Economic Disparity**

The expansion of "Mega-Dairies" is not a neutral economic development; it is a driver of rural inequity.

- Consolidation vs. Community: By flooding the market with industrial-scale milk production, Riverview systematically pushes small- and mid-sized family farms out of business. This destroys the fabric of rural Stevens County, replacing independent business owners with a transient, low-wage labor model.
- Environmental Justice: Industrial CAFOs are consistently sited in rural areas where residents have fewer resources to fight protracted legal battles. This places the "negative externalities" of corporate profit—pollution, road damage, and smell directly onto the shoulders of local citizens while the profits are exported.
- Lack of Oversight: In 2014, the MPCA Citizens' Board ordered an EIS for a much smaller version of this project. Since that board was abolished, the lack of a mandatory EIS for a project three times larger represents a failure of democratic oversight and a victory for corporate lobbying over public interest.

Conclusion

The MPCA must recognize that the "West River Dairy Expansion" is not a standard agricultural project; it is an industrial experiment at a scale Minnesota has never seen. I urge that a full EIS be conducted to study the cumulative impacts on our water, our climate, and our rural social structure.

Sincerely,
Gary Dukes

- **Watershed Impairments: MPCA Pomme de Terre River Watershed Report**
- **MPCA Environmental Assessment Worksheet (EAW): MPCA Environmental Review Projects**
- **Minnesota EQB Monitor: EQB Monitor Archives**
- **MN DNR Permitting and Reporting System (MPARS): DNR Water Appropriation Permit Search**
- **City of Morris Water Usage: City of Morris Public Works - Water Reports**
- **Pomme de Terre River Impairments: MPCA Pomme de Terre River TMDL Report**
- **Regulatory History: EPA FOIA Records (Site Assessments)**
- **Rivera, J. E., & Chará, J. (2021). CH4 and N2O emissions from cattle excreta: A review of main drivers and mitigation strategies in grazing systems. Frontiers in Sustainable Food Systems, 5. https://doi.org/10.3389/fsufs.2021.657936**
- **van der Weerden, T. J., Luo, J., Dexter, M., & Rutherford, A. J. (2014). Nitrous oxide, ammonia and methane emissions from dairy cow manure during storage and after application to pasture. New Zealand Journal of Agricultural Research, 57(4), 354-369. https://doi.org/10.1080/00288233.2014.935447**
- **PMC. (2026). Disparities in exposure to concentrated animal feeding operations (CAFOs) and other environmental justice variables. PubMed Central. https://pmc.ncbi.nlm.nih.gov/articles/PMC12413751/**

Martha Koehl — Letter 1261

I am one of the closest neighbors to West River Dairy, living in Horton Township just one mile from the proposed dairy expansion site. I grew up in Stevens County, and have lived here my entire life, having been a close neighbor to Riverview since 1995 when the first dairy was built. I have been part of the Riverview team for over a decade, choosing to return to my hometown after attending college out of state. Stevens County is a special place; made that way by the people that live here and the opportunities they've created through business and community growth to set current and future generations up for success.

Please see my attached comments on why the EAW shows that an additional EIS is not needed.

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Public Comment in Support of the West River Dairy Expansion

Submitted to: Charles Peterson, MPCA Resource Management and Assistance Division

I am writing in support of the proposed West River Dairy Expansion in Synnes Township, Stevens County, and to respectfully urge the MPCA Commissioner to issue a negative declaration on the need for an Environmental Impact Statement. As both a neighbor living one mile from the facility and a member of the Riverview team, I can speak to the care with which this operation is managed and to the thoroughness of the environmental review that has been conducted. It is my considered view that the

EAW adequately identifies and addresses the project's potential environmental effects and that an EIS is not warranted.

The EAW Is a Thorough and Sufficient Environmental Review

Under Minnesota Rules, an EIS is required only when a project has the potential for significant environmental effects that cannot be adequately anticipated, controlled, or mitigated through ongoing regulatory authority. The EAW before the Commissioner addresses every resource category required by Minnesota law and demonstrates, with supporting technical data, that each potential effect is localized, controllable, and well within existing state and federal regulatory limits. The document includes AERMOD dispersion modeling for air quality and odor, stormwater hydrology analyses, groundwater appropriation data, manure management acreage calculations, and cultural and natural resource reviews. These are not cursory treatments; they are detailed, conservative, and supported by professional engineering work. The EAW does precisely what Minnesota's environmental review program intends it to do: it lays out the facts and demonstrates that any potential effects from the project are mitigated and controlled and would not rise to the level of significance that would require further study.

Firsthand Observations as a Neighbor and Employee

I offer these comments as someone who has lived near Riverview's farms my entire life. I have personally observed the environmental practices that the EAW describes.

Manure management and nutrient planning. I have seen how carefully manure is handled at Riverview's farms. Application is done by knife injection at agronomic rates in accordance with an MPCA-approved Manure Management Plan. Manure is sampled regularly, and application rates are watched carefully. Local farmers have made far more acres than required available for application, which provides a significant buffer and eliminates the need to apply on unsuitable fields or during winter months. These are not abstract commitments in a permit document; they are practices I have witnessed carried out year after year by people who take the stewardship of the land seriously.

Odor control. Riverview's use of impermeable synthetic covers on liquid manure storage areas, combined with knife injection during land application and consistent housekeeping practices, keeps odor well managed. The EAW's AERMOD modeling confirms what my own experience tells me: odor levels at neighboring residences remain below the state's faint-odor threshold. Living where I do, I would be among the first to know if that were not the case.

Water quality and wellhead protection. The EAW demonstrates that permanent stormwater basins, sized more than twenty percent above what is required for a 25-year storm event, will capture runoff and reduce both annual runoff volume and modeled erosion compared to the current row-crop condition. The liquid manure storage areas are constructed with clay liners that exceed the required minimum, perimeter drain tile for monitoring, and fourteen months of storage capacity rather than the required nine.

Economic Benefits to the Community

The expansion will create skilled local employment and generate sustained demand for crops grown by area farmers. It replaces a significant volume of synthetic fertilizer with manure-based fertility, reducing input costs for local farmers. Approximately 2,200 acres of row crops will be converted to alfalfa, which sequesters carbon and reduces tillage. These are real, measurable benefits to the rural Stevens County economy and to the farming landscape of this region.

Regulatory Authority Is Sufficient

The EAW identifies a comprehensive package of overlapping permits and approvals governing this project, including an MPCA Individual NPDES Feedlot Permit, a Construction Stormwater Permit, DNR Water Appropriation amendments, a DNR Dam Safety permit, a Stevens County Conditional Use Permit, and others. Each carries enforceable conditions, monitoring obligations, and inspection requirements. Riverview has operated the existing West River Dairy under these frameworks since receiving a negative declaration in 2003, compiling more than two decades of permit compliance. That record of compliance provides additional confidence that the regulatory structure is sufficient to address the expansion's environmental effects.

Conclusion

The West River Dairy Expansion EAW is a complete, well-documented, and thorough environmental review. It identifies the project's potential effects, quantifies them against applicable standards, and demonstrates that project design, mitigation measures, and existing permit programs reduce those effects to levels that are not significant. As a neighbor and team member who has seen Riverview's commitment to environmental responsibility firsthand, I respectfully urge the MPCA Commissioner to issue a negative declaration on the need for an EIS and to allow the project to proceed under its proposed permit conditions.

Ben Weiland — Letter 1262

Dear Mr. Peterson,

My name is Ben Weiland, and I am the owner of Weiland Farms. We provide essential services and products to agricultural operations across Minnesota, including Riverview. I am writing today to express my full support for their proposed West River Dairy expansion in Stevens County.

Our business has been rooted in the Minnesota agricultural sector since 1997. Over nearly three decades, we have seen firsthand that a strong and stable livestock industry is the backbone of our rural economy. Operations like Riverview's create the consistent economic activity that allows businesses like ours to grow, hire local workers, and reinvest in our communities.

The proposed expansion represents a meaningful economic benefit to the region. Beyond the dairy itself, the project will generate significant demand for local vendors and support both immediate construction jobs and long-term employment. This growth is vital to the health of rural communities that rely on a thriving agricultural network.

From our direct professional experience, Riverview is a reliable and responsible partner. Their presence strengthens the local economy and supports a broad network of service-related businesses. Projects like this are essential to maintaining a competitive and sustainable rural economy in Minnesota.

Furthermore, I believe the state's current environmental review process is rigorous and more than sufficient to address any concerns; therefore, no Environmental Impact Statement (EIS) is needed. I respectfully encourage your support and approval of this important project.

Sincerely,
Ben Weiland Owner, Weiland Farms

Logan Tosel — Letter 1263

As a local business owner I have had the opportunity to do work for Riverview the past year. My personal experience has been nothing short of exceptional with them. The mentality that I have come up with is if you do your job they'll do there's. I personally think that we can look at the West River

Expansion the same way. The integrity of the company gives me confidence that they will uphold regulations to protect their neighbors, community, and natural resources. I support the West River Expansion.

David Jungst **Letter 1264**

"This permit requires the facility to be designed, operated, and maintained to prevent discharge to waters, except in an extreme storm event."

I have lived in this part of Minnesota for over 50 years. I know West central Minnesota gets extreme weather.

This facility, the Riverview LLP West River Dairy, will see extreme storm events and it will cause damages to the surrounding area. Just last summer in two days, July 27 and 28, the City of Morris got over seven inches of rainfall. When the storage ponds at this site over top, the storm water and manure will flow downstream to the east where just across the road is a large county tile drain pipe and draw that flows to the Pomme de Terre River less than four miles away.

Conversely, I have seen drought when the Pomme de Terre River completely stopped flowing and was reduced to puddles in its channel just downstream from this facility where the well is to be located to supply it.

An EAW (Environmental Assessment Worksheet) is insufficient for this site. The magnitude of this animal confinement operation, which will be the largest in the state of Minnesota, warrants that an Environmental Impact Statement should be required before a permit for this feedlot expansion can be issued.

Laura Aldrich-Wolfe **Letter 1265**

The proposed expansion more than doubles the number of animals held in a confined area, and brings the total to a number that poses an inherent risk to water quality and environmental quality more broadly. We need to reverse the way that animals are managed on the landscape in order to reintegrate their waste safely into the ecosystem. The proposed dairy expansion does the opposite and in a region of Minnesota facing ongoing challenges of water quality degradation. Poor water quality affects Minnesotan public health and biodiversity, impacting present day and future generations. As a scientist who studies effects of nitrogen on ecosystems, I strongly oppose this expansion.

Oscar Galan Trejo **Letter 1266**

I believe it is important to protect the evironment by ensuring proper manure management, preventing water contamination, and reducing air emissions and odors. Ongoing monitoring and sustainable practices should be required to minize environmental impact and protect community healt.

Thank you for cosnidering my comment.

Kari Visser **Letter 1267**

I support the Riverview West River expansion I feel like the plan is good and no EIS is needed

Julia Murillo **Letter 1268**

I support the West River Dairy expansion

No EIS Require

Bernardo Laines Alonzo **Letter 1269**

I soport the West Riverview expansion.

No EIS Required

Marc Stevens **Letter 1270**

EAW

I am in favor of the project. Riverview is a neighbor that I grow feed to sell to them and hope to get manure back. With the building of the processing plant south of Morris what better place to produce the product, close to the plant.

Feedlot permit

Riverview has an excellent record of being environmentally friendly and following and even exceeding regulations. I support giving Riverview the feedlot permit.

Dustin Hollermann **Letter 1271**

The EAW is very thorough. No additional benefit would result from an EIS. Please proceed for permit review.

Megan Horsager **Letter 1272**

I support the West River expansion without any additional EIS. As a neighbor of a Riverview dairy it is my experience that Riverview goes above and beyond the expectations of the MPCA when it comes to issues such as manure management and water quality. The extreame care and causion I have wittnessed Riverview exersize while applying manure is greater then my other operations in the area. Please consider the evidence and track record of Riverview when issuing this permit.

Daniel Granados **Letter 1273**

I support the west Riverview Expansion

No EIS Required

Jim Birkemeyer, R & J Broadcasting, LLC. **Letter 1274**

Dear Mr. Peterson,

My name is Jim Birkemeyer, and I am the Owner of R&J Broadcasting, LLC , a Radio Station that serves Minnesota's and North Dakota's agricultural community. I am writing to express my strong support for the proposed West River Dairy expansion in Stevens County.

Our working relationship with Riverview has given us firsthand insight into how they operate. In an industry built on trust, Riverview stands out for their honesty and transparency. We have always found them to be straightforward in their communications and clear about their operational goals, which allows us to collaborate effectively and reliably.

Beyond the numbers, Riverview demonstrates a genuine community commitment. They don't just operate in rural Minnesota; they invest in it. This expansion will create consistent economic activity that supports local jobs and drives the kind of investment that allows businesses like ours to grow and

reinvest in our own neighborhoods. Their presence strengthens the local economy and supports a vital network of agricultural and service-related businesses.

From our direct experience, Riverview is a professional partner that prioritizes doing things the right way. Projects like this are essential to maintaining a competitive and sustainable rural economy. We believe the state's environmental review process is rigorous and more than sufficient to oversee this project, and therefore, no EIS is needed.

I respectfully encourage your support and approval of this expansion, as it represents a positive step forward for our industry and our rural communities.

Sincerely,
Jim Birkemeyer]
R&J Broadcasting, LLC

Kelsey Olson, CURE **Letter 1275**

Mr. Peterson,

CURE is a rurally based, non-profit organization dedicated to protecting and restoring resilient towns and landscapes by harnessing the power of the people who care about them. On behalf of CURE, I am submitting the following comments regarding the proposed West River Dairy expansion environmental review. We urge the MPCA to take a comprehensive approach that reflects the long-term health of Minnesota's water, land, climate, and rural communities—doing so would be best accomplished with an Environmental Impact Statement (EIS) analysis to inform MCPA's decisions.

Riverview, LLP has applied to expand its West River Dairy animal feedlot to 26,397 animal units, housing 18,855 cows. If approved, this would be the largest feedlot operating in Minnesota. CURE urges the Minnesota Pollution Control Agency to mandate that the West River Dairy expansion undergoes an EIS to fully assess the risks of the dairy expansion. An EIS would ensure that all potential impacts of the proposed expansion are considered, including impacts to air, water, and soil quality, as well as the socioeconomic impacts to rural dairy farmers and the market influence such an operation would have on the milk industry in Minnesota. The preparation of an EIS would support the mission of the MPCA to ensure that every Minnesotan has healthy air, sustainable lands, clean water, and the ability to plan for, and not merely react to, drastic climate events—all of which may be negatively impacted by a facility of this size. Mitigating these harms is only possible if they are correctly identified and evaluated.

According to the state of Minnesota's 2026 Climate Action Framework, manure accounts for 4.1 million metric tons of CO2-equivalent (CO2-e) emissions, the third highest producer of greenhouse gases (GHGs) in the state, with nitrous oxide (N2O) from agricultural soil management, including the application of manure as fertilizer, being the leader in GHG emissions at 15.2 million metric tons CO2-e.2 The production of manure—roughly 520,000 tons annually—may result in significant amounts of methane emissions, strongly undermining the state's climate goals. Additionally, this manure, when held on the land, threatens soil quality and the drinking water of the entire region. And for an area that has already seen small dairy farms going out of business, this expansion further strains the local farming community and consolidates the dairy market in Minnesota. CURE believes that an EIS should be performed for not only this expansion, but any future proposals of this size. The impacts on the economy and land can only be understood through the kind of rigorous examination in an EIS.

I. Water Use and Availability

The scale of the proposed expansion raises serious concerns about groundwater withdrawals in a region already experiencing overuse/stress on aquifers. Large dairy operations require significant volumes of water for animal consumption, cleaning, and manure handling. Riverview is proposing that 226 million gallons of water a year be extracted from an off-site well.[1] This proposal is more than 100 times that of the neighboring city, and almost as much as the entire City of Morris.[2]

While the proposer claims that they "... strive [] to be good stewards of natural resources, including water,"[3] the company's recent actions in Arizona contradict this. Earlier this year, the Arizona Attorney General settled with Riverview, forcing the company to pay $11 million to fund new wells and haul water to the residents of Willcox, after depleting the town's water supply for use at the company's Sulphur Springs Valley dairies.[4]

In this instance, the MPCA should require a detailed, cumulative impact analysis of groundwater use, including potential drawdown effects on neighboring wells, wetlands, and surface waters. Protecting water as a shared public resource must remain a priority over concentrated private industrial use.

II. Manure Management, Water Quality and Climate Change

West River Dairy sits adjacent to the Pomme de Terre River, an impaired waterbody that is already considered one of the most polluted tributaries of the Minnesota River. The MPCA reports that within a 10-year period from 2007 to 2017/2018 there was an annual increase of 11% in nitrate- nitrogen, the leading cause of water pollution in Minnesota.[5] Further review of existing and foreseeable nitrate-nitrogen pollution is vital to determining the potential impacts of the proposed dairy expansion to this already stressed ecosystem.

Manure production and storage can also have significant impacts on water quality and greenhouse gas emissions.[6] That's why the state's updated Climate Action Framework specifically names fertilizer and manure management, as well as management of agricultural landscapes, as ways to reduce emissions and minimize nitrogen runoff and pollution.[7] Guiding these priorities is Minnesota's goal to reduce statewide GHG emissions by 50% by 2050.[8]

The expansion appears to be contradictory to these goals, substantially increasing the volume of manure generated by West River Dairy and heightening the risk of nutrient runoff, spills, and leaching into

[1] MPCA, Environmental Assessment Worksheet: Alternative EAW Form for Animal Feedlots: West River Dairy Expansion [p.35] 2.2.2026.
[2] Calculation estimate achieved from 700,000 gallons/day x 365 days in a year = 255,500,000 gallons https://www.wearewaterwcmn.com/morris-water#:~:text=is%20less%20hard.-,%E2%80%8B,is%20700%2C000%20gallons%20per%20day.
[3] MPCA, Environmental Assessment Worksheet: Alternative EAW Form for Animal Feedlots: West River Dairy Expansion [p.18] 2.2.2026.
[4] Kris Mayes, Attorney General, State of Arizona, https://www.azag.gov/ag-mayes-announces-riverview-settlement.
[5] MPCA, Watershed Information: Pomme de Terre River, https://www.pca.state.mn.us/watershed-information/pomme-de-terre-river.
[6] U.S. EPA, Agriculture Sector Emissions, https://www.epa.gov/ghgemissions/agriculture-sector-emissions.
[7] State of Minnesota, 2025 Climate Action Framework, https://climate.state.mn.us/sites/climate-action/files/cc-mn4-04.pdf.
[8] MPCA, Climate change initiatives, https://www.pca.state.mn.us/air-water-land-climate/climate-change-initiatives.

groundwater. And because manure emits methane, a potent greenhouse gas, increasing the amount of manure produced is likely to have significant impacts on our state's climate goals.[9]

The MPCA's Feedlot Permit explains that "This permit requires the facility to be designed, operated, and maintained to prevent discharge to waters, except in an extreme storm event." With extreme rain events becoming more frequent, considerations of the impact of possible discharge to waters need to be considered.[10]

The proposed adaptive strategy, as detailed in the EAW—covering Liquid Manure Storage Areas and sizing stormwater basins at 20% above a 25-year, 24-hour storm—does not adequately reflect current climate realities. Out of 12 "mega-rain" events to have occurred in Minnesota since 1860, where 6 inches or more of rain fell during one event, five have taken place since 2000 and the frequency of heavy rain events is expected to double by 2100.[11] Extreme weather events that included heavy rain and flooding occurred around the project location in April and June of 2023[12] and again in July 2025[13], demonstrating the increased frequency of unprecedented and unpredictable weather events.

According to the Minnesota Department of Natural Resources (DNR), mega-rainfall events like these are now more than 2.5 times as common as they were in the late 20th century,[14] with projections showing continued increases in both frequency and intensity.[15] Designing infrastructure using standards based on outdated precipitation data leaves a high risk of pollution overflow and water contamination.

Given that extreme precipitation events are growing more frequent and intense, an EIS is needed to ensure the suitability of proposed adaptations and to understand the potential impacts to surrounding aquifers of a discharge during such an event. Minnesota's current and predicted forecasted extreme weather events need to be correctly applied to proposed mitigation, for full and accurate evaluation. The current EAW does not do this.

According to the state of Minnesota's 2026 Climate Action Framework manure accounts for 4.1 million metric tons of CO2-equivalent emissions, the third highest producer of greenhouse gases in the state,

[9] State of Minnesota, 2025 Climate Action Framework, https://climate.state.mn.us/sites/climate-action/files/cc-mn4-04.pdf.
[10] Minnesota Department of Natural Resources (MN DNR), Climate Trends: What is Happening? https://www.dnr.state.mn.us/waters/watermgmt_section/shoreland/climate-trends/what-happening.html.
[11] Lucinda B. Johnson et al., "Impacts of Climate Change on Northern Ecosystems," (data derived from Wuebbles & Hayhoe, 2004).
[12] U.S. National Oceanographic and Atmospheric Administration, National Centers for Environmental Information, Storm Events Database – Search Results for Stevens County, Minnesota, https://www.ncei.noaa.gov/stormevents/listevents.jsp?eventType=%28Z%29+Flood&eventType=%28C%29+Heavy+Rain&beginDate_mm=01&beginDate_dd=01&beginDate_yyyy=2016&endDate_mm=01&endDate_dd=31&endDate_yyyy=2026&county=STEVENS%3A149&hailfilter=0.00&tornfilter=0&windfilter=000&sort=DT&submitbutton=Search&statefips=27%2CMINNESOTA.
[13] MN DNR, Severe Thunderstorms and Flooding, July 27-28, 2025, https://www.dnr.state.mn.us/climate/journal/severe-storms-flooding-july-27-28-2025.html.
[14] MN DNR, Climate Summaries and Publications, Historic mega-rain events in Minnesota, https://www.dnr.state.mn.us/climate/summaries_and_publications/mega_rain_events.html#:~:text=Mega%2Drains%20more%20common%20since%202000&text=Put%20another%20way%2C%20these%20major,decades%20of%20the%2020th%20century.
[15] Minnesota Go, Climate Change Trend Analysis, https://www.minnesotago.org/application/files/6016/4520/5690/Climate_Change_Jan_2022.pdf.

with nitrous oxides from agricultural soil management, including the application of manure as fertilizer, being the leader in GHG emissions at 15.2 million metric tons.[16]

At a time when Minnesota is working to meet climate goals, approving expansions of concentrated animal feeding operations without a full accounting of lifecycle GHG emissions is inconsistent with those commitments. The MPCA should require a thorough climate impact assessment and consider mitigation measures, including limits on herd size growth and investments in emission-reducing technologies. The MPCA must ensure that nutrient management plans are not only technically sufficient on paper but enforceable and resilient in practice and that they align with the state's climate goals, specifically: initiative 2.3.2, manage fertilizer and manure to reduce emissions; and 2.4.1 manage agricultural landscapes to minimize nitrogen runoff and pollution. The proposed mitigations for manure management, which include applying manure fertilizer on fields that are in operation and considering rates of application, still introduce increased manure and therefore N2O into the soil, water, and atmosphere.

III. Species of Special Concern

The Pomme de Terre River, just southeast of Morris, is home to one of the last, if not the only remaining reproducing population of Elktoe (Alasmidonta marginata) freshwater mussels in the Minnesota River watershed.[17] Elktoe mussels are listed as threatened on the MN DNR Rare Species Guide.[18] A primary threat to the Elktoe mussel is non-point source loading from agricultural practices including agricultural runoff from fertilized crops and animal waste (manure) introduced into water ways.[19] The Environmental Protection Agency specifically states that freshwater mussels are sensitive to changes in water quality including altered water flow, sedimentation and the introduction of contaminants, including those from land use activities from agriculture.[20] In fact, in a study published by the MPCA, DNR, and Macalester College stated, "We find that current state water quality standards may not be sufficiently protective of mussels."[21] An EIS is the way to evaluate and propose alternatives to management to ensure all possible protective measures are in place.

The federally protected Northern Long-Eared Bat has also been identified in the project area. According to a White Paper on the Northern Long-Eared Bat from the Little River Band of Ottawa Indians, "Energy extraction activities and agricultural activities are also frequently responsible for harmful and toxic substances entering water networks such as fertilizer runoff, brine, or other chemicals. Bats have been

[16] Minnesota Pollution Control Agency. (2026). 2026 Minnesota Climate Action Framework. p.18. GHG emissions and sequestration from natural and work lands graphic, https://climate.state.mn.us/sites/climate-action/files/cc-mn4-04.pdf.
[17] Minnesota River Basin Data Center, Mussel Survey, https://mrbdc.mnsu.edu/sites/mrbdc.mnsu.edu/files/public/pdf/askexpert/mussel%20survey.pdf.
[18] MN DNR, Rare Species Guide, 29 results for mussel, https://www.dnr.state.mn.us/rsg/filter_search.html?action=doFilterSearch&allstatus=Y&mussel=Y.
[19] New York Department of Environmental Conservation, Species Status Assessment, Elktoe Mussels, https://extapps.dec.ny.gov/fs/programs/dfw/SWAP2025/Freshwater%20Mollusks%20and%20Crustaceans/Elktoe.pdf.
[20] U.S. EPA Office of Pesticide Programs, EPA's Vulnerable Species-Freshwater Mussels, Sept. 24, 2024, https://storymaps.arcgis.com/stories/b8083203d9e147b3894b4f67c1402538.
[21] Bakshi, B. et al., Freshwater Mussels, Ecosystem Services, and Clean Water Regulation in Minnesota: Formulating an Effective Conservation Strategy, Water 2023, 15(14), 2560; https://doi.org/10.3390/w15142560.

observed using artificial water sources, including industrial holding ponds and pits."[22] An EIS is the only way to thoroughly investigate the agricultural impacts on this federally protected species.

IV. Economic and Market Impacts

The continued expansion of Riverview raises concerns about corporate consolidation and the long-term viability of independent family farms. Increasing concentration in the dairy sector can suppress milk prices, limit market access, and reshape rural economies in ways that reduce resilience and local ownership.[23] The local community has already seen a loss of small, family dairy operations that are unable to compete with the market of inexpensive milk that is produced by an operation of this capacity.[24] Statewide, we have lost 1,300 farms in the last two years alone.[25] The economic impacts of corporate consolidation on this scale severely constrain the health and competitiveness of Minnesota's milk market.[26] The MPCA should consider these broader socioeconomic impacts as part of its environmental review, recognizing that environmental sustainability and economic fairness are deeply interconnected.

Conclusion

The expansion of the West River View Dairy operation would result in the largest confined animal feedlot operation in Minnesota with 18,855 dairy cattle. This will undoubtedly have cumulative impacts on the watershed. The impacts of an operation of this size ripple through natural water systems, including the entirety of the 130-mile long Pomme de Terre River which flows past not only the existing West River Dairy site but also Riverview's Louriston Dairy.[27]

In closing, CURE asks the MPCA to uphold its responsibility to protect Minnesota's natural resources and communities by applying rigorous scrutiny to this proposal through an EIS. The proposed climate adaptation strategies detailed in the EAW require further investigation through an EIS to determine the efficacy of the proposed adaptations.

Decisions made today will shape water quality, climate resilience, and rural livelihoods for generations. A cautious, science-based approach is not only warranted—it is essential.

/s/ Kelsey Olson
Kelsey Olson

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[22] Cornman, A. M. 2014. A white paper on the northern long-eared bat, forest management, and threat interactions. Little River Band of Ottawa Indians Natural Resources Report No. 2014-2, https://www.researchgate.net/publication/317094298_A_white_paper_on_the_northern_long-eared_bat_forest_management_and_threat_interactions.

[23] Land Stewardship Project, Flooding the Market: How Dairy Consolidation is Drowning Minnesota's Farmers & Rural Communities, Apr. 23, 2026, https://landstewardshipproject.org/wp-content/uploads/Milk-Flood-C-4-23-26.pdf.

[24] Debbie Weingarten, 'There are ghosts in the land': how US mega-dairies are killing off small farm, THE GUARDIAN, June 1, 2021, https://www.theguardian.com/environment/2021/jun/01/there-are-ghosts-in-the-land-how-us-mega-dairies-are-killing-off-small-farms.

[25] Kent Erdahl, Minnesota has lost 1,300 farms in two years, many more on the brink, KARE11, Feb. 25, 2026, https://www.kare11.com/article/news/local/breaking-the-news/minnesota-has-lost-1300-farms-in-two-years-many-more-on-brink/89-20999e54-3f22-4b0c-84dc-285814f3b723.

[26] Hannah Tremblay, Dairy's Decline: The Harsh Reality for Farmers and What We Can Do About It, FARM AID, June 23, 2023, https://www.farmaid.org/blog/dairys-decline-harsh-reality-for-farmers/.

[27] See generally MPCA, Pomme de Terre River Watershed: Stressor Identification Update, Feb. 2024, https://www.pca.state.mn.us/sites/default/files/wq-ws5-07020002b.pdf.

Director of Environmental Stewardship

Eugene Strowbridge
Policy & Outreach Strategist

Gary Wertish, Minnesota Farmers Union **Letter 1276**

Dear Commissioner Kessler:

On behalf of Minnesota Famers Union (MFU) and responding to a vote from our Full Board, I write to request that you require an Economic Impact Statement (EIS) for Riverview LLP's permit to expand their West River Dairy in Stevens County. This scale of expansion is unprecedented in our state and we believe strongly that Minnesotans deserve a fuller examination of its environmental, economic, and social consequences.

MFU is a grassroots organization that has represented Minnesota's family farmers, ranchers and rural communities since 1918. Our membership and our Full Board include family dairies, including many who are struggling to stay in business while they shoulder prices below their cost of production. This challenge is not new with the number of Minnesota dairies declining by nearly half in the last decade, dropping from 3,470 in 2016[1] to just 1,600 farms today.[2] And while farms are declining, cows are consolidating into fewer operations. This one company is permitted for nearly a third of Minnesota's dairy herd.[3]

This consolidation has consequences not just for those families, but also for rural schools, small businesses, veterinary practices, churches, and other institutions that make life possible in rural Minnesota. According to an analysis from 2020, the average Minnesota dairy generates $1.6 million in economic activity.[4] A more complete analysis of the economic and social consequences of this project is needed.

Beyond that, we believe there are important environmental concerns that an EIS would more fully address. Our members understand that livestock projects draw water year-round and we want to ensure that we are stewarding this shared resource and safeguarding sufficient supply for neighboring farms. We also understand that consolidating livestock increases the potential consequences of a natural disaster, zoonotic disease, or human disease affecting workers.

To close, this project is different than those that are approved through our existing processes. From my memory of that time, when we established our current regulatory framework for feedlots in the late 1990s no-one contemplated a nearly 19,000 cow dairy operation. That is more than 60 times the average size herd in our state.

This project is different and deserves distinct consideration and the full public comment afforded by an EIS. If you have any questions, please contact our Government Relations Director, Stu Lourey, at stu@mfu.org or (320) 232-2047. Thank you for considering the needs and perspectives of Minnesota's farm families.

Sincerely,
Gary Wertish
President, Minnesota Farmers Union

[1] Minnesota Dairy Industry Profile. Minnesota Department of Agriculture, 2016. https://www.mda.state.mn.us/sites/default/files/inline-files/dairyindprofile.pdf.
[2] Dairy Industry Consolidates. Dairy Star, 2026. https://dairystar.com/stories/dairy-industry-consolidates,30685?.
[3] Proposed dairy in Morris would become Minnesota's largest feedlot. Star Tribune, March 16, 2026. https://www.startribune.com/proposed-dairy-in-morris-would-become-minnesotas-largest-feedlot/601596774.
[4] The Role of Dairy Farmers In Minnesota's Rural Economy. University of Minnesota Extension, June 9, 2020. https://conservancy.umn.edu/server/api/core/bitstreams/8b58793b-073e-4c43-81fd-96e0ffe1d172/content.

William Pelowski **Letter 1277**

A lot of people are asserting that an EIS is unnecessary for what would be the largest cattle operation in MN.

If your teenager insists that they got all As on their report card, yet refused to show it to anyone, should we just believe them? Wouldn't they be proud of their accomplishments and be eager to show the outcome of their hard work?

It does nothing to promote trust to attempt to avoid scrutiny. There are no good reasons to skip an EIS. Moreover, the Riverview employees that submitted comments in favor of the expansion and skipping the EIS are very biased and would be unaffected by the environmental disaster. But I don't blame them. They are very likely under pressure from their employers to make these comments.

Beth Slocum **Letter 1278**

The proposed significant expansion of the existing Riverview Dairy, bringing the total number of cows to 18,855 (potentially raising the number of Animal Units to 26,397) requires a significant environmental review – a proper Environmental Impact Statement.

An EIS is the only way to insure that the people pf Minnesota can be confident that this precedent-setting expansion can be thoroughly reviewed for the potential environmental impacts on our soil, air and waters, as well as the socio-economic impacts on our family-run small dairy farms, our rural communities and our Main Street businesses.

This mega-dairy concentrates too many cows, too much aquifer-drawn water, and too much manure to be permitted without the in-depth assessment process of an EIS.

Too many cows – there is much conversation about the use of electronic data gathering on individual cows and the enhanced genetics and robotic milking that occurs 3 times a day, however, it is disturbing that a dairy CAFO of this size requires a FACILITY 16: RENDERING DEPOT. That is not a facility necessary on the small family-run dairies where every cow gets looked at twice a day – or gets a seasonal break – where the family can provide the direct assessment of each cow's demeanor and health.

And what about the air quality for the families living within 1+ miles of this giant dairy? What will be the impact of the massive amount of manure produced every day at this Riverview expansion?

Too much water – Minnesotans can be sure that the 226 million gallons of water per year required for this expansion will have a significant impact on the health of the aquifer, which is also used for private wells & irrigations wells. There is no data on the MN Dept of Ag website about well testing in the townships of Stevens County, which means there is no base line information about the flow rate or recharge rates of the private wells that could be affected by the dairy's drawn-down of water – a draw-down which is equivalent, per year, of the water use of the entire city of Morris, 5000 people.

An EIS can be used to determine how this potential use of water by Riverview could impact other water users, an essential piece of information.

The EIS review can also examine how the cost of the DNR water permitting for the profit of this dairy expansion compares to the cost of water to the city of Morris, ultimately paid by its residents.

Ultimately who will bear the costs of Riverview's water use...could it be local residents, as happened with Riverview's mega-dairy in Arizona :

"Her office (Arizona Attorney General Kris Mayes) has entered an agreement with Riverview LLP, a Minnesota-based dairy company that moved into the area over the last decade and quickly became a major driver of the Willcox groundwater basin's decline. Under the agreement, the company is agreeing to reduce its groundwater usage by fallowing 2,000 acres of land and maintaining best practices to conserve water. The company also agreed to deliver $11 million to residents affected by the company's overpumping that will pay to redrill wells, haul water and ensure the community has access to the critical resource. " https://insideclimatenews.org/news/10012026/arizona-agreement-with-dairy-farm-to-cut-groundwater-pumping/?emci=965383e4-2014-f111-a69a-000d3a57593f&emdi=e81935b0-a116-f111-a69a-000d3a1f0a97&ceid=2641375

Too much manure -- 18,855 cows will produce approximately 285,000 gallons per day –for a total of 202,744,000 gallons per year. Where will that manure go?? So far, the manure application maps show that all the fields included in the manure application plan are within one township – Synnes in Stevens County. There certainly is a problem with millions of gallons of manure application in such a small area – application that is limited by season, weather conditions and truck travel. How can it be possible to spread these millions of gallons of manure in a timely fashion? In appropriate ag rates? Who will supervise all that data? What will happen when adverse conditions require emergency drawdowns of manure in storage?

How many trucks will it take to haul all that manure? How many miles over township and county and state roads will that require? Who will pay those costs? Again, the folks who will profit from this operation will not bear the cost of road maintenance, nor the consequences of manure that must be spread unseasonably.

An EIS is required to answer these questions and to insure that all worst case scenarios can be mitigated.

Manure storage is a crap shoot – pardon the pun – and even if "covered" can pose serious health concerns to local residents. Lined concrete pits with covers have a certain half-life. "Concrete..., as told me by someone who actually builds manure pits, " is new or it's leaking."

Noxious, toxic gases are produced in those storage pits and seep into the air – and charge into the surrounding air when the pits are stirred. Here's the problem...

"Manure pits that hold livestock and poultry waste give off foul-smelling toxic air pollutants that can be deadly to farmworkers and local residents, who often are powerless to defend the health of their families from the noxious emissions."

https://www.ewg.org/news-insights/news/manure-pits-emit-deadly-pollutants

Having been part of a data-gathering group monitoring emissions from a local hog barn with a buried pit, I can, from experience, say with certainty that emissions occur. And in dairy barns they occur when barns and milking parlors are cleaned and manure moved to storage lagoons, where all those millions of gallons wait...

An EIS will give local folks a chance to understand the impact of the expansion on air quality and their health.

Too much manure spread in a small area also leads to water contamination, and with no baseline water testing in the townships of Stevens County and Synnes Township, in particular, local residents with private wells will have no baseline of nitrate testing to insure that their water is healthy to drink. It seems imperative that the MN Dept of Ag proceed with well testing and MPCA proceed with an EIS.

Benefits? Really? An EIS will tell.

The proposers suggest that there will be 40 jobs -- "40 families"-- coming with this expansion, but if you think about who really works on these CAFO sites, most are immigrant men, only a few of whom bring their families from their country of origin. These will not be farm families that can contribute to multiple local and Main Street businesses:

"...family-scale dairy farms can have a far larger positive economic impact in local communities. That's because they support a broad network of local businesses, from veterinarians and feed suppliers to equipment dealers and milk haulers. When these farms disappear, those economic benefits are lost. Research shows that larger industrial-scale operations tend to spend less locally, concentrating economic activity rather than distributing it across rural communities."

Land Stewardship Project Myth Buster, December 2019, "Myth: Mega-Dairies = Mega-Benefits for Rural Communities," https://landstewardshipproject.org/repository/1/3116/myth_buster_56_mega_dairy.pdf

And here's something to think about... do we really want to be the home base to the 5th largest global dairy:

"Mega-scale dairy farms are primarily concentrated in China, Saudi Arabia, Russia, the United States, and Southeast Asia. These regions combine access to capital, land, and regulatory frameworks that allow this model of scale.

Rank Farm / Farm Group Country Raw milk production (t/year)
1 Mudanjiang Mega Dairy Farm China ≈2,000,000
2 Almarai Saudi Arabia ≈1,470,000
3 Modern Dairy China ≈1,280,000
4 EkoNiva Russia ≈1,200,000
5 Riverview LLP USA ≈800,000–1,000,000
6 Rockview Family Farms USA ≈1,000,000
7 Huishan Dairy China ≈800,000
8 Al Safi Dairy Farm Saudi Arabia ≈550,000
9 Greenfields Dairy Farm Indonesia ≈400,000–450,000
10 Fair Oaks Farms USA ≈350,000–400,000

Why are European dairy farms absent from the global top 10 ranking?

One outcome of this ranking is the absence of European Union dairy farms from the global Top-10. This is not due to missing data, but to structural differences in production models.

European dairy farming is dominated by family-owned farms, operating under strict environmental, animal-welfare, and land-use regulations. Scale is achieved primarily through cooperative aggregation, rather than through ultra-large, centrally owned farms. As a result, even Europe's largest individual farms fall well below the production thresholds required for inclusion in a global Top-10 ranking based on raw milk output per farm. Nonetheless, the EU's dairy sector is highly efficient and will be addressed in future articles."

https://ruminants.ceva.pro/global-dairy-production

Maybe we want to think about our first model – "family-owned farms... through cooperative aggregation" :

"In 1890, the Danish American community in Clarks Grove established one of the first cooperative creameries in Minnesota. The Clarks Grove Cooperative Creamery used new technology and a well-organized cooperative system. It became a model for the Minnesota dairy industry. Ten years later, there were more than 550 cooperative creameries in the state."

https://www.minnpost.com/mnopedia/2015/06/banding-together-better-butter-clarks-grove-was-one-minnesota-s-first-cooperative-c/

So many questions can be answered by an EIS.

So much more information can be gained by an EIS.

Clearly we need an EIS for this Riverview Dairy expansion proposal.

Thank you.
Beth Slocum

Kristin Lamberty **Letter 1279**

I am concerned about the potential negative impact this expansion would have on our local environment. I don't feel like there has been enough information gathered about how this expansion would impact the lives of people living nearby or the overall ecosystem in which it would be located.

I am opposed to this expansion happening without further study.

Ron Visser **Letter 1280**

Riverview is good for the dairy industry in Minnesota. I have watched the dairy industry exist the far north of Minnesota, nearly all of North Dakota and the Black Hills area of South Dakota. I have watched the dairy industry take off in part of Idaho, Texas, Indiana, South Dakota and currently in Kansas. The traditional heavy dairy areas of the Midwest and Northeast have had a transition away from small tri-stall barns to the addition of longer free stall barn. This will likely continue in these areas. The harsh reality is the areas that are losing cows are smaller farms. The areas that are gaining cows add larger farms. The traditional cow areas have a similar dynamic. Making large dairy permitting difficult or impossible, will only harm the dairy industry in Minnesota and move it somewhere outside of Minnesota. Making it easier to permit a dairy in Minnesota will improve the entire industry. The dairy industry is the dairy farms along with the processing, veterinarians, nutritionists, ag lenders-dairy, diary shipment dealers/repairs, etc. that go with it. Riverview helps keep all of this in the state of Minnesota. I support the Riverview West River expansion. I feel like the plan is good and no EIS is needed.

Aloriberto Vite **Letter 1281**

I support West Riverview expansion

No EIS Required

Jose Luis Quinter **Letter 1282**

I support west River expansion

Jose Luis Martinez **Letter 1283**

I support the West Riverview expansion.

John H Beste **Letter 1284**

ATTN: Charles Peterson

My name is John Beste, and I am the owner of Famo Feeds Inc., a Livestock Feed manufacturing business serving agricultural operations in Minnesota like Riverview. I am writing in support of their proposed West River Dairy expansion in Stevens County.

Through our work in the agricultural sector, we depend on a strong and stable livestock industry. Operations like Riverview's create consistent economic activity that supports local jobs, drives investment, and allows businesses like ours to grow and reinvest in our communities.

The proposed expansion represents a meaningful economic benefit to the region. It will generate demand for local vendors, support both construction and long-term employment, and contribute to the vitality of rural communities that rely on agriculture.

From our direct experience, Riverview is a professional and reliable partner that contributes positively to the communities where it operates. Their presence strengthens the local economy and supports a broad network of agricultural and service-related businesses.

Projects like this are essential to maintaining a competitive and sustainable rural economy in Minnesota. Continued investment in agriculture ensures that local businesses can continue to provide jobs, services, and economic stability close to home.

No EIS is needed as the state environmental review process is rigorous and very sufficient. I respectfully encourage your support and approval of this important project.

Sincerely,
John Beste
President
Famo Feeds Inc.

Lee Ann Hall **Letter 1285**

My name is Lee Ann Hall. I am a Norman County Commissioner in Minnesota. This is my 24th year in that elected position. I also owned an Office Supply/Technology Center in Ada, MN for over twenty years. I recently sold my business as part of my retirement process. I am also a board member of the Norman County Economic Development Authority and the Secretary/Treasurer of the Ada Chamber of Commerce.

I am writing in support of the proposed West River Dairy expansion in Stevens County. I have experienced firsthand the positive impact that Riverview/Waukon Dairy has had to the vitality and economics of Norman County, the Ada community, local businesses and our local farmers. Their operation located in Waukon Township has had a huge economic impact! They are dedicated to the local community and businesses in our County. They buy local, they fixed up an old apartment facility in Twin Valley during their construction process and turned it into an asset for the community, partnered with local farmers in buying from them direct for products needed and selling to them direct for different needs that they have on the farms and so much more! Riverview/Waukon Dairy has built a strong stable livestock business that creates consistent economic activity that supports local jobs and allows businesses for flourish and grow. The dairy has been a great neighbor to the surrounding farmers. They run a clean, efficient and necessary business in Norman County. As a Commissioner, I have heard nothing but great things about their operation and their commitment to work with our local farmers and communities. They are involved in many community events and also donate things like ice cream, cheese and help by volunteering to enhance the events.

The management of the Dairy has been a great partner, attending the Norman County Board meetings to give us updates while they were building the Dairy and after on updates with their Dairy operation. They also have attended the Norman County EDA meetings to keep us updated. They welcome tours of their facility with open arms and encourage people to check them out. We appreciate their willingness to be transparent and keep us "in the know."

The proposed expansion will bring a huge economic benefit to Stevens County by generating demand for local vendors, support construction and employment and add to the vitality of County. These types of projects are essential to maintaining a sustainable economy in rural Minnesota. The Norman County EDA works hard to get new businesses into our County. We were so excited and blessed that they considered and put their operation on our rural county!

No EIS is needed as the State Environmental Review process is rigorous and sufficient. I respectfully encourage your support and approval of this important project.

Sincerely,
Lee Ann Hall

Jaylon Nichols **Letter 1286**

I trust Riverview Way more than small dairy farmers when it comes to operating and upholding integral business practices. Their people and culture are unmatched. They have provided so much opportunity for me and my family, and I have never witnessed management purposely put profit over integral business practices.

Brady Janzen, Riverview, LLP **Letter 1287**

Dear Mr. Peterson,

For over 50 years, Riverview has successfully and responsibly operated regulated feedlots in Minnesota. As a feedlot permittee, Riverview has completed numerous Environmental Assessment Worksheets (EAWs) as part of Minnesota's rigorous environmental review process. The West River Dairy expansion EAW stands as the most comprehensive to date. The EAW process is designed to determine whether an environmental impact statement (EIS) is required for a proposed action. An EIS is prepared when there is a potential for significant environmental effects. As detailed below, the only reasonable conclusion based on the evidence developed after a thorough review is that this proposed project does not have the potential for significant environmental effects. Thus, we do not believe that further analysis through an EIS is warranted.

We thank the Minnesota Pollution Control Agency (MPCA), Department of Natural Resources (DNR), and other state agencies for their diligent work and for the opportunity to comment on this EAW. We offer the following information to address various comments and questions raised with respect to the project over the last few months.

I. Comprehensive Greenhouse Gas Accounting

The project's anticipated emissions are accounted in detail in the EAW, including differences between construction and operational emissions. Construction emissions encompass land conversion, transportation, as well as the use of stationary and mobile equipment during the building phase. Operational emissions include two kinds: Scope 1 direct emissions, and Scope 2 indirect emissions. Scope 1 emission sources include enteric fermentation, methane, and nitrous oxide released from the

barn and manure storage; nitrous oxide from land application; and combustion from stationary and mobile equipment. Scope 2 emissions account for the project's electricity consumption.

The EAW also addresses the project's relationship to the Minnesota Next Generation Energy Act goals. While the project will generate a certain amount of GHG emissions, overall emissions in Minnesota have declined approximately 14% since 2005. It is also worth highlighting that the Food and Agriculture Organization of the United Nations found that North American dairies are the most efficient in the world. In fact, North American dairies reduced absolute emissions by 5% while increasing milk production over a 10-year period.[1] And a peer-reviewed study published in the Journal of Animal Science found that the total carbon footprint of the U.S. dairy industry in 2007 was 41% lower than in 1944, even as total milk production increased by 59%.[2] On a per-unit basis, the carbon footprint per kilogram of milk produced in 2007 was only 37% of the 1944 level. Modern dairy practices required only 21% of the animals, 23% of the feedstuffs, 35% of the water, and 10% of the land needed to produce the same quantity of milk as in 1944. These improvements have continued: a follow-up study by the same researchers found that between 2007 and 2017, GHG emissions per unit of energy-corrected milk declined by an additional 19.2%, even as total U.S. milk production increased by 24.9%.[3] Minnesota's total dairy cow herd has declined from roughly 1.2 million head in 1960 to approximately 440,000 today. This logically demonstrates that Minnesota's dairy industry is producing the lowest level of GHG emissions at any point in its history. As global demand for dairy products increases,[4] Minnesota has an opportunity to lead in supplying that demand, and doing so in a way proven to have the lowest impacts on the environment.

Finally, the EAW highlights several opportunities in which emissions will be mitigated and/or reduced. The project will convert thousands of acres from row crops to alfalfa production (reducing approximately 1.21 tons of CO2e annually per acre), promote the use of cover crops, and offset reliance on synthetic fertilizer through organic manure application. Additional mitigation strategies, as described in the EAW, include the use of efficient Holstein-Jersey crossbred genetics, feed additives, variable frequency drives on motors and milking equipment, temperature-regulated ventilation and misting systems, LED lighting, plate cooler heat recovery, and the potential purchase of renewable electricity from the utility provider.

II. Sustainable Water Supply and Ongoing Compliance

Strategies to achieve a diversified and sustainable water supply plan are meticulously described throughout the EAW. Rather than seeking a new groundwater appropriation, Riverview will utilize an existing off-site well that was previously permitted for 452 million gallons per year, an amount that was previously found by MN DNR to be sustainable from this aquifer. Through a pending permit with the DNR, Riverview will reduce the appropriated volume by half, requesting only 226 million gallons per year. The original appropriation was granted after the completion of an aquifer test. The results of the aquifer test confirmed that the water-table aquifer can sustain the requested volume. The aquifer test also identified a hydraulic connection between the off-site well and the Pomme de Terre River,

[1] "Climate Change and the Global Dairy Cattle Sector: the role of the dairy sector in a low-carbon future." Food and Agriculture Organization of the United Nations. 2019. https://www.fao.org/3/CA2929EN/ca2929en.pdf
[2] Capper, J.L., R.A. Cady, and D.E. Bauman. "The Environmental Impact of Dairy Production: 1944 Compared with 2007." Journal of Animal Science 87, no. 6 (2009).
[3] Capper, J.L. and R.A. Cady. "The Effects of Improved Performance in the U.S. Dairy Cattle Industry on Environmental Impacts Between 2007 and 2017." Journal of Animal Science 98, no. 1 (2020).
[4] U.S. Dairy Export Council, International Demand Analysis (Data Through January 2026), available at https://www.usdec.org/economics-and-data/international-demand-analysis.

prompting the DNR to include groundwater appropriation restrictions based on river flow. These restrictions are responsive to, and will protect, surface water resources.

This hydraulic connection between the river and the aquifer is important for another reason: it represents a source of aquifer recharge. Given that, it's important to note that last year alone 120 billion gallons of water flowed past a nearby stream gage on the Pomme de Terre River.[5] West River Dairy's proposed appropriation represents 0.18% of that measured volume. Although West River will not be appropriating river water, knowing that the aquifer from which it will be appropriating has recharge connectivity to this volume of river water provides good perspective. With this perspective, it's easy to see why a groundwater appropriation volume that is double the currently-proposed amount was previously found to be sustainable in this location, and why the currently-proposed amount does not represent a potentially significant environmental impact.

Some commenters have compared the project's water use to the volume used by the nearby City of Morris, implying that the project poses a risk to the city's water supply. This comparison is not indicative of any potential environmental impact. The off-site well to be used for the West River Dairy expansion is located several miles downstream from the City of Morris's wells along the Pomme de Terre River. Because the water-table aquifer in this area is recharged by the Pomme de Terre River, the downstream position of the project's well means that any water use by West River Dairy would have no impact on the water supply available to the City of Morris, especially in light of the river flow restrictions to be imposed by DNR. This conclusion is further supported by the aquifer test conducted on this well, which found that significant interference is not expected to occur in any existing water wells. Additionally, a historic flow study of the Pomme de Terre River conducted by Moore Engineering found that stream flows have been materially increasing since 1991. This increasing trend in river flows—likely correlated to drainage improvements within the watershed—further supports the conclusion that adequate recharge exists for water appropriations from the Pomme de Terre River valley and reduces the likelihood that pumping restrictions would ever be required. It is also worth noting that the DNR's Groundwater Province Map indicates that groundwater availability is moderate to good in the surficial sand aquifers in this area. Finally, we are not aware of any evidence indicating hydrologic connectivity between the off-site well and the on-site wells at the existing dairy, which are screened in different aquifers. As noted above, the aquifer test report confirmed that significant interference is not expected to occur in any existing wells.

Furthermore, as a contingency and climate adaptation strategy, the project will also construct two water storage basins designed to hold a nine-month supply of water. These basins will allow the appropriation and storage of water when river flows are high and provide a buffer should groundwater appropriation ever need to be curtailed due to lower river flows. In addition, West River Dairy will offset groundwater needs by capturing and recycling rainwater from the farm itself. In total, the farm will be engineered to capture approximately 90 million gallons of rainwater annually (on average). All these features and strategies result in a diversified and sustainable approach to the project's water needs while reducing reliance on a single water source.

What's more, West River Dairy's water appropriation is subject to permitting and ongoing regulation by the DNR. When determining whether a project has the potential for significant environmental effects, the responsible governmental unit (RGU) shall consider the extent to which the environmental effects are mitigated by ongoing public regulatory authority. Minn. R. 4410.1700, subp. 7 (emphasis added). The West River Dairy expansion must obtain a groundwater appropriation permit from the DNR and is

[5] Minnesota Department of Natural Resources. "Cooperative Stream Gaging (CSG)." https://www.dnr.state.mn.us/waters/csg/index.html

therefore subject to the DNR's ongoing public regulatory authority. According to Minn. Stat. § 103G.287, subd. 5, a groundwater appropriation permit may be granted only if DNR determines that the use is "sustainable to supply the needs of future generations and the proposed use will not harm ecosystems, degrade water, or reduce water levels beyond the reach of public water supply and private domestic wells…."[6] Thus, by law, the DNR cannot issue a permit for West River Dairy's expansion if it determines that the water resources proposed to be used are not adequate, which eliminates the potential for significant environmental effects from water appropriation. Further, once issued, ongoing compliance frameworks — including water level monitoring, annual reporting, and enforceable pumping restrictions — remain in place to ensure continued protection of the state's water resources. And Minn. Stat. § 103G.261 prioritizes domestic water supply above all other uses.

Minnesota courts support an RGU's reliance on ongoing public regulatory authority when measures exist that are specific, targeted, and certain to be able to mitigate the environmental effects in question. Citizens Advocating Responsible Development v. Kandiyohi County Board of Commissioners, 713 N.W.2d 817, 834-35 (Minn. 2006). The DNR's permit measures clearly meet these criteria. Importantly, the Minnesota Court of Appeals has stated that the DNR water appropriation permit process is a sufficient means of preventing and mitigating significant environmental effects. In re Environmental Impact Statement, 849 N.W.2d 71, 82 (Minn. Ct. App. 2014); see also Friends of Twin Lakes v. City of Roseville, 764 N.W.2d 378, 382 (Minn. Ct. App. 2009). The Court of Appeals has also held that MPCA deferral to the DNR's permitting process in a nearly identical scenario was proper. See Matter of Decision on Need for an Env't Impact Statement for Proposed Barrick Fam. Farms, LLP - Lockhart 25 Project Lockhart Twp. Norman Cnty., 2021 WL 3716643, at *6 (Minn. Ct. App. Aug. 23, 2021) ("[B]ecause of the rigorous review process and strict statutory protections …, the MPCA could properly defer review of the potential impacts … to the DNR's permitting process.")

Considering the foregoing, MPCA must consider DNR's regulations with respect to water appropriation, and it's reasonable and proper to conclude that these regulations are sufficient to prevent the potential for significant environmental effects.

III. Stormwater Management

The project's stormwater management plan further demonstrates a commitment to climate adaptation. As described in the EAW, the project's stormwater basins are sized at least 20% larger than the minimum required for a 25-year, 24-hour precipitation event to account for projected increases in rainfall frequency and intensity. In practice, the oversizing is even greater: the two long-term water storage basins being constructed as part of this expansion provide an additional 157 million gallons of storage capacity. Stormwater captured in the on-site stormwater basins can be transferred to these long-term water storage basins, where this captured rainwater will be stored for recycling/reuse as a water supply for cattle. Together, these water storage basins provide several times the amount of required stormwater capacity. This layered approach to stormwater management thoroughly mitigates and eliminates any concerns regarding stormwater basin capacity, even under the most severe projected climate scenarios.

IV. Minnesota's Robust Permitting Process and the Project's Draft Individual Permit

The West River Dairy expansion will be governed by a "zero discharge" Individual National Pollutant Discharge Elimination System (NPDES) feedlot permit that imposes site-specific requirements, more stringent than those of the state's general feedlot permit. The dairy is designed so that no discharge of

[6] See also, Minn. R. 6115.0670 (providing that permits may not be issued if the water resources are not adequate or if " the appropriation is not reasonable, practical, and does not adequately protect public safety and promote the public welfare").

manure or process wastewater from the farm will occur. Further, among the more stringent provisions of the draft individual permit are earthen manure storage basins with clay liners more than twice as thick as those required under the general permit, additional notification requirements during construction of manure storage areas, mandatory agency approval before manure storage areas can be used, and notification requirements when land application of manure begins. None of these requirements are part of the general feedlot permit, under which most feedlots operate.

Additionally, as described in the EAW, the land application of manure is managed and regulated according to plans that are part of the NPDES permit designed so that the nutrients found in the manure are used in crop production and not lost to waterways. This includes soil testing, manure testing, agronomic rate requirements, etc. The application areas for the West River Dairy expansion were also carefully selected and evaluated to avoid and mitigate environmental effects, and more than enough acres are available to handle the manure that will be produced.

Moreover, the MPCA's own literature review of manure application runoff studies confirms that the incorporation of manure into soil—the method proposed to be used at West River Dairy—reduces runoff volume, soil loss, and nutrient transport compared to fields that did not receive manure. Importantly, the injection of liquid manure—consistent with the knife-injection method Riverview employs—resulted in greater reductions.[7]

V. Dairy Farm Trends

Some commenters have suggested that this project should be evaluated in light of economic trends within the dairy industry. The purpose of an EAW is to assess potential significant environmental effects—not to serve as a vehicle for broader economic policy debates.

Even setting that aside, the data does not support the argument that larger-scale dairy farming is causing other farms to exit the industry. Dairy farms have been declining in Minnesota since at least the 1940s. According to USDA Agricultural Census data, approximately 90% of the dairy farms that have exited Minnesota since 1940 had done so by 1992—well before large-scale dairy farming existed in the state. Since the emergence of larger dairy farms in the early 2000s, the rate of decline in farm numbers has continued largely unchanged, while Minnesota's dairy herd numbers have stabilized. Similar trends of farm declines have been even more pronounced in neighboring North Dakota, where large-scale dairy farming does not exist to any meaningful degree, yet dairy farm numbers have declined even more dramatically. These facts suggest that other factors—not farm size—are the primary drivers of dairy farm exits. Meanwhile, demand for dairy products continues to grow both domestically and internationally, with approximately $10 billion invested in U.S. dairy processing capacity recently and significant new processing investments in the upper Midwest region. This growing demand represents an opportunity for Minnesota's entire dairy industry, and projects like the West River Dairy expansion help sustain the milk supply that supports regional processors, which in turn benefits dairy producers of all sizes.

VI. Conclusion

The West River Dairy expansion EAW is a thorough document that demonstrates the proposed project has been carefully designed to avoid, minimize, or mitigate potential environmental effects. It is also clear that the regulatory framework governing the project provides robust and ongoing environmental protection. Riverview appreciates the work of the MPCA, DNR, and other agencies involved in this process and is confident in Minnesota's environmental review and permitting process. We respectfully

[7] "Runoff Reductions with Incorporated Manure." Minnesota Pollution Control Agency. May 2018. Publication wq-f1-08.

urge the MPCA to follow the process established in law and issue a negative declaration on the need for an Environmental Impact Statement.

Sincerely,
/s/ Brady Janzen
Brady Janzen
Authorized Partner, Riverview, LLP

Blaine Hill **Letter 1288**

To whom it may concern. I grew up in Morris and recently retired as the city manager here. I'm writing in support of the West River Dairy expansion project. I believe that Minnesota has some of the best, if not best regulations in the world when it comes to protecting the environment and our natural resources. I've had the opportunity to work with the state on many projects as a city manager and I've had the opportunity to work with local companies like Riverview as they continued to grow. I'm a grandfather now and have the opportunity to watch grandchildren and as I drive back and forth from Hancock to Morris, I'm amazed at the quality of the operations that are taking place with regards to the farmland. This includes the process of distribution of manure from Riverview Dairy. I worry about our water, land and air resources like everyone else. I believe Riverview Dairy knows and understands the importance too and quite frankly this is their home like it is mine. They are good people and will do the right things and I know and understand that the MPCA, DNR and other state agencies are good at their jobs. Together we will all be better moving forward. I'm here like they are because our ancestors immigrated to this area to begin a new life farming land they were given. Some made it, some didn't. These are the ones that made it and it is because of the way they do business. I did not grow up on a farm but my friends did and I had the chance to work on farms as a young high school kid. I love where I live. I like what Riverview Dairy is doing. Again I'm writing in support of their project. Thank you.

Eric Lindberg, Minnesota Center for Environmental Advocacy **Letter 1289**

Comments on the Environmental Assessment Worksheet

for the West River Dairy Expansion

May 7, 2026

INTRODUCTION

Agribusiness giant Riverview, LLP ("Riverview") is the largest dairy farming company in Minnesota, the second largest in the United States, and the fifth largest in the world.[1] Riverview's proposed West River Dairy Expansion project (the "Expansion Project") in Stevens County would be the largest dairy Concentrated Animal Feeding Operation ("CAFO") in Minnesota, if approved. The Expansion Project would swell the existing West River Dairy 7,855-cow facility by adding 11,000 dairy cows to a total of 18,855 dairy cows (26,397 animal units). The 15,400 animal units added by the Expansion Project—

[1] MILICA KOCIC & TORSTEN HEMME, IFCN DAIRY RSCH . NETWORK , IFCN TOP-10 LIST: DAIRY FARMING COMPANIES WORLDWIDE 2020 (2020), https://ifcndairy.org/wp-content/uploads/2020/02/IFCN-Top-10-List-Dairy-Farming-Companies-Worldwide-2020.pdf [Exhibit 1] (listing Riverview as the fifth largest dairy company worldwide by number of cows and fourth largest by production of raw milk); see also Ana Sofia Santos, Global Dairy Production: *Top 10 Largest Dairy Farms in the World*, CEVA SANTÉ ANIMAL (Jan. 21, 2026), https://ruminants.ceva.pro/global-dairy-production [Exhibit 2] (ranking Riverview as the fifth largest dairy farming company worldwide by raw milk production and the largest in the United States).

standing alone—would be the second largest CAFO by total animal units in Minnesota. The expanded West River Dairy would be the largest CAFO in the State.[2]

There are multiple reasons why the Minnesota Pollution Control Agency("MPCA") should conclude that Riverview's Expansion Project has the potential for significant environmental effects. First, the Environmental Assessment Worksheet("EAW") acknowledges that the Expansion Project would add at least 72,000 tons of greenhouse gas ("GHG") emissions annually to the existing West River Dairy facility.[3] Yet the EAW fails to fully (1) account for its full GHG emissions footprint, (2) consider the impacts of those emissions, and (3) consider alternate ways to mitigate those emissions. Even with the incomplete information contained in the EAW, the MPCA should recognize the potential for significant environmental effects and order an Environmental Impact Statement ("EIS") to further examine those effects. Fully assessing the GHG emissions of the Expansion Project is especially important because the agriculture sector is the second largest source of GHG emissions in Minnesota, responsible for approximately 25% of the State's net emissions.[4]

Second, the EAW's assessment of water availability relies upon an aquifer test that is nearly two decades old, and the EAW fails to consider the water quality impacts attendant to appropriating over 200 million gallons of water per year from an aquifer hydrologically connected to the Pomme de Terre River. Third, the EAW's plan to protect water quality from the massive amount of manure the Expansion Project will add to the Pomme de Terre River Watershed is inadequate. The EAW's cumulative effects analysis does not recognize the poor water quality already existing in this part of Minnesota and how the Expansion Project will exacerbate the problem. The EAW must include a full assessment of the cumulative effects of applying so much additional manure to fields in a region where surface waters are already impaired with agricultural pollutants. Finally, the EAW entirely fails to assess one of the largest impacts the Expansion Project will have on Minnesota. Riverview's massive size and scale has distorted Minnesota's dairy market, driving out small and mid-sized producers. This is a major environmental effect the EAW entirely overlooks and one MPCA should study through an EIS

I. STATUTORY AND REGULATORY BACKGROUND

Under the Minnesota Environmental Policy Act ("MEPA"), a responsible governmental unit ("RGU") conducting an EAW review must consider all impacts "that may be reasonably expected to occur from the project" to determine whether the Expansion Project has "the potential for significant

[2] Minn. Pollution Control Agency (MPCA) & Minn. Geospatial Commons, Feedlots in Minnesota, https://gisdata.mn.gov/dataset/env-feedlots (last visited May, 5, 2026).

[3] The original Environmental Assessment Worksheet (EAW) for the Expansion Project estimated a total of 66,324 tons of greenhouse gas (GHG) emissions annually—about 9% less than the current estimate. The revised estimate likely increased because the revised feedlot GHG calculation applied MPCA's standard dairy-cow manure-calculation liveweight of 680 kg/head, or about 1,500 lb/head, rather than the 1,200 lb/head average weight reflected in West River Dairy's Manure Management Plan. *Riverview's EAW for West River Dairy, infra* note 17, at Attachment 23. Because manure CH_4 and N_2O calculations scale directly with animal liveweight under MPCA's methodology, the manure-related emissions increased 5,886 tons CO_2e/year. The revision demonstrates that the EAW's GHG estimate is highly sensitive to animal liveweight assumptions. However, the EAW contains inconsistent liveweight assumptions—approximately 1,500 lb/head in the revised GHG calculation, 1,400 lb/head in animal-unit accounting, and 1,200 lb/head in the Manure Management Plan. MPCA should require Riverview to reconcile these assumptions, disclose the expected actual average liveweight of the Holstein–Jersey crossbred herd, and confirm that manure generation, nutrient loading, storage capacity, land-application acreage, enteric methane, and fertilizer-offset calculations are all based on consistent livestock characterization. Given that a single assumption change increased annual emissions by nearly 6,000 tons CO_2e/year, additional sensitivity analysis and verification is warranted.

[4] ANNE CLAFLIN ET AL., MPCA, GREENHOUSE GAS EMISSIONS IN MINNESOTA 2005-2022 at 9 (2025), https://www.pca.state.mn.us/sites/default/files/lraq-3sy25.pdf [Exhibit 3; hereinafter "MPCA GHG EMISSIONS IN MINNESOTA"].

environmental effects."[5] The agency must take a "hard look" at the issues involved, and "genuinely engage[] in reasoned decision making."[6] The Minnesota Court of Appeals explained that, in order to determine whether a project has the potential for significant environmental effects, the environmental review process must include an analysis of environmental impacts "reasonably expected" to occur, even if not contemplated on the EAW form.[7] The Minnesota Environmental Quality Board ("EQB") and MPCA have adopted guidance requiring all project applicants to complete an environmental study on, for example, their expected GHG emissions and whether they have considered ways to reduce those emissions.[8]

Serious consideration of GHG emissions in environmental review processes aligns with Minnesota law and policy, which, since 2007, has called for steep reductions in GHG emissions throughout the State "across all sectors producing greenhouse gas emissions."[9] Yet, the agricultural sector's emissions have actually increased. Minnesota's 2007 Next Generation Energy Act acknowledges the threat that GHG emissions pose to public health and welfare by setting State goals to reduce statewide GHG emissions, with an ultimate goal of achieving net-zero emissions by 2050.[10] Unfortunately, Minnesota has fallen short both of its 2015 goal to decrease GHG emissions 15% below the 2005 baseline, and its 2025 goal of a 30% decrease.[11] The agricultural sector is particularly off-track: unlike other sectors, such as electricity generation and transportation, which have seen reduced emissions since 2005, emissions from agriculture increased 1% between 2005 and 2023.[12]

MPCA's reporting shows that the agriculture sector is the second largest source of GHG emissions in the State, responsible for approximately 25% of net emissions.[13] Animal agriculture is the largest source of methane in Minnesota, with the methane coming mainly from cattle digestion and manure storage, and a significant portion of the agriculture sector's nitrous oxide emissions stem from manure management

[5] Minn. R. 4410.1700, subp. 6.
[6] *Citizens Advocating Responsible Dev. v. Kandiyohi Cnty. Bd. of Comm'rs*, 713 N.W. 2d 817, 832 (Minn. 2006).
[7] In re Denial of a Contested Case Hearing Request & Modification of a Notice of Coverage Under Individual Nat'l Pollution Discharge Elimination Sys. Feedlot Permit No. MN0067652, No. A19-0207, 2019 WL 5106666, at *7–8 (Minn. Ct. App. Oct. 14, 2019).
[8] MINN . ENV'T QUALITY BD., ENVIRONMENTAL ASSESSMENT WORKSHEET (EAW) GUIDANCE: DEVELOPING A CARBON FOOTPRINT AND INCORPORATING CLIMATE ADAPTATION AND RESILIENCE (2024), https://www.eqb.state.mn.us/sites/eqb/files/2024_eaw_climate_guidance_2.pdf]; MPCA, Environmental Review, https://www.pca.state.mn.us/business-with-us/environmental-review (last visited May 7, 2026).
[9] MINN. STAT . § 216H.02, subd. 1(a).
[10] MPCA GHG EMISSIONS IN MINNESOTA, supra note 4, at 5; MINN . STAT . § 216H.02, subd. 1(a).
[11] Establishing the Climate Change Subcabinet and the Governor's Advisory Council on Climate Change to Promote Coordinated Climate Change Mitigation and Resilience Strategies in the State of Minnesota, Minn. Exec. Order No. 19-37 (Dec. 2, 2019), https://mn.gov/governor/assets/2019_12_2_EO_19-37_Climate_tcm1055-412094.pdf [Exhibit 4].
[12] MPCA GHG EMISSIONS IN MINNESOTA, supra note 4, at 9; Minnesota Greenhouse Gas Inventory, Main Sources of GHG Emissions and Sequestration by Sector in 2023, MPCA, https://data.pca.state.mn.us/views/Greenhousegasemissionsdata/Sourcesofemissions2023 (last visited May 5, 2026) [Exhibit 5, hereinafter "MPCA GHG Inventory: Main Sources"].
[13] MPCA GHG EMISSIONS IN MINNESOTA, supra note 4, at 9.

and growingfeed for livestock.[14] Minnesota will not meet its GHG emission reduction goals without addressing emissions from massive feedlots like the one proposed.[15]

There are other serious environmental risks from the Expansion Project. The massive amount of water the Expansion Project needs and the manure produced by the additional 11,000 cows risk further degrading water quality and other natural resources in the Pomme de Terre River Watershed. And Riverview's rapidly expanding hoofprint is changing rural Minnesota, driving out small and mid-sized dairies who are unable to compete.

To comply with the law and Minnesota public policy, MPCA must consider whether the Expansion Project has the potential to cause significant environmental effects based on the following criteria, set out in Minn. R. 4410.1700, subp. 7:

A. type, extent, and reversibility of environmental effects;

B. cumulative potential effects, including:

   i. whether the cumulative potential effect is significant;

   ii. whether the contribution from the project is significant when viewed in connection with other contributions to the cumulative potential effect;

   iii. the degree to which the project complies with approved mitigation measures specifically designed to address the cumulative potential effect; and

   iv. the efforts of the proposer to minimize the contributions from the project;

C. the extent to which the environmental effects are subject to mitigation by ongoing public regulatory authority. The RGU may rely only on mitigation measures that are specific and that can be reasonably expected to effectively mitigate the identified environmental impacts of the project; and

D. the extent to which environmental effects can be anticipated and controlled as a result of other available environmental studies undertaken by public agencies or the project proposer, including other EISs.[16]

This comment will show that, applying these criteria, there is the potential for significant environmental effects from the proposed Expansion Project. Consequently, MPCA must order an EIS.

II. MPCA MUST ORDER AN EIS BECAUSE THE EXPANSION PROJECT'S GHG EMISSIONS HAVE THE POTENTIAL FOR SIGNIFICANT ENVIRONMENTAL EFFECTS

The Expansion Project's GHG emissions easily clear the threshold for a full EIS. Riverview's own estimate shows a net increase of 72,210 tons of CO_2e per year and approximately 2.17 million tons of CO_2e over the Expansion Project's 30-year life, primarily from enteric fermentation and manure storage. But that estimate is not the outer bound of the Expansion Project's climate impact; it is likely an understatement.

[14] Id. at 3, 10; Minnesota Greenhouse Gas Inventory, Sector-Level Details, Agriculture Sector, MPCA, https://data.pca.state.mn.us/views/Greenhousegasemissionsdata/Sectordetails (last visited May 5, 2026) [Exhibit 6, hereinafter "MPCA GHG Inventory: Agriculture Sector Details"]. Minnesota is comparable to the rest of the nation in this respect. Animal agriculture is the largest agricultural emitter in the United States: nearly 80% of U.S. agriculture emissions are from the production of animals for food and their feed. PETER H. LEHNER & NATHAN A. ROSENBERG , FARMING FOR OUR FUTURE: THE SCIENCE, LAW, AND POLICY OF CLIMATE-NEUTRAL AGRICULTURE 43 (2021) [Exhibit 7].

[15] See MPCA GHG EMISSIONS IN MINNESOTA, supra note 4, at 9; see also Climate Change Trends and Data, MPCA, https://www.pca.state.mn.us/air-water-land-climate/climate-change-trends-and-data (last visited May 5, 2026).

[16] Minn. R. 4410.1700, subp. 7.

The EAW relies on conservative inventory-based modeling, analyzes methane only under a 100-year global warming potential ("GWP"), omits or selectively accounts for substantial lifecycle and scope 3 emissions, and claims mitigation credits that are indefinite, unsupported, or overstated. At the same time, the Expansion Project's emissions must be evaluated against Minnesota's persistently high and increasing agricultural methane and nitrous oxide emissions, the cumulative nature of climate harm, and the absence of any meaningful regulatory program that will cap, monitor, or reduce feedlot GHG emissions after approval. Taken together, the type, extent, irreversibility, cumulative effects, inadequate mitigation, and lack of regulatory control all demonstrate that the Expansion Project has the potential for significant environmental effects and that MPCA must order an EIS.

A. The Type, Extent, And Irreversibility Of The Expansion Project's GHG Emissions Weighs Strongly In Favor Of An EIS

According to Riverview, the West River Dairy Expansion creates "a net increase of 72,210 CO2 e [tons] per year in GHG emissions, primarily from livestock digestion (enteric fermentation), and manure storage."[17] The "total net GHG emissions during the life of the [West River Dairy Expansion] (~30 years), including the construction and operation phases, is estimated to be 2.17 million tons CO_2e."[18] For comparison, a recent EAW estimates that the total construction and operation emissions of a 287,000 square foot rare-earth magnet manufacturing facility is 1.68 million tons CO_2e over a 50-year period.[19] Riverview's estimate reflects substantial GHG emissions at levels that weigh in favor of further environmental review.

While even Riverview's estimate describes exceptionally high emissions, the EAW likely understates the extent of the Expansion Project's GHG emissions. The EAW uses the MPCA calculator, which in turn relies on models adopted from the U.S. Environmental Protection Agency ("EPA"). The underlying methodology results in conservative estimates, including because the methodology requires assumptions and extrapolations based on representative systems.[20] Compared to models of carbon dioxide emissions from the fossil fuel industry, the EPA's models of nitrous oxide and methane emissions from agriculture are considered far less certain, and the resulting estimates have wide confidence intervals.[21] According to experts, the range of uncertainty between the upper and lower bounds of U.S. agricultural emissions equates to the annual emissions of more than 100 coal-fired power plants.[22]

This high degree of uncertainty is due in part to the use of an inventory-based, "bottom-up" approach, which involves multiplying the number of animals present by "emissions factors" specific to animal types and regions (i.e., estimates of how much gas is produced by each animal over a set period of time).[23] These emission factors are typically derived from controlled studies, representative farm systems, or

[17] MPCA, RIVERVIEW 'S ENVIRONMENTAL ASSESSMENT WORKSHEET FOR WEST RIVER DAIRY EXPANSION 65 (2026) https://webapp.pca.state.mn.us/eqb-search/project-detail/88731?siId=88731-PROJ0000000004 [hereinafter "*Riverview's EAW for West River Dairy*"].
[18] *Id*. at 65–66.
[19] MPCA, NIRON MAGNETICS 'S ENVIRONMENTAL ASSESSMENT WORKSHEET 49 (2026), https://webapp.pca.state.mn.us/eqb-search/project-detail/264817?siId=264817-PROJ0000000001 [Exhibit 8].
[20] *See Riverview's EAW for West River Dairy, supra* note 17, at 62; *see also* MPCA, ITEM 18 GREENHOUSE G AS (GHG) EMISSIONS/CARBON FOOTPRINT (2025), https://www.pca.state.mn.us/sites/default/files/p-ear1-16.pdf [Exhibit 9] (using a combination of EPA-approved methodologies and state-specific tools to estimate emissions from feedlots).
[21] LEHNER & ROSENBERG , *supra* note 14, at 54.
[22] Id. at 55.
[23] Matthew N. Hayek and Scot M. Miller, *Underestimates of Methane from Intensively Raised Animals Could Undermine Goals of Sustainable Development*, 16 ENV'T RSCH . LETTERS 1, 3–7 (2021) [Exhibit 10]; Olga Gavrilova et al., *Chapter 10: Emissions from Livestock and Manure Management, in* 2019 REFINEMENT TO THE 2006 IPCC GUIDELINES FOR NATIONAL GREENHOUSE GAS INVENTORIES 10.50–10.52 (2019), https://www.ipcc-nggip.iges.or.jp/public/2019rf/pdf/4_Volume4/19R_V4_Ch10_Livestock.pdf [Exhibit 11]

modeled averages, and are then applied broadly across diverse real-world operations. As a result, the approach simplifies complex biological and environmental processes—such as feed composition, animal health, manure handling, weather conditions, and management practices—into standardized assumptions. Since this "bottom up" approach requires many inputs—each with its own uncertainty—the resulting uncertainty of the total emissions estimate can be more than that of any individual input.[24]

The alternative to a "bottom-up" approach is a "top-down" approach, which uses atmospheric measurements from livestock production regions to produce emissions estimates or corroborate a model's emissions estimates. One comparison of bottom-up and top-down estimates found that animal methane emissions in the U.S. may be 39% to 90% higher than bottom-up studies predict.[25] This may be because bottom-up models like that used by the EPA and adopted by MPCA fail to account for animal diseases that increase enteric fermentation and rely on manure emission factors that are based on laboratory experiments, rather than real-world settings.[26] The Expansion Project's EAW should acknowledge the uncertainty of its modeling with an uncertainty range. The EAW should also include a sensitivity analysis to model scenarios involving variables such as alternative feeds and high or low productivity cases.

Another problem with the EAW is that it relies only on a 100-year global warming potential (GWP100) value. Even though under GWP100, methane is converted to CO_2e emissions using a factor of 28 (meaning 1 ton of methane is treated as having the same warming impact as 28 tons of CO_2 over a 100-year period), this approach can still obscure the near-term climate impacts of the Expansion Project's emissions. Given that methane is a short-lived but highly potent GHG, the analysis should also present emissions using a 20-year global warming potential (GWP20), which better reflects the Expansion Project's 30-year operational lifetime and the acute warming effects of methane during that period. Presenting both GWP100 and GWP20 values would provide a more complete and policy-relevant understanding of the Expansion Project's climate impact.

More critically, the Expansion Project's EAW also misses much of the Expansion Project's scope 3 emissions. A company's GHG emissions can be classified into three scopes:

> Scope 1 emissions are direct emissions from owned or controlled sources. Scope 2 emissions are indirect emissions from the generation of purchased energy. Scope 3 emissions are all indirect emissions (not included in scope 2) that occur in the value chain of the reporting company, including both upstream and downstream emissions.[27]

While the EAW includes a table of the Expansion Project's scope 1 and scope 2 emissions, it fails to clearly quantify scope 3 emission.[28] The EAW narratively acknowledges several upstream and downstream emissions that typically fall under scope 3, but it does not fully quantify them in its final total. These full value chain or lifecycle emissions include, for example, emissions from feed production (including fertilizer manufacture and soil emissions), transportation of inputs and products, and downstream processing and distribution. As one example of a failure to count scope 3 emissions, while the EAW narratively identifies that there will be vehicle emissions from contractor and employee

[24] Hayek & Miller, *supra* note 23, at 4.
[25] *Id*. at 5.
[26] *Id*. at 6–7.
[27] *FAQ*, GREENHOUSE GAS PROTOCOL, https://ghgprotocol.org/sites/default/files/2022-12/FAQ.pdf (last visited May 7, 2026) [Exhibit 12, hereinafter "Greenhouse Gas Protocol FAQ"].
[28] *Riverview's EAW for West River Dairy, supra* note 17, at 62–63.

commuting, milk hauling, and feed delivery and discusses strategies to mitigate these,[29] it does not include calculated estimates for these specific transport activities in its 72,210 tons/year total.

At the same time, the EAW selectively quantifies certain upstream and downstream impacts when doing so results in claimed emissions reductions, but miscategorizes them as scope 1 rather than scope 3. Inexplicably, the EAW does not quantify the total annual GHG emissions generated from feed production, but does quantify a specific reduction (or carbon sink credit) related to growing feed.[30] In another example, the upstream reduction from avoided synthetic fertilizer manufacturing (-9,038 tons) and the carbon sink credit for converting land to alfalfa feed (-2,662 tons) are both included in the total as scope 1 adjustments.[31] Such misleading and erroneous calculation methods result in significant asymmetry. Upstream and downstream emissions are included when they decrease the Expansion Project's reported footprint but excluded when they would increase it. Such one-sided accounting does not provide a complete or balanced picture of the Expansion Project's climate impacts and results in a significant understatement of total emissions.

And the Expansion Project's scope 3 emissions are likely large and material.[32] Figure 1 below provides estimated percentages of the U.S. dairy industry's lifecycle GHG emissions for fluid milk in 2008.[33] As the figure shows, emissions from enteric fermentation and manure management—which are scope 1 emissions for a dairy farm like West River Dairy—only comprise 51% of life cycle emissions. The other 49% of emissions—which are all scope 3 emissions—are from feed production, refrigeration and packaging, and distribution to retail and consumers. Newer research suggests that feed production in particular may contribute more than the 20% estimate from the 2008 data: in 2017, the U.N. Food and Agricultural Organization estimated that feed production and processing alone account for 45% of GHG emissions from livestock production.[34] As another example, U.S. dairy farm giant Rockview self-reported that its 2024 scope 3 emissions amounted to 537,144 metric tons CO_2e, over 67% of its total GHG footprint.[35] But almost all scope 3 emissions are left out of the Expansion Project's EAW. By omitting these scope 3 sources of emissions, the EAW likely ignores at least half of the Expansion Project's true GHG emissions.

U.S. Dairy Industry Fluid Milk GHG Emissions Allocation	
Fluid Milk Production Process	Approximate GHG Emissions
Enteric Emissions	26%

[29] *Id*. at 61.
[30] *Id*. at 62.
[31] *Id*. at 62–63.
[32] Scope 3 emissions "often represent a company's biggest greenhouse gas impacts." Greenhouse Gas Protocol FAQ, *supra* note 27.
[33] INNOVATION CTR . FOR U.S. DAIRY , SCOPE 3 GHG INVENTORY GUIDANCE FOR U.S. DAIRY COOPERATIVES AND PROCESSORS 12 (2024), https://www.usdairy.com/getmedia/2e8a6a15-6254-4bdc-a323-7be3b3d973da/scope_3_guidance_handbook_2024_final_reduced.pdf?ext=.pdf [Exhibit 13] (citing Greg Thoma et al., *Greenhouse Gas Emissions from Milk Production and Consumption in the United States: A Cradle-to-Grave Life Cycle Assessment Circa 2008*, 31 INT 'L DAIRY J. S3–S14 (2013) [Exhibit 14]).
[34] FOOD AND AGRIC. ORG . OF THE UNITED NATIONS , GLOBAL DATABASE OF GHG EMISSIONS RELATED TO FEED CROPS: METHODOLOGY 4 (2017), https://openknowledge.fao.org/server/api/core/bitstreams/c3b15795-3030-41c4-986e-31a090aa2ab4/content [Exhibit 15].
[35] Our *Sustainability Efforts*, ROCKVIEW FARMS , https://www.rockviewfarms.com/sustainability-efforts/ (last visited May 5, 2026) [Exhibit 16].

Manure Management	25%
Feed Production	20%
Refrigeration and Packaging	9%
Distribution, Retail and Consumer	20%

Figure 1. Allocation of fluid milk GHG emissions from the U.S. dairy industry in 2008.

For these reasons, the EAW's failure to quantify emissions from feed production is problematic and likely contributing to a significant understatement of emissions. The EAW does not list the total acres of crops required to feed the Expansion Project's cattle each year, only referring to the 2,200 acres of alfalfa proposed as a mitigation.[36] But 2,200 acres is generally not sufficient to feed 11,000 dairy cows as their primary forage source for a full year. For intensive dairy operations, a common guideline is 1.5 to 2.0 acres per cow to provide enough forage.[37] According to this guideline, 11,000 cows would require between 16,500 acres and 22,000 acres. Peer-reviewed data from high-producing Minnesota freestall dairy herds indicate dry matter intake of approximately 24.3 kg/cow/day, with forage comprising about 52% of the ration.[38] For 11,000 cows, that translates to approximately 97,565 metric tons of feed dry matter per year. Applying peer-reviewed carbon-footprint factors for common U.S. dairy feeds indicates that feed production alone would likely generate approximately 27,000 to 53,000 metric tons CO_2e per year.[39] This is not a minor or speculative source of emissions. It is a major lifecycle emissions category that the EAW fails to quantify.

Because these scope 3 emissions are both foreseeable and substantial, their exclusion and incomplete reporting thwarts MPCA's ability to evaluate the Expansion Project's true climate impact and its consistency with State climate goals. An EIS is required by law and is necessary to assess these lifecycle emissions and their cumulative effects, as discussed further in infra Part II.C.

Once the Expansion Project's GHGs are emitted their impacts are effectively irreversible. The Intergovernmental Panel on Climate Change (IPCC) has explained that the "very long lifetime of CO_2 in the atmosphere" means that "part of the CO_2 emitted by humans remains . . . for centuries to millennia."[40] As a result, GHGs accumulate and the warming they produce continues long after the underlying GHGs are emitted. This persistence means that the warming effects caused by GHG emissions are not only long-term but nearly impossible to fix within a meaningful duration, even if significant mitigation efforts occur.[41] Rapidly reducing short-lived GHGs like methane could provide an emergency brake on the rate of warming, slowing near-term temperature increases and reducing peak warming, but it cannot immediately undo the underlying climate harms that have already been set in motion.[42]

[36] See discussion *infra* notes 53-8 and accompanying text.
[37] Virginia A. Ishler, Dairy Sense: *Keeping the Dairy Right Sized*, PENN STATE EXTENSION (Mar. 2020) (updated Dec. 8, 2025), https://extension.psu.edu/dairy-sense-keeping-the-dairy-right-sized [Exhibit 17].
[38] M.I. Endres & L.A. Espejo, *Feeding Management and Characteristics of Rations for High-producing Dairy Cows in Freestall Herds*, 92 J. OF DAIRY SCI . 822–829 (2010), https://doi.org/10.3168/jds.2008-2007 [Exhibit 18].
[39] Felix Adom et al., *Regional Carbon Footprint Analysis of Dairy Feeds for Milk Production in the USA*, 17 INT'L J. LIFE CYCLE ASSESSMENT 520–534 (2012). https://doi.org/10.1007/s11367-012-0386-y [Exhibit 19].
[40] *See* IPCC, *Climate Change 2021: The Physical Science Basis: Frequently Asked Questions, 4.2* (2021), https://www.ipcc.ch/report/ar6/wg1/downloads/faqs/IPCC_AR6_WGI_FAQ_Chapter_04.pdf [Exhibit 20].
[41] Susan Solomon et al., *Irreversible Climate Change Due to Carbon Dioxide Emissions*, 106 PNAS 1704-1709 (2009), https://doi.org/10.1073/pnas.081272110 [Exhibit 21].
[42] *See, e.g.*, Hannah Bäck et al., *Effect of Methane Mitigation on Global Temperature Under a Permafrost Feedback*, 2 GLOB. ENV'T CHANGE ADVANCES 100005, at 1, 8 (2024), https://doi.org/10.1016/j.gecadv.2024.100005 [Exhibit 22] (finding that rapid methane cuts can slow warming in the near term but do not produce meaningful long-term temperature reductions).

Indeed, committed warming due to ocean uptake and delayed equilibrium responses means that the environmental harms associated with climate change will persist independently of future mitigation efforts. Furthermore, even where recovery is theoretically possible, the long recovery lags oftenexhibited by ecological systems may extend recovery timelines for affected species and habitats by decades.[43]

In sum, GHG emissions from the Expansion Project pose threats of a type and extent that are significant and harmful to Minnesota's environment. The Expansion Project significantly increases, without effective mitigation or offsets, the emission of GHG pollutants contrary to state policy mandating reductions in all sectors. Moreover, the harms associated with the Expansion Project's GHG emissions are long-term, cumulative, and effectively irreversible. Accordingly, the type, extent and irreversibility of these potential effects weigh in favor of determining that the Expansion Project has the potential for significant environmental effects.

B. The EAW's Mitigation Plans Weigh In Favor Of An EIS

In addition to underestimating the GHG emissions of the West River Dairy Expansion, the EAW fails to fully grapple with mitigation methods. To fulfill the purpose of environmental review, the EAW must include a robust discussion of potential mitigation measures sufficient for meaningful public review.[44] As recognized by the Minnesota Supreme Court, mitigation analysis in an EAW "gives the public the assurance that the agency has indeed considered environmental concerns in its decisionmaking process . . . and, perhaps more significantly, provides a springboard for public comment."[45]

Rules and guidance make clear that the mitigation analysis must include not only a detailed description of planned mitigations and their efficacy, but also additional mitigation efforts that could be implemented to further reduce environmental effects.[46] Indeed, for purposes of avoiding an EIS, measures identified to mitigate potential adverse environmental effects must be "specific, targeted, and . . . certain."[47] The mitigation plans included in the EAW are not robust and do not fulfill these requirements.

While some categories of mitigation Riverview identifies may have value in the abstract—for example, certain feed formulations (such as those with lower crude protein and higher digestibility) can reduce enteric methane emissions from ruminants,[48] as can some feed additives,[49] and feed sources developed through lower carbon intensity practices can reduce total feedlot-associated GHGs[50] —they are largely

[43] Sarah Weiskopf et al., *Climate Change Effects on Biodiversity, Ecosystems, Ecosystem Services, and Natural Resource Management in the United States*, SCI. OF THE TOTAL ENV'T 137782 (2020), https://doi.org/10.1016/j.scitotenv.2020.137782 [Exhibit 23].
[44] *See* Minn. R. 4410.0300, subd. 3.
[45] *Minn. Ctr. for Env't. Advoc. v. Minn. Pollution Control Agency*, 644 N.W. 2d 457, 468 (Minn. 2002) (quoting *Robertson v. Methow Valley Citizens Council*, 490 U.S. 332, 349 (1989)).
[46] *See id*.; MINN. ENV'T QUALITY BD., ENVIRONMENTAL ASSESSMENT WORKSHEET (EAW) GUIDANCE, supra note 8, at 14–16; Minn. R. 4410.1200(D).
[47] *Citizens Advocating Responsible Dev. v. Kandiyohi Cnty. Bd. of Comm'rs*, 713 N.W.2d 817, 835 (Minn. 2006).
[48] Yue Wang et al., *Mitigating Greenhouse Gas and Ammonia Emissions from Beef Cattle Feedlot Production: A System Meta-Analysis*, 52 ENV'T SCI. TECH. 11232, 11236–37 (2018), https://doi.org/10.1021/acs.est.6b06430 [Exhibit 24].
[49] While some feed additives have shown promise, many of them have not been tested or adopted by industry at scale, and their mitigation potential is limited. Daina Bray, *Reining in Animal Agriculture's Emissions by Shrinking the Herd: Early Signs of a Necessary Global Policy Shift*, 54 ENV'T L. 489, 523–31 (2024), https://law.lclark.edu/live/files/36859-5braypdf [Exhibit 25]; *see also* F.-X. Philippe & B. Nicks, *Review on Greenhouse Gas Emissions from Pig Houses: Production of Carbon Dioxide, Methane, and Nitrous Oxide by Animals and Manure*, 199 AGRIC., ECOSYSTEMS & ENV'T 10, 21 (2015), https://doi.org/10.1016/j.agee.2014.08.015 [Exhibit 26].
[50] Muxi Cheng et al., *Climate Change and Livestock Production: A Literature Review*, 13 ATMOSPHERE 140, 8 (2022) [Exhibit 27].

untested and their mitigation potential is limited. In trying to apply such mitigation practices here, the EAW lacks evidentiary support and enforceable implementation commitments needed to show that they will meaningfully reduce the Expansion Project's actual emissions.

The mitigations proposed in the EAW are indefinite and incomplete and cannot be reasonably expected to effectively mitigate the identified environmental impacts of the Expansion Project. To start, Riverview concedes that "it is difficult to accurately quantify the GHG reductions" of almost all the listed mitigation methods.[51] Despite the many mitigation activities touted in the EAW, Riverview itself acknowledges that "only two have clearly quantified reductions: (1) Alfalfa Conversion Carbon Sink, and (2) Area Ammonia Replacement."[52] The EAW also omits many alternative emission mitigation methods that could be reasonably expected to effectively mitigate the identified environmental impacts of the Expansion Project. Riverview does no alternative scenario modeling.

1. Mitigations identified in the EAW are unreliable and overstated

Several of Riverview's proposed mitigation approaches are flawed and unreliable, including its reliance on emissions reductions from alfalfa conversion and ammonia replacement.

As a threshold matter, the theoretical reductions in emissions from row crop conversion cannot count as "mitigations" for purposes of the MPCA determination because emissions from crop production (scope 3) were not included in the calculation of the Expansion Project's emission total. Riverview cannot claim a benefit from the possible GHG emissions avoided by row crop to alfalfa conversion when the EAW fails to identify crop production emissions as operational emissions.

a. Conversion of row crops to alfalfa

The EAW claims that converting row crops to alfalfa is an emissions-negative way to meet required feed production for the Expansion Project and that "1.21 tons CO_2e are avoided annually for each acre of row crop converted to alfalfa. The Project's cattle will require approximately 2,200 acres of alfalfa produced for feed each year," thus resulting in "a reduction in GHG emissions by 2,662 tons CO_2e per year."[53] But that assumed rate equates to approximately 2.99 tons CO_2e per hectare per year, or roughly 0.81 tons C per hectare per year—a relatively high soil-carbon sequestration assumption compared to published syntheses. For example, a global synthesis of soil organic carbon under perennial crops found that conversion from annual to perennial crops produced an average gain of 6.0 ± 4.6 Mg C/ha over 20 years in the 0–30 cm soil layer—approximately 0.30 Mg C/ha/year—with substantial variability and uncertainty across sites.[54] Similarly, a synthesis of 103 publications and 160 sites found that farmland-to-grassland conversion increased soil carbon stocks by approximately 0.30 Mg/ha/year.[55] More regionally relevant literature also counsels caution. A review of long-term Iowa studies found that conversion of cropland to perennial grassland increased soil organic carbon by 0.21–0.74 Mg C/ha/year, but emphasized that soil carbon responses were highly variable, slow to detect, and not always statistically significant.[56] And a 30-year study in southern Wisconsin found that alfalfa-based dairy forage systems actually lost an average of 0.54 ± 0.13 Mg C/ha/year—meaning alfalfa-based systems represent

[51] *Riverview's EAW for West River Dairy, supra* note 17, at 65.
[52] *Id*.
[53] *Id*.
[54] Alicia Ledo et al., *Changes In Soil Organic Carbon Under Perennial Crops*, 26 GLOB CHANGE BIOL. 4158 (2020), https://nora.nerc.ac.uk/id/eprint/527969/1/N527969JA.pdf [Exhibit 28].
[55] Lei Deng et al., *Global Patterns of the Effects of Land-Use Changes on Soil Carbon Stocks*, 5 GLOB ECOLOGY & CONSERVATION 127 (2016), https://doi.org/10.1016/j.gecco.2015.12.004 [Exhibit 29].
[56] Jim Jordahl et al., *Carbon Storage in Cropland Soils: Insights from Iowa, United States*, 12 LAND 1630 (2023), https://doi.org/10.3390/land12081630 [Exhibit 30].

a carbon source, not a carbon sink.[57] Applied to Riverview's claimed 2,200 acres of alfalfa, the Wisconsin study's rate would imply approximately +1,763 metric tons CO_2/year rather than an emissions reduction. These studies show that the EAW cannot simply treat the alfalfa acreage as a fixed, annual emissions-negative credit without further support.

Even assuming that all feed production needs will be met by the 2,200 acres of alfalfa—which is not realistic as discussed above[58] —using land to grow alfalfa still results in emissions, even if those emissions are lower than they would be if the land was used to grow row crops. Rather than a mitigation that reduces the Expansion Project's emissions, the alfalfa conversion merely generates fewer emissions for the Expansion Project than row crops would. To illustrate this with a hypothetical, if row crops for required feed production generate 50,000 tons of emissions per year, and the alfalfa conversion reduces those emissions by 2,662 tons CO_2e per year, then the total feed-production-related emissions would be 47,378 tons CO_2e per year (50,000 minus 2,622). This number is greater than zero, and certainly not a mitigation, as the EAW claims.

The EAW's claim of net negative emission from feed production seems to stem from the following erroneous assumption:

> The nearby cropland that will be used for feed production for the Project is already in crop production. Since the Project will not trigger new crop production and will create a market for crops already being grown, a reduction in GHG emissions is anticipated due to the shorter transportation distance of those crops to the Project.[59]

This assumption ignores the reality that, by removing the supply of row crops already in production to feed the Expansion Project's cattle, market forces will replace the displaced row crops production in another location. This indirect land-use change may result in even greater emissions than the emissions reduction from the alfalfa conversion. And if required feed production for the Expansion Project's cattle is not entirely met by the 2,200 acres of alfalfa (as seems likely), then the EAW is also ignoring the emissions generated by other feed production required to meet the need of the Expansion Project's cattle. The EAW itself seems to assume that some amount of other row crops will be required for feed production, as evidenced by the statement discussed earlier that the Expansion Project will use nearby cropland.

Additionally, the EAW's alfalfa credit is unsupported because it assumes that 2,200 acres of alfalfa represent a durable conversion from row crops to an emissions-negative feed source. In the Upper Midwest, however, alfalfa is commonly grown as part of a crop rotation, not as a permanent replacement for annual row-crop production. A regional study of alfalfa stand length and subsequent crop patterns in Minnesota, Iowa, Wisconsin, Nebraska, North Dakota, and South Dakota found that corn was the most common crop planted in both the first and second years after alfalfa—79% and 61% of cases, respectively—and soybean was also commonly planted after alfalfa.[60] Thus, it is unclear whether the Expansion Project would actually convert permanent row-crop acreage to long-term alfalfa production, or merely introduce alfalfa temporarily within existing row-crop rotations. This distinction matters because any claimed soil-carbon benefit from alfalfa depends on duration, permanence,

[57] C. Dietz et al., *Soil Carbon Maintained By Perennial Grasslands Over 30 Years But Lost in Field Crop Systems in a Temperate Mollisol*, 5 COMMC'NS EARTH ENV'T 360 (2024), https://doi.org/10.1038/s43247-024-01500-w [Exhibit 31].
[58] *See supra* notes 37-39 and accompanying text.
[59] Riverview's EAW for West River Dairy, supra note 17, at 64.
[60] Matt Yost et al., Alfalfa Stand Length and Subsequent Crop Patterns in the Upper Midwestern United States, AGRONOMY J. 1697-1708 (2014), https://doi.org/10.2134/agronj14.0014 [Exhibit 32].

management, and what happens after the alfalfa stand is terminated. If the acreage returns to corn or soybean production after a short rotation, any carbon benefit may be temporary, reduced, or reversed.

The EAW's claimed alfalfa credit is also unreliable because it is impossible to determine whether Riverview accounted for the nitrous oxide emissions associated with alfalfa production. The EAW treats conversion of row crops to alfalfa as a fixed emissions reduction, claiming that 1.21 tons CO_2e are avoided annually per acre and that 2,200 acres of alfalfa would therefore reduce emissions by 2,662 tons CO_2e per year.[61] But as a nitrogen-fixing crop, alfalfa can increase soil nitrogen availability and contribute to nitrous oxide emissions—a particularly powerful GHG—through nitrification and denitrification, particularly following rainfall, irrigation, and other soil-wetting events. A recent study found that continuous alfalfa growth was a substantial N_2O source, that short-term "hot moments" accounted for up to 57% of annual N_2O emissions, and that N_2O emissions reduced the system's carbon-sink potential by up to 14% annually.[62] When harvested biomass removal was considered, N_2O emissions offset 70% of the remaining ecosystem carbon sink.[63] The EAW does not disclose whether its alfalfa credit is net of N_2O emissions, whether it assumes any site-specific soil carbon sequestration, or whether it accounts for carbon removed from fields through repeated alfalfa harvests and later converted to CO_2 and methane when used as cattle feed. This omission is material. The Expansion Project cannot claim alfalfa as an emissions-negative feed source while failing to evaluate the GHG emissions generated by producing, harvesting, and fertilizing that alfalfa.

b. Ammonia-replacement credit

The EAW also claims that replacing ammonia fertilizer used on farms in surrounding areas with manure generated by the Expansion Project will mitigate the Expansion Project's emissions,[64] because ammonia from other sources would likely be produced through the energy-intensive Haber-Bosch process.[65] However, the EAW's modeling of emissions from the electricity required by the Haber-Bosch process relies on an emissions factor for the Midwest Reliability Organization West ("MROW") region.[66] While the MROW region includes Minnesota, it also includes parts of eight other states with various fuel mixes to generate electricity.[67] A more accurate model would use the emissions factor for Minnesota's electricity generation, which has a resource mix for electricity generation that is cleaner than the MROW region,[68] resulting in a lower emissions factor. Employing a lower, Minnesota-specific emissions factor in the EAW would result in a smaller emissions reduction from area ammonia replacement than Riverview claims.

Additionally, the EAW's ammonia-replacement credit assumes, without support, a particular fertilizer-sourcing baseline. The EAW claims that manure generated by the Expansion Project will replace approximately 1,545 tons per year of anhydrous ammonia and therefore reduce emissions by 9,038 tons CO_2 per year.[69] But the EAW does not establish what synthetic fertilizer products are currently used on the receiving fields, where those fertilizers are produced, whether the displaced product would in fact be anhydrous ammonia, or whether manure application would displace synthetic fertilizer on a one-for-

[61] Riverview's EAW for West River Dairy, supra note 17, at 65.
[62] Tyler L. Anthony et al., *Carbon-Sink Potential of Continuous Alfalfa Agriculture Lowered by Short-Term Nitrous Oxide Emission Events*, 14 NATURE COMMC'NS 1926 (2023), https://www.nature.com/articles/s41467-023-37391-2 [Exhibit 33].
[63] Riverview's EAW for West River Dairy, supra note 17, at 64.
[64] Id. at 65.
[65] See Id.
[66] Id. at Attachment 21.
[67] Power Profiler for MROW, EPA, https://www.epa.gov/egrid/power-profiler#/MROW (last visited May 5, 2026) [Exhibit 34].
[68] Compare id. with MPCA GHG EMISSIONS IN MINNESOTA, supra note 4, at 13 (describing Minnesota's electricity generation resource mix).
[69] Riverview's EAW for West River Dairy, supra note 17, at 65.

one basis. These omissions matter because, while Minnesota is a major ammonia-consuming state, it appears to have no in-state ammonia production facilities: nearly all ammonia fertilizer used in Minnesota is produced outside the State and transported long distances, often from the Gulf Coast.[70] Thus, the EAW's claimed ammonia-replacement credit rests on an unsupported assumption about the source and emissions intensity of the fertilizer being displaced. At minimum, the EAW should identify the baseline fertilizer products used on the relevant fields, the likely production region and fuel mix for those products, and the amount of synthetic fertilizer that would actually be displaced before treating ammonia replacement as a fixed emissions reduction.

The EAW's modeling also assumes that the emissions factor for electricity generation will remain constant throughout the Expansion Project's lifespan. A more accurate model would take into account likely future emissions intensity reductions for the Haber-Bosch process to produce ammonia. Along with many states within the MROW region, Minnesota has reduced emissions from electricity generation over recent decades and has adopted climate goals to further reduce those emissions. For example, Minnesota reduced its GHG emissions from electricity generation by 50% from 2005 to 2022, and the "Minnesota Legislature adopted a new Clean Electricity Standard that requires electric utilities to provide net-zero, or 100% carbon-free, electricity by 2040."[71] More accurate modeling would reduce the scale of the mitigation from the Expansion Project's area ammonia replacement.

c. Other proposed mitigation methods

Other mitigation methods proposed in the EAW lack quantified emissions reductions, are theoretically flawed, and/or lack adequate supporting evidence. For instance, the EAW claims that the Expansion Project's use of Holstein-Jersey crossbred dairy cows will reduce GHG emissions per unit of milk produced, as compared to traditional Holstein cows.[72] Yet this claim is only supported with research on the emissions of Jersey cows compared to Holstein cows.[73] The EAW fails to provide any research on potential emissions reductions from the crossbred Holstein-Jersey cows that will be used in the Expansion Project.

The EAW also claims that the Expansion Project will employ efficient feed practices, "including research and use of feed additives such as Rumensin, to reduce GHG emissions by up to 4,365 tons CO_2e per year."[74] Yet the EAW provides zero citations or research on potential emissions reductions from efficient feed practices or feed additives, making it unclear why the EAW mentions Rumensin specifically and how Riverview calculated the alleged reduction of 4,365 tons CO_2e. Finally, the EAW claims that "[i]f market conditions allow, and renewable electricity is purchased from the utility provider for the Project, there would be a potential GHG offset of 5,520 tons CO_2e per year."[75] First, this mitigation is tentative

[70] Quailan Homann et al., Roadmap for Distributed Green Ammonia in Minnesota, RMI (June 2024), https://rmi.org/wp-content/uploads/dlm_uploads/2024/06/roadmap_for_distributed_green_ammonia_in_minnesota.pdf [Exhibit 35] (reporting that Minnesota is the fourth-highest ammonia-fertilizer-consuming state, accounting for more than 10% of market demand, but has no ammonia production facilities); Noah Fish, Local Ammonia Project Could Stabilize Fertilizer Supply For Southern Minnesota Farmers, A G WEEK (Mar. 17, 2026), https://www.agweek.com/local-ammonia-project-could-stabilize-fertilizer-supply-for-southern-minnesota-farmers [Exhibit 36]. Fertilizer sales data from the Minnesota Department of Agriculture is not helpful on this point, as it tracks fertilizer sales and distribution in Minnesota, rather than the state or region of production. Fertilizer Use, Nutrient Management Survey, MINN. DEP'T OF AGRIC., https://www.mda.state.mn.us/pesticide-fertilizer/fertilizer-use-sales-data (last visited May 5, 2026).
[71] MPCA GHG EMISSIONS IN MINNESOTA, *supra* note 4, at 13.
[72] *Riverview's EAW for West River Dairy, supra* note 17, at 63.
[73] *Id*.
[74] *Id*. at 66.
[75] *Id*.

and expressly conditioned on market conditions. Second, it lacks any citations to support the calculation of a 5,520 CO_2e offset.

The EAW also contends that "[m]eeting growing global dairy demand from less-efficient dairy production outside of North America would have a more detrimental impact on global climate change" than by meeting that demand with more-efficient dairy production inside of North America.[76] Even assuming that (1) global dairy demand will increase, (2) unmet demand would be satisfied through imports, and (3) North American dairy production is more emissions-efficient on a per-unit basis, this argument is beside the point and does not bear on the inquiry before MPCA. The question under environmental review is not whether the Expansion Project might be more efficient than hypothetical production elsewhere, but rather whether the Expansion Project's actual, incremental emissions have the potential to cause significant environmental effects in Minnesota.[77]

Moreover, the argument improperly substitutes emissions intensity (emissions per unit of production) for absolute emissions.[78] While it is often asserted that U.S. or North American dairy systems are more efficient on a per-unit basis, improvements in efficiency do not necessarily reduce total emissions.[79] In fact, increased productivity has historically coincided with increases in total sector emissions as production expands.[80] This reflects a well-established phenomenon: efficiency gains can lower emissions per unit while still increasing total emissions when overall output grows.

Most importantly, this line of reasoning is legally and analytically irrelevant to MPCA's obligations. The argument assumes that denying or conditioning this Expansion Project would result in increased production elsewhere, rather than reduced demand, substitution, or shifts in consumption. Such leakage-style arguments rest on speculative and unsupported assumptions about global market responses. The EAW provides no basis for making these assumptions.

The Minnesota Supreme Court held in *Citizens Advocating Responsible Development v. Kandiyohi County Board of Commissioners* that an RGU may not rely on vague or unsupported mitigation concepts.[81] Riverview is making a generalized claim that the Expansion Project is preferable to an imagined alternative production scenario somewhere else in the global dairy market. This argument does not reduce the Expansion Project's actual emissions. It does not impose any enforceable operational requirement. It does not identify a specific avoided source. And it does not provide substantial evidence that any claimed global emissions reduction will occur. At most, it is a policy argument about the relative efficiency of North American dairy production. It cannot be treated as mitigation, cannot offset the Expansion Project's quantified GHG emissions, and cannot support a negative EIS determination. Accepting such reasoning would effectively allow any high-emitting project to evade scrutiny by asserting that emissions might be higher elsewhere, undermining the purpose of environmental review entirely.

2. The EAW fails to discuss several mitigation measures that could actually reduce the Expansion Project's emissions

[76] *Riverview's EAW for West River Dairy, supra* note 17, at 65.
[77] Minn. R. 4410.1700, subp. 7.
[78] News Release, Climate Council, What's the difference between absolute emissions and emissions intensity? (Aug. 4, 2015), https://www.climatecouncil.org.au/what-is-the-difference-between-absolute-emissions-and-emissions-intensity/ [Exhibit 37].
[79] *See, e.g.*, Andrew Hunt, *Discover How U.S. Cows Are Shattering Milk Production Efficiency Records!*, BULL VINE (Aug. 23, 2024), https://www.thebullvine.com/news/discover-how-u-s-cows-are-shattering-milk-production-records [Exhibit 38].
[80] C.A. Rotz et al., *Fifty Years of Environmental Progress for United States Dairy Farms*, 107 J. OF DAIRY SCI. 6, 1 (2024) [Exhibit 39].
[81] 713 N.W.2d 817, 835 (Minn. 2006).

The EAW does not consider scenarios that improve manure management, build out renewable energy, or improve livestock conditions. Approaches such as these have been shown to reduce GHG emissions from animal agriculture.[82] Despite the Expansion Project's significant and continuous energy demands and emissions, the EAW does not quantify potential emissions reductions from these readily available and increasingly cost-effective strategies, nor does it evaluate their feasibility or effectiveness. Without that information, MPCA and the public cannot determine whether feasible mitigation measures could materially reduce the Expansion Project's emissions; whether the EAW's proposed mitigation is adequate, durable, or enforceable; or whether the Expansion Project's GHG impacts can be reduced below the level of significance.

a. Manure management

The Expansion Project will use clay-lined basins with impermeable covers to collect and store manure and wastewater, with liquid manure subsequently land applied as fertilizer on cropland.[83] As such, the Expansion Project's manure management system will be a major and persistent source of methane and nitrous oxide emissions. The EAW entirely fails to discuss alternatives, such as dry or composting systems, that can significantly reduce methane emissions.

Manure management makes up a significant portion of dairy cow emissions.[84] As dairy operations have gotten bigger, they increasingly produce and collect large volumes of liquid (rather than solid) manure.[85] This Expansion Project's manure management strategy is no exception. Storing liquid manure in anaerobic environments—such as ponds, lagoons, and the clay-lined basins proposed here—promotes bacterial activity that leads to methane production.[86] Per the EPA: "[M]anure management systems with the most substantial methane emissions are those associated with confined animal management operations where manure is handled in liquid-based systems."[87] Stored manure also produces nitrous oxide and carbon dioxide.[88] Thus, the Expansion Project's proposed manure management system reflects precisely the type of system that is widely recognized as a major and persistent source of GHG emissions.

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[82] LEHNER & ROSENBERG , *supra* note 14, at 81.

[83] Riverview's EAW for West River Dairy, supra note 17, at 2.

[84] Søren O. Petersen, Greenhouse Gas Emissions from Liquid Dairy Manure: Prediction and Mitigation, 101 J. DAIRY SCI. 6642, 6651 (2018) [Exhibit 40].

[85] ENVIRONMENTAL PROTECTION AGENCY, INVENTORY OF U.S. GREENHOUSE GAS EMISSIONS AND SINKS : 1990–2022, 5-12 to 5-13 (2024), https://www.epa.gov/system/files/documents/2024-04/us-ghg-inventory-2024-main-text_04-18-2024.pdf [Exhibit 41, hereinafter "EPA GHG INVENTORY "].

[86] CARRIE HRIBAR, NAT'L ASS'N OF LOCAL BDS. OF HEALTH, UNDERSTANDING CONCENTRATED ANIMAL FEEDING OPERATIONS AND THEIR IMPACT ON COMMUNITIES 7 (2010) [Exhibit 42]; Paul Jun et al., CH_4 and N_20 Emissions from Livestock Manure, in GOOD PRACTICE GUIDANCE AND UNCERTAINTY MANAGEMENT IN NATIONAL GREENHOUSE GAS INVENTORIES 321, 322-23 (IPCC 2000), https://www.ipcc-nggip.iges.or.jp/public/gp/gpg-bgp.html [Exhibit 43]; FAO, GREENHOUSE GAS EMISSIONS FROM RUMINANT SUPPLY CHAINS : A GLOBAL LIFE CYCLE ASSESSMENT 68–70 (2013), https://www.fao.org/3/i3461e/i3461e.pdf [Exhibit 44]; EMMETT INST. ON CLIMATE CHANGE & ENV'T, UCLA L. SCH., MITIGATING EMISSIONS FROM CALIFORNIA'S DAIRIES: CONSIDERING THE ROLE OF ANAEROBIC DIGESTERS 16 (2024), https://law.ucla.edu/sites/default/files/PDFs/Publications/Emmett%20Institute/UCLA_Emmett_CA_Dairies_1%2018%2024.pdf [Exhibit 45]; Riverview's EAW for West River Dairy, supra note 17, at 2. According to EPA, "manure management systems with the most substantial methane emissions are those associated with confined animal management operations where manure is handled in liquid-based systems." EPA GHG INVENTORY , supra note 85, at 5-12; see also IPCC, GOOD PRACTICE GUIDANCE AND UNCERTAINTY MANAGEMENT IN NATIONAL GREENHOUSE GAS INVENTORIES 1, 322–23 (2000), available at https://www.ipcc-nggip.iges.or.jp/public/gp/gpg-bgp.html.

[87] EPA GHG INVENTORY, supra note 85, at 5-12; see also Jun et al., supra note 86, at 323.

[88] Jun et al., supra note 86, at 323; Philippe & Nicks, supra note 49, at 12.

When manure is applied to fields, exposure to oxygen and microbes in the soil can convert nitrogen from the manure into nitrous oxide, and the manure also produces carbon dioxide as it breaks down.[89] Cattle raised in the United States often live on farms that produce more manure than the surrounding land can absorb,[90] leading to nutrient runoff that creates GHGs and other pollution.[91]

That these clay-lined basins will be fitted with impermeable covers provides little relief.[92] While the use of impermeable covers may reduce certain emissions pathways—such as limiting ammonia volatilization and reducing rainfall infiltration that can increase storage volume—it does not eliminate methane generation from the stored manure. Methane production continues beneath the covers, and covered systems remain a significant source of GHG emissions.[93] Moreover, the scale of the proposed operation—generating over 200 million gallons of manure and wastewater annually—means that even marginal per-unit emission rates will translate into substantial absolute emissions increases over time.[94]

The Expansion Project's reliance on land application of manure compounds these impacts. Although manure can displace some synthetic fertilizer use, its application—particularly at the volumes contemplated here—increases the risk of nitrous oxide emissions from soils, especially under conditions of excess nitrogen, variable weather, and saturated soils.[95] In addition, nutrient runoff associated with over-application or extreme precipitation events contributes to downstream water quality degradation, which in turn can drive secondary GHG emissions, including nitrous oxide from aquatic systems.

The EAW fails to adequately evaluate whether the surrounding cropland can consistently and safely absorb the Expansion Project's manure supply. The EAW states that the Expansion Project will require approximately 7,700 acres for manure application and that the combined Expansion Project and existing facility will require approximately 13,200 acres, with 16,669 acres identified as available.[96] But those acres are not simply co-located immediately around the facility: the EAW identifies manure application sites across five townships in Stevens County and two townships in Swift County.[97] At the same time, the EAW does not provide a field-by-field nutrient balance, distance-weighted transport analysis, or average and maximum manure movement distances. Nor does it quantify the emissions associated with pumping, transferring, hauling, or otherwise moving manure to those fields. As such, the EAW does not demonstrate that the Expansion Project's manure can be applied at agronomic rates each year without

[89] Jan Broucek, Nitrous Oxide Production from Cattle and Swine Manure, 5 J. ANIMAL BEHAV. & BIOMETEOROLOGY 13, 13-16 (2017) [Exhibit 46]; Philippe & Nicks, supra note 49, at 12.
[90] HRIBAR, *supra* note 86, at 2–3 (explaining that the quantity of manure produced by concentrated animal feeding operations (CAFOs) cannot all be used as fertilizer); *see also* RUTHIE LAZENBY, CTR. FOR AGRIC. & FOOD SYS., VT. L. SCH., RETHINKING MANURE BIOGAS: POLICY CONSIDERATIONS TO PROMOTE EQUITY & PROTECT THE CLIMATE & ENVIRONMENT 18 (2022), https://www.vermontlaw.edu/sites/default/files/2022-08/Rethinking_Manure_Biogas.pdf [Exhibit 47] ("[V]ery large facilities often cannot dispose of all of their manure safely through land application without exceeding the amount of nutrients the land can take up . . . .").
[91] Jake Beaulieu et al., *Climate Benefits of Reducing Nutrient Pollution in Aquatic Ecosystems* (EPA, 2021 Social Cost of Water Pollution Workshop, 2021) [Exhibit 48]; Michael A. Mallin et al., *Industrial Swine and Poultry Production Causes Chronic Nutrient and Fecal Microbial Stream Pollution*, 226 WATER, AIR, & SOIL POLLUTION 1, 10–11 (2015) [Exhibit 49].
[92] Riverview's EAW for West River Dairy, supra note 17, at 2.
[93] Semra Bakkaloglu et al., Methane Emissions Along Biomethane and Biogas Supply Chains are Underestimated, 5 ONE EARTH 724-736 (2022), https://www.cell.com/one-earth/fulltext/S2590-3322(22)00267-6 [Exhibit 50].
[94] Riverview's EAW for West River Dairy, supra note 17, at 63.
[95] John A. Lory et al., Calculating Plant-Available Nitrogen and Residual Nitrogen Value in Manure, UNIV. OF MO. EXTENSION (Dec. 2007), https://extension.missouri.edu/publications/g9186 [Exhibit 51].
[96] Riverview's EAW for West River Dairy, supra note 17, at 8.
[97] Id. at 24.

increasing nitrous oxide or transport-related emissions,[98] and (as discussed more in infra Part IV) runoff risk and other pollution.

Transitioning from long-term liquid storage systems to dry or composting systems paired with non-digester covered storage can significantly reduce methane emissions.[99] Whereas liquid manure systems maintain oxygen-deprived environments that are ideal for methanogenic bacteria,[100]dry handling and composting systems promote aerobic conditions, in which oxygen is present and microbial communities instead produce carbon dioxide (a substantially less potent GHG) rather than methane.[101]

Solid manure management systems, including scrape-and-stack methods, frequent removal from housing areas, and composting, reduce the residence time of manure in anaerobic conditions and limit the accumulation of large volumes of wet waste.[102] Composting, in particular, can be managed to maintain optimal temperature, moisture, and aeration levels, further suppressing methane formation

[98] Curtis Dell et al., Challenges and Opportunities for Manureshed Management Across U.S. Dairy Systems: Case Studies From Four Regions, 51 J. OF ENV'T QUALITY 521–539 (2022), https://doi.org/10.1002/jeq2.20341 [Exhibit 52] (finding that where manure production exceeds nearby cropland's assimilative capacity, off-farm transport becomes necessary, but transportation costs and logistics complicate effective redistribution); Sheri Spiegal et al, Manuresheds: Advancing Nutrient Recycling in US Agriculture, 182 AGRIC. SYSTEMS 102813 (2020), https://doi.org/10.1016/j.agsy.2020.102813 https://www.sciencedirect.com/science/article/pii/S0308521X19311679 [Exhibit 53] (finding that manure nutrients often concentrate in source regions where they threaten environmental health, and that manure may need to be moved long distances to reach land capable of assimilating excess nutrients).

[99] FAO, GREENHOUSE GAS EMISSIONS FROM RUMINANT SUPPLY CHAINS, supra note 86; Broucek, supra note 89, at 13–16; Philippe & Nicks, supra note 49, at 12.

[100] Frederik Dalby et al., Understanding Methane Emission from Stored Animal Manure: A Review to Guide Model Development, 50 J. ENV'T QUALITY 817–835 (2021), https://doi.org/10.1002/jeq2.20252 [Exhibit 54]. Even if mitigation methods were to be proposed to help reduce emissions from the planned liquid manure system, such methods are limited and inadequate. If the applicant were to propose installing a biodigester, the limitations and counterproductive results of that technology are critical to consider. Anaerobic digesters, often promoted as a methane mitigation strategy, present significant limitations and risks. We're Challenging the NC Permit for Hog Waste Operations Causing Pollution and Harm to Communities, S. ENV'T L. CTR. (Aug. 4, 2022), https://www.southernenvironment.org/news/were-challenging-the-n-c-permit-for-hog-waste-operations-causing-pollution-and-harm-to-communities [Exhibit 55]; see also LAZENBY, RETHINKING MANURE BIOGAS, supra note 90 at 18. They do not eliminate methane emissions and can leak substantial amounts of methane across the biogas supply chain. Thomas Flesch et al., Fugitive Methane Emissions from an Agricultural Biodigester, 35 BIOMASS & BIOENERGY 3927, 3927 (2011) [Exhibit 56]; Bakkaloglu et al., supra note 93 at 730–731; Norah Efosa et al., Emissions of Nitrous Oxide and Methane After Field Application of Liquid Organic Fertilizers and Biochar, 356 AGRIC, ECOSYSTEMS & ENV'T 1, 1 (2023) [Exhibit 57]; Thomas Kupper et al., Ammonia and Greenhouse Gas Emissions from Slurry Storage – A Review, 300 AGRIC., ECOSYSTEMS & ENV'T 1, 1 (2020) [Exhibit 58]; Alyssa Valdez et al., Evaluating the Impact of Anaerobic Digesters on Point Source Methane Emissions from California Dairies from Remote Sensing, 21 ENV'T RSCH. LETTERS 064018 (2026), https://iopscience.iop.org/article/10.1088/1748-9326/ae4fe4/pdf [Exhibit 59]. In addition, digesters can exacerbate other pollutants, including nitrous oxide and ammonia, particularly after land application of digestate. They have also been associated with safety hazards such as gas buildup, explosions, and storage failures, posing risks to human health and the environment. Ji-Qin Ni, Cases, Causes, and Impacts of Safety Incidents at AD Systems, (unpublished workshop presentation, PURDUE UNIV.) 7–23 (Mar. 10, 2023), https://engineering.purdue.edu/adt/workshop/230310/ni.pdf [Exhibit 60]; Frank H. Hedlund, Biomass Accident Investigations—Missed Opportunities for Learning & Accident Prevention, 25TH EUR. BIOMASS CONF. & EXHIBITION (June 2017) [Exhibit 61]. Finally, biogas production is costly and typically relies on substantial subsidies, raising questions about its long-term viability as a climate solution. Aaron Smith, What's Worth More: A Cow's Milk or Its Poop?, AG DATA NEWS SUBSTACK (Feb. 3, 2021), https://agdatanews.substack.com/p/whats-worth-more-a-cows-milk-or-its [Exhibit 62].

[101] Sarah Nordahl et al., *Greenhouse Gas and Air Pollutant Emissions from Composting*, 57 ENV'T SCI. TECH. 2235-2247 (2023), https://pmc.ncbi.nlm.nih.gov/articles/PMC9933540/ [Exhibit 63]; Justine Owen & Whendee Silver, *Greenhouse Gas Emissions From Dairy Manure Management: A Review Of Field-Based Studies*, GLOB. CHANGE BIOLOGY (2014), https://matteroftrust.org/wp-content/uploads/2015/11/Owen-and-Silver-GCB-2014.pdf [Exhibit 64].

[102] LAZENBY, RETHINKING MANURE BIOGAS, *supra* note 90, at 26; Dave Chadwick et al., *Manure Management: Implications for Greenhouse Gas Emissions*, 166 ANIMAL FEED SCI. & TECH 514-531 (2011), https://doi.org/10.1016/j.anifeedsci.2011.04.036 [Exhibit 65]; D. Meyer et al., *Survey of Dairy Housing and Manure Management Practices in California*, 94 J. OF DAIRY SCI. 4744-4750 (2011), https://doi.org/10.3168/jds.2010-3761 [Exhibit 66].

while stabilizing nutrients.[103] When properly implemented, these systems can result in orders-of-magnitude reductions in methane emissions compared to conventional liquid storage.[104]

Additionally, where some degree of storage remains necessary, transitioning to covered storage that minimizes moisture inputs (e.g., by excluding precipitation) without creating sealed anaerobic conditions can further reduce emissions. Unlike impermeable lagoon covers that trap and concentrate methane beneath them, requiring a vent or adsorbents to avoid explosion, non-digester covered or dry-stack storage systems aim to prevent excess water infiltration while maintaining conditions that discourage methanogenesis.[105]

Importantly, these alternative systems can also provide co-benefits, including reduced risk of catastrophic spills, improved nutrient management, and lower potential for downstream water contamination.[106] While they may require different infrastructure and management practices, they represent a well-established pathway for materially reducing the climate impact of manure management—particularly for large-scale operations where liquid systems would otherwise generate substantial and continuous methane emissions.

b. Renewable energy buildout

Renewable energy buildout is another concrete mitigation pathway the EAW should have evaluated, rather than treating renewable electricity as a contingent, market-dependent offset. The Expansion Project will create substantial ongoing electricity and fuel demand for cross-ventilated barns, milking and milk-cooling operations, ventilation systems, pumps, lighting, manure handling, and related equipment; yet the EAW does not model whether those loads could be reduced through on-site solar arrays, dedicated wind procurement or development, electrification of diesel-powered machinery and other farm equipment, or battery storage and demand-response measures to manage peak loads and maximize on-site renewable use.[107]

Peer-reviewed research supports the relevance of these measures: dairy-specific studies have found that photovoltaic ("PV") systems can feasibly supply dairy-farm electricity loads and reduce the GHG intensity of farm electricity by up to 29%, and a recent techno-economic assessment of dairy-farm solar PV with battery storage found substantial CO_2 reductions under farm-specific operating profiles.[108] Studies of large-scale dairy farms also show that milking and related operations contribute to electricity demand peaks, and that demand flexibility or storage technologies can reduce peak impacts.[109]

Likewise, agricultural machinery electrification is a feasible decarbonization pathway for replacing diesel equipment, and life-cycle assessment research has found battery-electric tractors to have substantially

[103] E. Pattey et al., *Quantifying the Reduction of Greenhouse Gas Emissions as a Result of Composting Dairy and Beef Cattle Manure*, 72 NUTRIENT CYCLE AGROECOSYST 173–187 (2005), https://doi.org/10.1007/s10705-005-1268-5 [Exhibit 67].
[104] *Id*.
[105] Herald Wilson Ambrose et al., *Additives and Methods for the Mitigation of Methane Emission from Stored Liquid Manure*, 229 BIOSYSTEMS ENG'G 209-245 (2023), https://doi.org/10.1016/j.biosystemseng.2023.03.015 [Exhibit 68].
[106] Shidi Ba et al., *Meta-Analysis of Greenhouse Gas and Ammonia Emissions From Dairy Manure Composting*, 193 BIOSYSTEMS ENG'G 126-137 (2020), https://doi.org/10.1016/j.biosystemseng.2020.02.015 [Exhibit 69]; *20,000 Gallons of Liquid Manure Leak From Tank at Albany, Minn. Farm*, FOX 9 (Sept. 25, 2019), https://www.fox9.com/news/20000-gallons-of-liquid-manure-leak-from-tank-at-albany-minn-farm [Exhibit 70].
[107] *Riverview's EAW for West River Dairy, supra* note 17, at 64, Attachment 21.
[108] Jonathan Dean et al., *Modelling Solar Photovoltaic Systems on Dairy Farms for Cost Savings and GHG Emission Reduction*, 948 SCI. OF THE TOTAL ENV'T 174874 (2024), https://doi.org/10.1016/j.scitotenv.2024.174874 [Exhibit 71].
[109] Jefferson Dew et al., *Reducing Electricity Demand Peaks on Large-Scale Dairy Farms*, 25 SUSTAINABLE PROD. & CONSUMPTION 248 (2021), https://doi.org/10.1016/j.spc.2020.08.014 [Exhibit 72].

lower GWP than conventional tractor systems when evaluated over the full use phase and life cycle.[110] Dedicated wind energy should also have been assessed as a low-carbon electricity source, subject to site-specific resource, interconnection, and land-use constraints.[111]

c. Livestock management

Improved livestock management can also significantly reduce the volume and intensity of GHG emissions from feedlots. Reducing use of nontherapeutic antibiotics can prevent increased methane emissions from animals' disrupted microbiomes.[112] Healthier animals are more productive and emit fewer GHGs per unit of output.[113] By contrast, animals in overcrowded conditions experience more stress, contributing to disease spread and inefficient feed conversion, all of which can increase methane and nitrous oxide emissions per animal.[114]

The cows living in the proposed feedlot will be housed in a cross-ventilated, total-confinement, free-stall barn.[115] In free-stall total confinement systems, cows are housed indoors year-round in controlled environments. Such systems are typically associated with higher reliance on energy inputs (e.g., ventilation, cooling) and, as discussed above, centralized manure collection systems that can increase methane emissions if manure is stored in liquid form.[116] Moreover, large-scale confinement can exacerbate the stress and disease pressures that reduce feed efficiency and increase emissions intensity.

By contrast, pasture-based systems allow cows to engage in a broader range of natural behaviors, including grazing, walking, and social interaction in more dynamic environments.[117] Access to pasture is generally associated with improved hoof health, lower rates of lameness, and increased behavioral expression.[118] Pasture systems can also reduce stress by allowing animals to self-regulate movement,

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[110] Elia Scolaro et al., *Electrification of Agricultural Machinery: A Review*, 9 IEEE ACCESS 164520-164541 (2021), https://doi.org/10.1109/ACCESS.2021.3135037 [Exhibit 73]; Oscar Lagnelov et al., *Life Cycle Assessment of Autonomous Electric Field Tractors in Swedish Agriculture*, 13 SUSTAINABILITY 11285 (2021), https://doi.org/10.3390/su132011285 [Exhibit 74].

[111] M. Faizan & I. Afgan, *Life Cycle Assessment Of Wind Turbine Systems: A Statistical Synthesis Approach To Address Greenhouse Gas Emissions*, 226 RENEWABLE AND SUSTAINABLE ENERGY REVIEWS 116429 (2026), https://doi.org/10.1016/j.rser.2025.116429 [Exhibit 75].

[112] Tobin J. Hammer et al., Treating Cattle with Antibiotics Affects Greenhouse Gas Emissions, and Microbiota in Dung and Dung Beetles, 283 PROCEEDINGS ROYAL SOC' Y BIOLOGICAL SCI. 1, 5 (2016) [Exhibit 76].

[113] FAO, PATHWAYS TOWARDS LOWER EMISSIONS: A GLOBAL ASSESSMENT OF GHG EMISSIONS & MITIGATION OPTIONS FROM LIVESTOCK AGRIFOOD SYSTEMS 1, 32 (2023) [Exhibit 77] (reporting that increased productivity and improved animal health can reduce global livestock emissions by 30%); Tara L. Felix, *Beef Cattle Spacing Requirements*, PENN STATE EXTENSION (Mar. 7, 2023), https://extension.psu.edu/beef-cattle-spacing-requirements [Exhibit 78].

[114] FAO, PATHWAYS TOWARDS LOWER EMISSIONS, *supra* note 113, at 24; Felix, *supra* note 113; *see also* WORLD ORG. FOR ANIMAL HEALTH, TERRESTRIAL ANIMAL HEALTH CODE Ch.7.1. (2018), https://www.woah.org/fileadmin/Home/eng/Health_standards/tahc/2018/en_chapitre_aw_introduction.htm [Exhibit 79] (suggesting giving animals more space to improve their health).

[115] *Riverview's EAW for West River Dairy, supra* note 17, at 2.

[116] Dan McFarland, *Ventilation Systems, Efficiency, and Maintenance for Dairy Housing*, PENN STATE EXTENSION (Dec. 3, 2025), https://extension.psu.edu/ventilation-systems-efficiency-and-maintenance-for-dairy-housing [Exhibit 80] ("The ventilation system on your dairy housing consumes 20% to 25% of the total energy used on the dairy").

[117] M. Verdon et al., *Invited Review: Animal Welfare in Pasture-Based Dairy Systems—A Systematic Scoping Review to Identify Progress, Priorities, and Future Directions*, 108 J OF DAIRY SCI. 12924-12948 (2025), https://doi.org/10.3168/jds.2025-26981 [Exhibit 81]; G. Arnott et al., *Review: Welfare of Dairy Cows in Continuously Housed and Pasture-Based Production Systems*, 11 ANIMAL 261-273 (2017), https://doi.org/10.1017/S1751731116001336 [Exhibit 82].

[118] Kathryn McLellan et al., *Effects Of Free-Choice Pasture Access on Lameness Recovery and Behavior of Lame Dairy Cattle*, 105 J. OF DAIRY SCI. 6845-6857 (2022), https://doi.org/10.3168/jds.2021-21042 [Exhibit 83]; Anne-Marieke Smid et al., *The Influence of Different Types of Outdoor Access on Dairy Cattle Behavior*, 7 FRONT. VET. SCI. 257 (2020), https://doi.org/10.3389/fvets.2020.00257 [Exhibit 84].

rest, and feeding patterns.[119] From a welfare perspective, the ability to graze is often considered a core behavioral need for ruminants, and its absence in confinement systems is a key point of concern.[120]

Indeed, the most impactful strategy to reduce GHG emissions from feedlots is to directly address the scale and intensity of animal production.[121] Such approaches would align with Minnesota's longstanding commitment to maintaining small, family-owned farms:

> The legislature finds that it is in the interests of the state to encourage and protect the family farm as a basic economic unit, to insure it as the most socially desirable mode of agricultural production, and to enhance and promote the stability and well-being of rural society in Minnesota and the nuclear family.[122]

Yet, despite this statutory commitment, the number of permits for new farms is going down while the number of animals per farm goes up.[123] Dairy feedlots in the United States have become increasingly consolidated, with a small number of large operations handling most cattle.[124] The trend in Minnesota mirrors this national shift and would be exacerbated by the proposed dairy expansion.[125]

This concentration significantly magnifies GHG emissions and cumulative environmental impacts per site.[126] From a climate perspective, concentration creates GHG "hotspots" with emissions comparable to industrial sources.[127] Moreover, as discussed above, the volume of manure generated at these facilities often exceeds the nutrient absorption capacity of surrounding land, leading to runoff and leaching that pollutes water sources and contributes further to nitrous oxide emissions.[128]

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[119] Andrew Crump et al., *Pasture Access Affects Behavioral Indicators of Wellbeing in Dairy Cows*, 11 ANIMALS 902 (2019), https://doi.org/10.3390/ani9110902 [Exhibit 85].
[120] G. Arnott et al., *supra* note 117.
[121] Bray, *supra* note 49, at 523–31.
[122] MINN. STAT. § 500.24, subd. 1.
[123] Office of the Legis. Auditor, *Animal Feedlot Regulation*, MINN. LEG., https://www.auditor.leg.state.mn.us/ped/1999/fedlt99.htm (last visited May 5, 2026) [Exhibit 86]; *see also* Request for Comments, MPCA 2 (2025), https://www.pca.state.mn.us/sites/default/files/wq-rule4-29a.pdf [Exhibit 87] (There are "[f]ewer total number of feedlots in the state [since the last major update to the Feedlots Rule in 2000], with feedlots now having more animal units per facility.").
[124] USDA, OVERVIEW OF THE U.S. CATTLE INDUSTRY 14 (2016), *available* at https://usda.library.cornell.edu/concern/publications/8s45q879d [Exhibit 88] (noting the combined capacity of large feedlots with over 1,000 head of cattle increased by 100,000 head between 2006 and 2016). Across the county, roughly 5% of feedlots house more than 1,000 cattle, yet those facilities are responsible for over 85% of all beef cattle production. *Id.; Sector at a Glance: Cattle & Beef*, ECON. RSCH. SERV. (May 22, 2025), https://www.ers.usda.gov/topics/animal-products/cattle-beef/sector-at-a-glance [Exhibit 89].
[125] *Request for Comments, supra* note 123 (There are "[f]ewer total number of feedlots in the state [since the last major update to the Feedlots Rule in 2000], with feedlots now having more animal units per facility.").
[126] April Leytem et al., *Methane Emissions from Dairy Lagoons in the Western United States*, 100 J. OF DAIRY SCI. 6785 (2017), https://doi.org/10.3168/jds.2017-12777 [Exhibit 90]; Horacio A. Aguirre-Villegas & Rebecca A. Larson, *Evaluating Greenhouse Gas Emissions from Dairy Manure Management Practices Using Survey Data and Lifecycle Tools*, 143 J. OF CLEANER PROD. 169-179 (2017), https://doi.org/10.1016/j.jclepro.2016.12.133 [Exhibit 91]; Qingbo Qu et al., *A Model to Identify Entry Points to Curb Emissions from Complex Manure Management Chains*, 415 J. OF CLEANER P ROD . 137787 (2023), https://doi.org/10.1016/j.jclepro.2023.137787 [Exhibit 92].
[127] A meta-analysis of 104 studies showed that a single feedlot emits approximately 2,786 kg CO_2-equivalent per animal unit annually, primarily through enteric fermentation and manure management. Wang et al., *supra* note 48, at 11232–33.
[128] ECON. RSCH. SERV., MANAGING MANURE TO IMPROVE AIR AND WATER QUALITY 2, 40 (2005), https://ers.usda.gov/sites/default/files/_laserfiche/publications/46336/29004_err9.pdf?v=98631 [Exhibit 93]; Ben Chugg et al., *Detecting Environmental Violations with Satellite Imagery in Near Real Time: Land Application under the Clean Water Act*, 31 ASS'N FOR COMPUTING MACH. INT'L CONF. ON INFO. & KNOWLEDGE MGMT. 3052, 3053 (2022) [Exhibit 94].

High-density operations are also more vulnerable to climate-related events, such as heavy rainfall and lagoon overflows, increasing the likelihood of catastrophic pollution events.[129] As MPCA's feedlot program manager recently commented: "Minnesota has also been getting more extreme and unpredictable rain storms than it did when its [feedlot] rules were last updated [in 2000], which have caused manure lagoons to overflow and increased runoff on farms."[130] If GHG emissions reductions are not required from larger and denser feedlots, Minnesota risks entrenching a model of production that not only worsens climate impacts but also undermines broader environmental, public health, and equity goals.

The EAW fails to evaluate alternative livestock management approaches. This omission is significant because different production systems—such as pasture-based or hybrid models, reduced stocking densities, distributed smaller-scale operations, or alternative manure handling systems—can materially alter both the magnitude and intensity of GHG emissions, as well as associated environmental and public health impacts. An adequate environmental review would assess whether feasible alternatives could achieve similar production objectives with lower emissions and reduced risk. Without such an analysis, the record does not allow MPCA to meaningfully compare the proposed high-density, confinement-based model against less emissions-intensive approaches or to determine whether the Expansion Project represents the least environmentally harmful practicable alternative.

In sum, the EAW fails to identify any ways in which the Expansion Project would be subject to mitigation by ongoing public regulatory authority or any other mitigation measures that could reasonably be expected to effectively mitigate the significant increase in GHG emissions from the Expansion Project. This factor weighs in favor of requiring an EIS.

C. The Expansion Project's Cumulative Potential Effects Weigh Heavily In Favor Of An EIS

The Expansion Project's GHG emissions must be considered in the context of its cumulative potential effects. Minnesota's environmental-review rules define "cumulative potential effects" as incremental effects "in addition to other projects in the environmentally relevant area" that may affect the same environmental resources.[131] The rule also recognizes that significant cumulative potential effects can result from individually minor projects over time, and that the RGU must consider historic and forecasted trends when determining whether future projects are reasonably likely to occur.[132]

For GHG emissions, the environmentally relevant area cannot be limited to the facility footprint, manure-spreading fields, or a one-mile well radius. The relevant environmental resource is the atmosphere and climate system, and the relevant cumulative context is the aggregate contribution of existing and reasonably foreseeable emission sources that affect that same resource. The Minnesota Court of Appeals has recognized GHG emissions as a cumulative potential effects issue in environmental review. In Mankato Motorsports Park, the court reversed a negative EIS declaration where the RGU had failed to adequately consider cumulative GHG impacts, explaining that the cumulative-effects criterion required the RGU to place the project in context rather than evaluating its incremental emissions in

[129] JoAnn Burkholder et al., *Impacts of Waste from Concentrated Animal Feeding Operations on Water Quality*, 115 ENV'T HEALTH PERSPECTIVES 308, 308 (2007) [Exhibit 95].
[130] Greg Stanley, *Minnesota Looks to Tighten Regulations on Feedlots to Deal with Persistent Pollution from Manure*, MINN . STAR TRIBUNE (June 13, 2025), https://www.startribune.com/minnestoa-will-rewrite-feedlot-rules-to-curb-nitrate-pollution-in-drinking-water/601369770 [Exhibit 96]; Minn. R. Ch. 7020.
[131] Minn. R. 4410.1200(E), 4410.0200, subp. 11a.
[132] *Id*. 4410.0200, subp. 11a.

isolation.[133] The court also held that omitting an important source of GHG emissions from the project's analysis rendered the GHG analysis arbitrary, capricious, and unsupported by substantial evidence.[134]

The West River Dairy EAW suffers from the same fundamental flaw. Although the EAW quantifies the Expansion Project's operational GHG emissions at 72,210 tons CO_2e/year, the actual cumulative potential effects analysis in Item 21 does not discuss climate impacts at all.[135] Instead, Item 21 defines the "Environmentally Relevant Area" as the Expansion Project site, the dedicated manure application acreage for the Expansion Project and existing facility, and a one-mile radius around the off-site well, then limits the cumulative discussion to overlapping manure application and groundwater extraction.[136] That is not a cumulative climate analysis. It does not evaluate whether the Expansion Project's substantial annual GHG emissions will combine with existing and reasonably foreseeable emissions from other animal agriculture operations to affect the same climate resource.

That omission is material, especially because the agricultural sector's emissions in Minnesota have remained persistently high, and because large feedlot operations are a significant and growing source. Each additional major source compounds the problem, making it more difficult to achieve State and regional climate goals. GHG emissions are cumulative and long-lived; once emitted, they contribute to warming for decades or hundreds of years. As a result, the Expansion Project's emissions will cause irreversible environmental harm that cannot be fully mitigated after the fact.

In Minnesota, dairy cattle were the largest source of enteric fermentation and second largest source of manure management emissions in 2023.[137] That year, the State's methane emissions from manure management and enteric fermentation together were more than 8.8 million metric tons of CO2 equivalent, more than all emissions from the commercial sector (about 7.3 million) and the waste sector (about 1.5 million) combined.[138] And methane emissions from animal agriculture are trending upward in Minnesota: "[S]ince 2005, methane emissions from animal agriculture have increased 10% in the state . . . ."[139] The trend in emissions from manure management is especially concerning, as those emissions have grown about 30% in Minnesota from 2005 to 2023.[140] To fully understand the scope of animal agriculture emissions relative to other sources, see Figure 2 below from Minnesota's 2026 Climate Action Framework, which shows that manure management and enteric fermentation combined emit more in Minnesota than heavy-duty trucks, passenger cars, aviation, or natural gas in the industrial, residential, or electricity generation sectors.

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[133] *Matter of Determination of Need for Env't Impact Statement for Mankato Motorsports Park*, A23-0091, 2023 WL 8177126, at *7 (Minn. Ct. App. Nov. 27, 2023).
[134] *Id*.
[135] *Riverview's EAW for West River Dairy, supra* note 17, at 70.
[136] Id.
[137] *Minnesota Greenhouse Gas Inventory, Greenhouse Gas Emissions by Activity, Sector, Source, GHG, and Year*, MPCA, https://data.pca.state.mn.us/views/Greenhousegasemissionsdata/Fullresultstable (last visited May 5, 2026).
[138] *MPCA GHG Inventory: Main Sources, supra* note 12.
[139] Ben Lilliston, *Minnesota Agriculture Emissions: The CAFO Challenge*, INST. FOR AGRIC. & TRADE POL'Y 2 (Mar. 2023), https://www.iatp.org/sites/default/files/2023-03/MN%20GHG%20analysis%202023.3.pdf [Exhibit 97].
[140] *MPCA GHG Inventory: Agriculture Sector Details, supra note* 14 (showing that manure management emissions have risen from about 3.2 million metric tons of CO_2 equivalent in 2005 to 4.1 million in 2023).

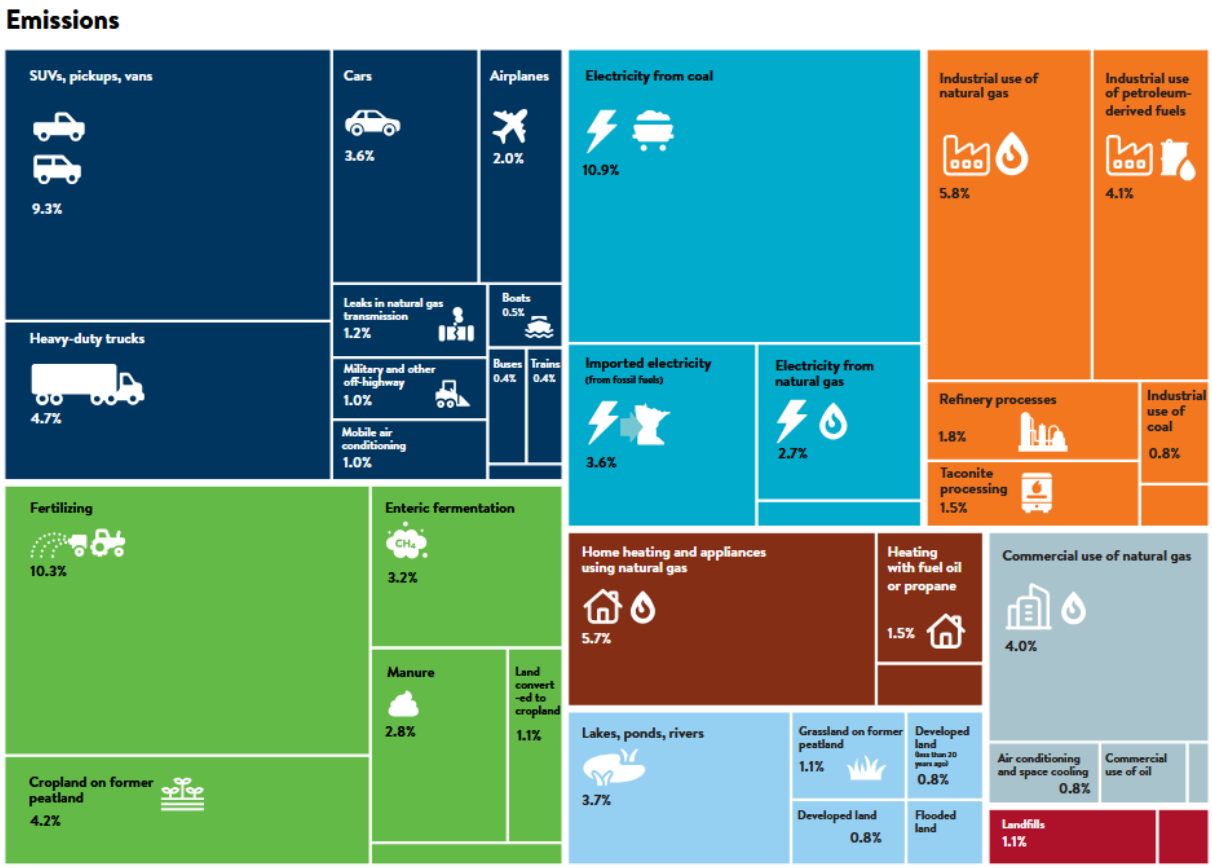


Figure 2: Minnesota's 2026 Climate Action Framework Emissions Breakdown.

By adding tens of thousands of tons of CO_2-equivalent emissions annually over the Expansion Project's lifetime, the Expansion Project will contribute meaningfully to climate change. GHG emissions accumulate in the atmosphere and drive increases in global temperatures. Methane and nitrous oxide—the primary emissions associated with this Expansion Project—are particularly potent climate pollutants, with significantly greater warming potential than carbon dioxide over relevant time horizons.

Methane is about 80 times more warming than carbon dioxide over a 20-year period.[141] But because of its relatively short persistence in the atmosphere—with an average methane molecule remaining for about ten years[142] (as compared to carbon dioxide, which can cause warming for thousands of years[143])—reducing methane emissions in the coming years can play an important role in curbing warming.[144]

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[141] Piers Forster et al., *The Earth's Energy Budget, Climate Feedbacks and Climate Sensitivity, in* CLIMATE CHANGE 2021: THE PHYSICAL SCIENCE BASIS. CONTRIBUTION OF WORKING GROUP I TO THE SIXTH ASSESSMENT REPORT OF THE INTERGOVERNMENTAL PANEL ON CLIMATE CHANGE 923, 1017 tbl.7.15 (Valérie Masson-Delmotte et al. eds., 2021) [Exhibit 98].

[142] *Understanding Global Warming Potentials*, EPA (last updated Dec. 29, 2025), https://www.epa.gov/ghgemissions/understanding-global-warming-potentials.

[143] *Id*.

[144] U.N. ENV'T PROGRAMME, GLOBAL METHANE ASSESSMENT 8, 11 (2021), https://www.ccacoalition.org/sites/default/files/resources//2021_Global-Methane_Assessment_full_0.pdf ("Reducing human-caused methane emissions is one of the most cost-effective strategies to rapidly reduce the rate of warming and contribute significantly to global efforts to limit temperature rise to 1.5ºC.") [Exhibit 100, hereinafter "GLOBAL METHANE ASSESSMENT"]. As observed by one of the lead reviewers of a 2021 U.N. Intergovernmental Panel on Climate Change report: "Cutting methane is the biggest opportunity to slow warming between now and 2040. We need to face this emergency." Fiona Harvey, *Reduce Methane or Face Climate Catastrophe, Scientists Warn*, GUARDIAN (Aug. 6, 2021),

Moreover, reducing carbon dioxide emissions without serious action on super-pollutants, including methane, will preclude achievement of the Paris Climate Agreement and Minnesota's GHG reduction goals.[145]

Nitrous oxide, like methane, is a climate super-pollutant closely associated with animal farming.[146] Nitrous oxide is one of the most powerful GHGs—estimated to contribute 273 times more than carbon dioxide to global warming over a 100-year timescale[147] —and is also harmful to the ozone layer.[148] Human-caused emissions of nitrous oxide have increased more than 40% over the past forty years, driven in large part by the use of nitrogen fertilizer and manure from farmed animals.[149] According to a U.N. estimate, animal agriculture is responsible for at least half of global anthropogenic nitrous oxide emissions.[150] The agricultural sector is responsible for nearly all of Minnesota's nitrous oxide emissions, and a significant portion of those emissions are attributed to the land application of manure.[151] Since 2005, "nitrous oxide emissions related to both manure and synthetic fertilizer use have increased 9%" in Minnesota.[152]

Thus, the Expansion Project's GHG emissions will aggravate the consequences of climate change in Minnesota. The Expansion Project's emissions will contribute to increased frequency and severity of extreme weather events, including heavy rainfall, flooding, heat waves, and drought. These impacts are particularly relevant in Minnesota, where recent trends show increasing precipitation intensity and temperature.

Rising temperatures and the increase in size and frequency of storms and disasters has resulted in unprecedented damage.[153] Per MPCA: "Daily average minimum temperatures during winter (Dec-Feb) have increased 7.3 degrees from 1895-2021 in northern Minnesota, 6 degrees in central Minnesota and 4.9 degrees in southern Minnesota."[154] Lakes are now experiencing an average of up to two fewer weeks of ice cover each year.[155] These changes put an increasing strain on Minnesota's budget.[156] According to MPCA: "Over the past decade . . . our state has been experiencing a much higher rate of

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https://www.theguardian.com/environment/2021/aug/06/reduce-methane-or-face-climate-catastrophe-scientists-warn; see also GLOBAL METHANE ASSESSMENT, *supra* note 144, at 8 ("Reducing human-caused methane emissions is one of the most cost-effective strategies to rapidly reduce the rate of warming and contribute significantly to global efforts to limit temperature rise to 1.5ºC.").

[145] Gabrielle B. Dreyfus et al., *Mitigating Climate Disruption in Time: A Self-Consistent Approach for Avoiding Both Near-Term and Long-Term Global Warming*, PROCS. NAT'L ACAD. SCIS., May 23, 2022, at 1–8 [Exhibit 102].

[146] MPCA GHG EMISSIONS IN MINNESOTA, *supra* note 4, at 3.

[147] *Understanding Global Warming Potentials, supra* note 142.

[148] Robert Portmann et al., *Stratospheric Ozone Depletion Due to Nitrous Oxide: Influences of Other Gases*, 367 PHIL. TRANSACTIONS ROYAL SOC'Y B 1256, 1263 (2012) [Exhibit 103].

[149] Hanqin Tian, *Global Nitrous Oxide Budget* (1980-2020), 16 EARTH S YS . S CI . DATA 2543, 2545, 2549 (2024) [Exhibit 104].

[150] Pierre J. Gerber et al., *Tackling Climate Change Through Livestock: A Global Assessment of Emissions and Mitigation Opportunities*, FOOD & AGRIC. ORG. OF THE U.N. (FAO) 15 (2013), https://www.fao.org/3/i3437e/i3437e.pdf [Exhibit 105] (relying on 2004 and 2005 data).

[151] MPCA GHG EMISSIONS IN MINNESOTA, *supra* note 4, at 9; *MPCA GHG Inventory: Agriculture Sector Details, supra* note 14.

[152] Lilliston, *supra* note 139.

[153] *Climate Change Impacts*, MPCA, https://www.pca.state.mn.us/air-water-land-climate/climate-change-impacts (last visited May 5, 2026).

[154] *Id*.

[155] *Id.*

[156] *See id*. ("Costly repairs to infrastructure, increasing home and crop insurance rates, destructive shifts in our native ecosystems, and more hospitalizations for heat-related illness are some of the impacts climate change is having on Minnesotans and the economy.").

natural disasters, with a higher number of individual storms that cause more than $1 billion in damage."[157]

Climate-driven increases in precipitation intensity and runoff will exacerbate nutrient pollution associated with manure management. As temperatures rise and rainfall events become more extreme, nitrogen and phosphorus losses from manure- applied fields are expected to increase, contributing to eutrophication of lakes, rivers, and downstream waters.[158] These impacts include harmful algal blooms, hypoxia, and degradation of drinking water sources.[159] Given the scale of manure generation associated with the Expansion Project, even small increases in runoff rates can translate into significant additional pollutant loading.

Agricultural producers are themselves intensely vulnerable to the impacts of climate change. In the summer of 2023, the administrator of the U.S. Department of Agriculture's (USDA's) Farm Service Agency observed:

> The recent heat domes plaguing many parts of the country have proven to be unsurvivable for some animals and temperatures are not expected to let up any time soon. This is one of the latest, many examples of how a changing climate is creating immediate challenges for farmers and ranchers. . . .[160]

According to MPCA, farmers are already experiencing (and can expect to continue experiencing) a range of negative impacts from climate change.[161] Rising temperatures, unpredictable precipitation, and more frequent extreme weather events are disrupting planting schedules, reducing crop yields, and increasing crop losses from pests, diseases, and disasters.[162] While some areas experience heavy rainfall and flooding, others suffer from prolonged dry spells and drought, often within the same growing season. This variability not only lowers crop yields but also degrades soil and water quality.[163] Here in Minnesota, climate change is driving more intense and erratic droughts in this water-rich state, and extreme droughts are stressing water supplies and state budgets. Just a few years ago in 2021, a historic drought across the State prompted $10 million in emergency funding to help producers withstand the dry conditions.[164] The lack of rain has also prompted producers to increase irrigation. In the summer of 2021, farmers collectively withdrew 6.1 billion gallons of water more than their permits allowed.[165]

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[157] MPCA GHG EMISSIONS IN M INNESOTA, supra note 4, at 2.
[158] Marin Skidmore et al., *The Impact of Extreme Precipitation on Nutrient Runoff*, 2 J. OF THE AGRIC. & APPLIED ECON. ASS'N 769–785 (2023), https://doi.org/10.1002/jaa2.90 [Exhibit 106].
[159] Rose Mumbi et al., *Drought to Inundation: Precipitation Extremes Exacerbate Phosphorus Loss in Artificially Drained Watersheds*, 316 AGRIC. WATER MGMT. 109606 (2025), https://doi.org/10.1016/j.agwat.2025.109606 [Exhibit 107]; Ethan Bahe, *Five Years After EWG's First Analysis, Manure Still Overloads Minnesota*, ENV'T WORKING GRP. (May 15, 2025), https://www.ewg.org/research/five-years-after-ewgs-first-analysis-manure-still-overloads-minnesota [Exhibit 108].
[160] News Release, U.S. Department of Agriculture (USDA), USDA Updates Livestock Disaster Payment Rate to Assist Producers Hard-Hit by Heat and Humidity (Aug. 25, 2023), https://www.fsa.usda.gov/news-events/news/08-25-2023/usda-updates-livestock-disaster-payment-rate-assist-producers-hard-15 [Exhibit 109].
[161] *Climate Impacts on Agriculture*, MPCA, https://www.pca.state.mn.us/air-water-land-climate/climate-impacts-on-agriculture (last visited May 5, 2026).
[162] *Id.; Farmers Face New Challenges for Crops*, Livestock, OUR MINNESOTA CLIMATE, https://climate.state.mn.us/farmers-face-new-challenges-crops-livestock (last visited Apr. 20, 2026) [Exhibit 110].
[163] *Climate Impacts on Agriculture, supra* note 161; *Climate Change in Minnesota*, UNIV. OF MINN. CLIMATE ADAPTATION P'SHIP, https://climate.umn.edu/climate-change-minnesota-0 (last visited May 5, 2026) [Exhibit 111].
[164] Press Release, Office of Governor Tim Walz & Lt. Governor Peggy Flanagan, Governor Walz Announces $10 Million Drought Relief Package for Farmers, Producers, Minn. (Sept. 24, 2021), https://mn.gov/governor/newsroom/press-releases/?id=1055-500585 [Exhibit 112].
[165] Dionne Searcey, *Big Farms and Flawless Fries Are Gulping Water in the Land of 10,000 Lakes*, N.Y. TIMES (Sept. 3, 2023), https://www.nytimes.com/interactive/2023/09/03/climate/minnesota-drought-potatoes.html [Exhibit 113].

Reports from Smithfield Grain, a major feed purchaser and subsidiary of Smithfield Foods—one of the world's largest pig producers—highlight how these climate stressors are already affecting Minnesota producers. In June 2025, spring crop planting and development in some parts of the Upper Midwest was delayed by extreme weather events including strong winds, dust storms, and erratic rainfall that disrupted planting and damaged crops.[166] The University of Minnesota Research and Outreach Center at Lamberton reported below-average rainfall and the lowest soil moisture levels in five years.[167] Abnormally dry to moderate drought conditions were documented across western and northern Minnesota.[168] These impacts not only threaten crop yields and farm incomes but can also increase feed costs and risk food system instability.

Climate change is also producing more severe storms that dump large amounts of water on the land in a short amount of time. These "mega-rain" events are not as helpful for growing crops as slow, soaking rains, and climate change is bringing more of these intense, unhelpful storms to Minnesota.[169] Minnesota farmers increasingly face the added burden of managing wet pastures and feed soaked by storms, and animals suffer and have even drowned in flash flood conditions.[170] The Minnesota State Cattlemen's Association president observed in 2024: "With this drastic change in cool to hot and the water stresses, we did have a feedlot call that had fairly higher death loss due to some of this water and stress that they're dealing with in cattle . . . ."[171]

Rising temperatures will further harm livestock health and productivity. For example, "[h]eat-stressed hogs eat less, and heat may interfere with breeding, gestation, and lactation."[172] Indeed, the EAW notes that "[h]igher temperatures and humidity increase the potential for animal heat stress and decreased milk production."[173] However, the EAW fails to fully assess the impact of temperature increases on its herd—and, as discussed above, to propose adequate mitigation strategies to reduce the Expansion Project's contributions to these dangers.

During a heat wave in 2011, an estimated 1,000 cattle died in south central and southwestern Minnesota due to extreme temperatures, causing estimated losses of roughly $1 million.[174] MPCA has itself said that, because "[d]airy cattle operations in Minnesota typically do not currently have the equipment necessary to mitigate the risks of high temperatures," milk production decreases on very hot days.[175] Thus, MPCA modeling of scenarios where GHG emissions continue unabated predict that production value "[l]osses increase later in the century due to more significant temperature increases,

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[166] Kent Thiesse, *Crops Have Been Slow to Develop in the Upper Midwest*, SMITHFIELD GRAIN (June 5, 2025), https://smithfieldgrain.com/story-crops-been-slow-develop-upper-midwest-0-255565 [Exhibit 114].
[167] *Id.*
[168] *Id*.
[169] *Mega-Rains Overwhelm Rivers, Roads, and Budgets*, OUR MINNESOTA CLIMATE, https://climate.state.mn.us/mega-rains-overwhelm-rivers-roads-and-budgets (last visited May 5, 2026) [Exhibit 115];Alexandra Witze, *Why Extreme Rains Are Getting Worse*, 563 NATURE 458, 458 (2018), https://www.nature.com/articles/d41586-018-07447-1 [Exhibit 116].
[170] *Managing Grazing Livestock During Wet Weather*, UNIV. OF MINN. EXTENSION (reviewed in 2026), https://extension.umn.edu/beef-cow-calf/managing-grazing-livestock-during-wet-weather [Exhibit 117]; Cows Swept Away by Flash Flooding in Southeastern Minnesota, FOX 5 N.Y. (June 30, 2019), https://www.fox5ny.com/news/cows-swept-away-by-flash-flooding-in-southeastern-minnesota [Exhibit 118].
[171] Mark Dorenkamp, *Flooding Results in Livestock Losses*, BROWNFIELD (June 25, 2024), https://www.brownfieldagnews.com/news/flooding-results-in-livestock-losses [Exhibit 119].
[172] Farmers Face New Challenges for Crops, Livestock, supra note 162.
[173] Riverview's EAW for West River Dairy, supra note 17, at 13.
[174] Elizabeth Baier, Cattle Dying Due to Heat Wave, MPR NEWS (July 20, 2011), https://www.mprnews.org/story/2011/07/20/cattle-die-from-heat-wave [Exhibit 120].
[175] MPCA, Report to the Legislature: Minnesota Climate Adaptation and Resilience Cost Study (March 2026), 61, https://www.pca.state.mn.us/sites/default/files/lrcc-mn-1sy26.pdf [Exhibit 121].

with more instances of daily temperatures crossing heat stress thresholds."[176] Figure 3 below lists the projected mid-century cost of inaction in three emissions scenarios modeled by MPCA.

		Dairy Milk
		Lost production value
Mid-Century (2040–2059)	Intermediate	$1,000 (-$440 to $3,300)
	High	$1,900 ($780 to $3,300)
	Very High	$1,500 (-$1,100 to $3,700)

Annual costs (in millions, 2024$) for three time periods and three emissions scenarios (see Section 2.2.2 for more details). Costs are incremental to baseline and averaged across six climate models (range across climate models provided in parentheses). See Appendix B for more details on methodology and limitations.

Figure 3. Quantified Costs of Inaction (Millions per Year): Livestock.

Accordingly, climate change driven by GHG emissions poses significant risks to Minnesota's agricultural sector, including increased crop variability, reduced yields under heat stress, and greater input costs associated with water management and adaptation. Ironically, while the Expansion Project is intended to grow agricultural production, its emissions contribute to broader climate impacts that threaten the long-term viability of the sector. In addition, climate-related damages—such as flooding, infrastructure degradation, and water quality impairment—impose significant economic costs on the State and its residents.

The Expansion Project's EAW acknowledges that agriculture emissions have not declined statewide. Yet there is no analysis of cumulative regional dairy expansion, no carbon budget framing, and no comparison against Minnesota climate targets. Moreover, even though Riverview predicts that the Expansion Project's lifetime emissions will total 2.17 million tons CO 2 e, the EAW lacks a policy compatibility assessment. The EAW does not quantify economic climate damages, such as by providing a social cost of carbon, and does not compare the Expansion Project's emissions to state-sector reduction needs.

These challenges and deficiencies underscore the urgent need for MPCA to require an EIS that fully evaluates GHG emissions from the proposed feedlot. Addressing these emissions will not only protect against future climate damage but also help stabilize Minnesota's agricultural economy and food supply in the face of increasing environmental volatility.

* * *

The EAW, both on its face and in what it failed to disclose, demonstrates that the Expansion Project has the potential for significant environmental effects from its contribution to increasing levels of GHG emissions. Emissions from the Expansion Project are not effectively mitigated or offset; and they are contrary to Minnesota law and policy directing steep reductions in emissions. Because the Expansion Project has the potential for significant environmental effects, the MPCA must order an EIS.

III. THERE ARE POTENTIAL SIGNIFICANT ENVIRONMENTAL EFFECTS ASSOCIATED WITH RIVERVIEW'S PROPOSED GROUNDWATER ALLOCATION

The Expansion Project intends to quench its thirst with a truly extraordinary sequence of features. Riverview plans on pumping 226 million gallons of groundwater per year ("MGY") from a well located

[176] Id.

miles away from the Expansion Project.[177] The groundwater will be pulled from a surficial aquifer hydrologically connected to the Pomme de Terre River, where it will travel three-plus miles in a buried waterline that crosses multiple roads before reaching the Expansion Project. As part of the Expansion Project, Riverview intends to construct two massive water storage basins at the feedlot, each of which needs a dam safety permit from DNR, to store water on-site. Water for the feedlot will be pulled from the storage basins, which will be recharged from groundwater pumped from the surficial aquifer three-plus miles away.

Riverview is seeking to use a well and a water appropriation that DNR previously granted to a proposed ethanol plant nearly two decades ago. The ethanol plant was never built; the permit has expired; and no water was ever appropriated under the permit. Riverview has apparently secured DNR's agreement to provide an appropriation permit to Riverview based on the analysis conducted to support the ethanol plant permit (the "2007 Aquifer Report"). That analysis, from 2007, allegedly assessed the suitability of withdrawing groundwater from a surficial aquifer near the Pomme de Terre River. DNR has not conducted any independent or separate environmental review to justify a water appropriation permit for the proposed Expansion Project and is instead relying on this draft EAW. No analysis is provided in the EAW to justify the water appropriation other than the 2007 Aquifer Report.

The EAW claims that environmental impacts from this plan have been considered and mitigated. But this claim rests upon an outdated aquifer report that considers old information that tells an incomplete story about the environmental impacts of Riverview's water allocation plan. Because the potential for significant environmental effects from Riverview's water appropriation is high, MPCA must prepare an EIS.

A. The 2007 Aquifer Report MPCA Relies Upon In Analyzing Potential Groundwater Impacts Is Almost Two Decades Out-Of-Date

Riverview seeks permission to withdraw 226 MGY of water for the Expansion Project. Riverview's proposed water source is an off-site well approximately three miles southeast of the Expansion Project (Well Id No. 740629, "the Off-Site Well").[178] The Off- Site Well was first permitted for a 452 MGY appropriation in 2008 to serve a proposed ethanol plant (Permit #2008-0230).[179] In 2014, this permit was amended to allow 226 MGY to be used for livestock watering, with the other half still allocated for the ethanol plant. As part of this arrangement, Riverview was listed as an "authorized agent."[180] Water was never actually appropriated from this well under either the 2008 permit or the amended 2014 permit.[181] In May 2025, Riverview submitted an application for a new water appropriation permit to pump 226 MGY from the Off-Site Well.[182]

The EAW states that prior to obtaining the 2008 water appropriation permit, the ethanol plan conducted an aquifer test (the "2007 Aquifer Test")[183] The 2007 Aquifer Test reveals that the Off-Site Well is hydraulically connected to the Pomme de Terre River, and that "pumping from the aquifer would . . .

[177] Riverview's EAW for West River Dairy, supra note 17, at 35.
[178] Id. at 35.
[179] *Id*. at Attachment 11 (2008 APEC Permit).
[180] *Id*. (2014 APEC Permit). The permit amendment was in response to an agreement between APEC and Riverview, and the conditions of the 2008 permit were incorporated into the amended 2014 permit. *Id*. (Letter from DNR).
[181] Nathan Kestner, Minn. Dep't of Nat. Res., West River Dairy Expansion EAW (Mar. 17, 2026) [Exhibit 122].
[182] *Riverview's EAW for West River Dairy, supra* note 17, at Attachment 11 (Riverview Letter). This letter was in response to an apparent dispute between DNR and Riverview about whether Riverview could use the existing permit for its proposed expansion project. The EAW indicates that the water appropriation permit amendment for the Off-Site Well is pending. *Id*. at 23 (permit number 2008-0230).
[183] *Riverview's EAW for West River Dairy, supra* note 17, at 35.

reduce the long-term average flow rate in the river by approximately the average pumping rate."[184] Using the 2007 Aquifer Report, DNR imposed pumping restrictions on the Off-Site Well that curtail appropriations based on the flow of the Pomme de Terre River.[185]

These pumping restrictions are to remain in place for Riverview, and the EAW leans on the 2007 Aquifer Report to explain away environmental concerns associated with the proposed water allocation. However, for multiple reasons the accuracy of the 2007 Report has faded with time, resulting in the potential for significant environmental effects not considered and resolved by the 2007 Aquifer Report.

1. The 2007 Aquifer Report is outdated

There are many reasons to doubt the continued utility of the 2007 Aquifer Report. First, the 2007 Aquifer Report uses pre-2007 data and conditions to reach conclusions about protecting the river and natural resources. For example, the report helps justify permit conditions curtailing withdrawals to protect the Pomme de Terre River when flow drops to 31 cubic feet per second ("CFS"), the rate determined in 2007 to be when adverse impacts occur. This adverse rate was established by looking at the annual flow rate that occurred for at least 90% of the time for the relevant reach of river in 2005. Flows have changed since then,[186] and given the direct connection between the Pomme de Terre River and the surficial aquifer, more recent data about protected flow rates should be considered.

Second, since 2007, new wells have been dug into the same surficial aquifer that Riverview seeks to access. Well data from the Minnesota Department of Health shows new wells drilled in 2023 and 2013 that are close in proximity to the Off-Site Well.[187] These are active irrigation wells that permitted to access the same water source years after the 2007 Aquifer Test was completed. Because the wells did not exist when the study was completed, the 2007 Aquifer Test's conclusion that the well pump rate will not cause interference drawdown in existing wells or impacts to nearby wetlands is no longer trustworthy.

Third, the quality of the data is low. The nearest flow monitoring device is over 30 river-miles downstream from the Off-Site Well, near the town of Appleton. This is where river flow data that informs the Off-Site Well's permit conditions is collected. In other words, the Expansion Project's water appropriation levels are limited based on river flow data collected far downstream. But this is not a good indication of river levels just downstream of the Off-Site Well, where the natural resource impacts from withdrawing water from the Off-Site Well will be felt because of the hydrologic connection between the Pomme de Terre River and the aquifer. Comparing Pomme de Terre River discharge rates from the flow monitor at Appleton and the nearest upstream monitor, located over 50 river miles north, shows that river flows vary significantly this section of the river.[188] For example, data collected on May 1, 2026 shows river discharge at the Appleton monitor to be 365 CFS, over twice as high as the upstream discharge rate of 165 CFS. This means that Pomme de Terre River flow at Appleton is not a suitable proxy for river conditions adjacent to the Off-Site Well.

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[184] *Id*. at Attachment 26 (hereinafter "2007 Aquifer Report") at 18.
[185] *Riverview's EAW for West River Dairy, supra* note 17, at 35.
[186] MPCA, POMME DE TERRE WATERSHED RESTORATION AND PROTECTION STRATEGY REPORT UPDATE 2024 32-36 (Aug. 2024), https://www.pca.state.mn.us/sites/default/files/wq-ws4-100a.pdf [Exhibit 123, hereinafter "Pomme de Terre WRAPS"]; MPCA, POMME DE T ERRE R IVER W ATERSHED BIOTIC S TRESSOR IDENTIFICATION 139-40 (June 2012), https://www.pca.state.mn.us/sites/default/files/wq-iw7-36n.pdf [Exhibit 124].
[187] MN Dep't of Health, Minn. Well Index Well No. 869936, https://mnwellindex.web.health.state.mn.us/mwi/index.xhtml?wellId=869936 [Exhibit 125]; MN Dep't of Health, Minn. Well Index Well No. 792962, https://mnwellindex.web.health.state.mn.us/mwi/index.xhtml?wellId=792962 [Exhibit 126].
[188] Greg Kruse, *Hydrology and Hydrologic Analysis* 10-11, DNR, https://files.dnr.state.mn.us/waters/gwmp/thresholds/gw-thresholds-project_hydrology.pdf [Exhibit 127].

Finally, new information and knowledge about groundwater sustainability and water quality in this region has been developed since 2007. The 2007 Aquifer Report explains that the ethanol plant was exploring accessing the surficial aquifer to mitigate water availability questions from an existing well drilled into a confined aquifer. Concerns about well interference, but not groundwater sustainability, motivated the search for a different source of water. Presently, however, DNR recognizes that there are "potential sustainability concerns" in the surficial aquifer, and that the buried aquifer system in this region of the state "is likely over-allocated,"[189] The 2007 Aquifer Report did not mention groundwater sustainability as a potential concern about the water appropriation. Less than two decades later, however, DNR acknowledges that groundwater levels are being impacted by water appropriations. DNR has explained that decreasing groundwater availability could be due to "intensified local groundwater consumption," and noted a downward trend in groundwater levels for 7.5% of wells between 2000 and 2019 in the area of Minnesota where the Expansion Project would be located.[190] Groundwater demand is "high in western Minnesota, where the groundwater supply is limited."[191] These recent findings undermine the credibility of the 2007 Aquifer Report, which did not cite groundwater sustainability as a risk from the appropriation.

Moreover, new reports assessing water quality trends across the Pomme de Terre River watershed highlight the threat land use change and altered hydrology have on the region's aquatic resources.[192] These studies did not exist when the 2007 Aquifer Report was prepared. Given that they are available now, decisions about water appropriation should be made with this more recent data in mind.

2. The 2007 Aquifer Report fails to identify the potential for significant environmental effects from water appropriation

There are also multiple reasons why the Expansion Project's proposed water allocation has the potential for significant environmental effects despite the 2007 Aquifer Report. First, the 2007 Aquifer Report does not address the potential water quality impacts from withdrawing 226 MGY from an aquifer hydrologically connected to the Pomme de Terre River. Groundwater pulled from the Off-Site Well corresponds to a reduction in Pomme de Terre River flow,[193] which can concentrate pollution in the river. Much of the groundwater pumped from the Off-Site Well will be mixed with manure, and later nearly all the liquid manure will be applied on cropland within the watershed. This is confirmed in the EAW, which reports that Riverview intends to land apply all the liquid manure produced by the additional 11,000 cows.[194] This land-applied liquid manure will have high nitrate concentrations and nitrate loads and eventually work its way back into the river, either as groundwater baseflow or via the artificial drainage network, which is a main driver of water quality impairments in the region.[195] Given the extent of the drainage infrastructure in Stevens County, the need to evaluate the potential water

[189] DNR, *Groundwater Technical Review* 1 (Jan. 13, 2025) [Exhibit 128].
[190] DNR, *Water Availability and Assessment Report 2025* 23, https://www.eqb.state.mn.us/sites/eqb/files/appendix_c.pdf [Exhibit 129, hereinafter "*Water A&R Report*"].
[191] *Id*. at 29.
[192] Pomme de Terre WRAPS, *supra* note 186; MPCA, *Pomme de Terre River Watershed Total Maximum Daily Load Report 2024* (Aug. 2024) [Exhibit 130], hereinafter "Pomme de Terre TMDL").
[193] 2007 Aquifer Report, *supra* note 184, at 18 ("Because the river is the primary discharge area for the water-table aquifer, the long-term impact of public from the aquifer would be to reduce the long-term average flow rate in the river by approximately the average pumping rate.).
[194] *Compare Riverview's EAW for West River Dairy, supra* note 17, at 8 (showing 202,744,000 gallons of liquid manure each year if the Expansion Project is constructed) *with id* at 41-42 (explaining that the entirety of the 113,619,000 gallons of liquid manure produced by the additional cows for the Expansion Project will be land-applied in the watershed).
[195] Pomme de Terre WRAPS, *supra note* 186, at 32 – 34.

quality impacts is paramount.[196] This concern is not discussed in the 2007 Aquifer Report because it was well-beyond the scope of the report—the water intended for the ethanol plant was not going to be mixed with manure and applied on the nearby landscape. Indeed, discharges from an industrial facility like an ethanol plant are specifically regulated to ensure they will not pollute receiving waters; the discharge of Riverview's 226 GPY appropriation will not be regulated.

Second, the appropriation demand on the surficial aquifer has not been adequately reviewed. Since 2007, new irrigation wells have been drilled into the same surficial aquifer the Off-Site Well accesses. The EAW does not discuss these new wells, pointing instead to the 2007 Aquifer Report as proof that the requested appropriation is sustainable. But the 2007 report predated DNR's more recent assessment of water resources in the area that indicates the need to consider all nearby wells for risk of interference.[197] This work appears to remain outstanding.

Last, the EAW does not address the impact altered hydrology has on river flow and thus whether the flow-based permit conditions will protect natural resources. Although the Pomme de Terre's flow is increasing, the additional flow is being driven by artificial drainage, which supplies a significant volume of water from discrete conveyances.[198] The artificial drainage network interrupts natural river hydrology, and can impact the volume and duration of low, medium, and high flow events. This is because drainage systems quickly shunt water off the landscape, where the water traverses the drainage network before reaching a surface water. The volume of water funneled through the drainage network causes rivers to be more "flashy," meaning that average flow figures may not present a clear picture of river conditions.[199] This means that local impacts to wetlands and other aquatic resources cannot be accurately projected by flow conditions based on data collected far downstream. This data gap should be filled in by an EIS.

Although DNR has indicated that if certain conditions are met (such as pumping restrictions dependent on flow conditions in the Pomme de Terre River) an updated aquifer test will not be needed for the new permit,[200] MPCA nonetheless has an obligation to accurately evaluate potential water quality and other natural resource impacts from pumping groundwater at the Off-Site Well. An updated aquifer test is needed to properly evaluate potential negative impacts to groundwater quantity and quality resulting from the Expansion Project, and MPCA should analyze the results of that test within an EIS.

B. MPCA Must Analyze The Cumulative Impacts Of The Proposed Groundwater Withdrawals For Both The Expansion Project And The Existing Riverview Facility

The EAW indicates that a different well (UN# 768109) exists within the Expansion Project footprint and has an existing DNR water appropriation permit for irrigation and livestock watering (Permit #2009-0492).[201] However, this well is not included in the EAW's list of "water sources," which lists only the Off-Site Well, stormwater collection/reuse, and water storage basins.[202] The amount of water that is used, or will be used, by this well is not stated in the EAW; per DNR comments on the EAW, it has an

[196] Stevens Cty., *MN Statutes 103E*, https://www.co.stevens.mn.us/DocumentCenter/View/3223/Ditch-System-Brochure-PDF- [Exhibit 131] ("Stevens County consists of 114 Public Drainage Systems and countless miles of privately owned tile.").
[197] 2007 Aquifer Report, supra note 184, at 2.
[198] Pomme de Terre WRAPS, *supra* note 186, at 21, 32.
[199] Minn. Ctr. for Envt'l Advocacy, *Replumbing Minnesota's Landscape* 8-11, https://www.mncenter.org/sites/default/files/pdfs/MCEA-Replumbing-Minnesota-Spreads-072825.pdf [Exhibit 132].
[200] Riverview's EAW for West River Dairy, supra note 17, at Attachment 11.
[201] *Riverview's EAW for West River Dairy, supra* note 17, at 31. Although the EAW indicates that the well has an existing water appropriation permit, elsewhere in the document it describes this permit as "planned." *Id*. at 23.
[202] *Id*. at 35.

appropriation limit of 21.3 MGY for livestock watering and 64.4 MGY for irrigation.[203] There is an additional set of wells Riverview uses for livestock watering that is only obliquely mentioned in the EAW (as four commercial wells that exist at the current facility).[204] These wells, per DNR comments, have a water appropriation limit of 95 MGY, with permit number 2004-1023.

MPCA's analysis of groundwater quantity impacts focuses solely on the Off-Site Well. The EAW states that because the Off-Site Well is in a Quaternary Water Table Aquifer, and the five on-site wells are in the Quaternary Buried Artesian Aquifer beneath the Expansion Project site, that Riverview's approach to groundwater is "diversified."[205] As a result, MPCA did not consider the potential for cumulative impacts from the water withdrawals from the Off-Site Well and the five on-site wells on local groundwater resources.

This is a mistake. As DNR pointed out in its own comments on the EAW, the two aquifers are part of one connected system, and "water availability from these aquifers is limited."[206] Failing to fully describe the water appropriation from the on-site wells is a significant flaw in the EAW, and makes it more difficult to determine what the impacts of the Off-Site Well's water withdrawals will be on local groundwater resources. This problem is exacerbated because, as noted earlier, the most recent aquifer test is from 2007, and so it cannot be assumed to already include the usage of these wells.[207]

C. The Water Storage Basins Are An Inadequate Contingency For Appropriation Restrictions During Low Flow Events

The 2008 water appropriation permit for the Off-Site Well contains restrictions on pumping under certain flow conditions in the Pomme de Terre River, and these would be expected to also be incorporated into the new permit.[208] If pumping needs to be restricted, Riverview's plan is to use two water storage basins as a contingency measure, which would be filled from both the Off-Site Well and from stormwater collection.[209] This plan is not sufficient, and creates a serious risk that Riverview could overdraw from the Off-Site Well even when flow conditions are poor.

The drought conditions that could cause low flow in the Pomme de Terre River (and thus pumping restrictions) are also likely to reduce the amount of stormwater available to be diverted to the water storage basins. Minnesota has experienced severe dry conditions and drought in recent years, which will continue to worsen as the climate changes,[210] and so the risk of drought causing both low flow conditions and reduced stormwater availability is significant.[211]

An additional reason for caution is that Riverview has a history of causing groundwater depletion. Earlier this year, Riverview reached a settlement with the state of Arizona to reduce Riverview's groundwater usage, after Riverview's operations depleted local groundwater and left community members unable to

[203] Kestner, *supra* note 181.
[204] *Riverview's EAW for West River Dairy, supra* note 17, at 31.
[205] *Id.* at 36.
[206] Kestner, *supra* note 181.
[207] Additionally, Riverview's plan to capture stormwater for use on the Expansion Project could also have an impact on groundwater recharge for the on-site wells; this possibility should also be evaluated by MPCA to determine potential impacts on groundwater resources. 2
[208] *Riverview's EAW for West River Dairy, supra* note 17, at Attachment 11.
[209] *Id*. at 35.
[210] S. Clark et al., *Climate Change and Drought in Minnesota and the Midwest*, UNIV. OF MINN. CLIMATE ADAPTATION P'SHIP (2023), https://climate.umn.edu/sites/climate.umn.edu/files/2023-10/Drought%20in%20MN%20-%20V1%20%281%29.pdf [Exhibit 135].
[211] *Water A&R Report, supra* note 190, at 5.

use their own wells.[212] In Minnesota, a DNR technical report found that Riverview's proposed Twelvemile Dairy should not use a deep aquifer as a water source in part because "water levels at the nearby [Riverview] Dollymount Dairy continue to decline and have not yet stabilized."[213] Riverview exceeded its permit limits for pumping at the Dollymount Dairy in both 2020 and 2021.[214]

IV. AN EIS IS NECESSARY TO ASSESS WATER POLLUTION RISKS NOT ADEQUATELY DISCUSSED IN THE EAW

The EAW fails to accurately capture and mitigate the risks the Expansion Project has on water quality. Because of the potential for significant environmental effects on water quality, MPCA should require the Expansion Project to complete an EIS.

A. The EAW Does Not Consider All Pollutants Of Concern

Mega-dairies like the proposed Expansion Project are major sources of water pollution. Manure "is a primary source of nitrogen and phosphorus to surface and groundwater."[215] But, dairy waste is not just nutrients; it also contains a hazardous cocktail of sediments, pesticides, pharmaceuticals, salts, metals and ions such as magnesium, sodium, potassium, and chloride.[216] CAFOs also handle a variety of other potential pollutants including detergents and other chemicals.[217] When discharged to waters, these pollutants pose serious threats to human health and to ecosystems.[218] Yet, the EAW covering the

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[212] Settlement and Release Agreement Between Riverview and Arizona, https://mcusercontent.com/cc1fad182b6d6f8b1e352e206/files/b0aaf293-9839-a6b7-4abb-e3a6e4121d71/Groundwater_Access_Settlement_Agreement_Arizona_Riverview.pdf [Exhibit 136]; Kris Mayes, *Attorney General Mayes Announces Precedent-Setting Settlement with Riverview Dairy to Reduce Groundwater Usage, Securing $11M for Well Drilling, Water-Hauling and Groundwater Access* (Jan. 8, 2026), https://www.azag.gov/ag-mayes-announces-riverview-settlement [Exhibit 137].

[213] DNR, *Aquifer Test Technical Review* 1 (Apr. 11, 2022), https://www.co.traverse.mn.us/wp-content/uploads/2022/08/2022-04-11-RiverviewTwelvemileAqTestReportTechReview.pdf [Exhibit 138].

[214] *Id*. at 9.

[215] U.S. EPA, *Estimated Animal Agriculture Nitrogen and Phosphorus from Manure*, https://www.epa.gov/nutrient-policy-data/estimated-animal-agriculture-nitrogen-and-phosphorus-manure [Exhibit 139].

[216] 68 Fed. Reg. 7,176, 7,181 (Feb. 12, 2003); JoAnn Burkholder et al., *Impacts of Waste from Concentrated Animal Feeding Operations on Water Quality*, 115(2) ENV'T HEALTH PERSPS. 308 (Feb. 2007), https://www.ncbi.nlm.nih.gov/pmc/articles/PMC1817674/ [Exhibit 140].

[217] EPA, RISK ASSESSMENT EVALUATION FOR CONCENTRATED ANIMAL FEEDING OPERATIONS, EPA/600/R-04/042, at 63, 72-73 (May 2004), https://cfpub.epa.gov/si/si_public_record_Report.cfm?Lab=NRMRL&dirEntryId=85107 [Exhibit 141, hereinafter, "EPA CAFO R ISK A SSESSMENT "]; EPA, MANAGING MANURE NUTRIENTS AT CONCENTRATED ANIMAL FEEDING OPERATIONS at 2-1-–2-4 (Dec. 2004), https://www.epa.gov/sites/default/files/2015-08/documents/cafo_manure_guidance.pdf [Exhibit 142 hereinafter, "EPA, M ANAGING CAFO MANURE"].

218 See, e.g., 68 Fed. Reg. 7176, 7186, 7263; Xunde Li et al., Fecal Indicator and Pathogenic Bacteria and Their Antibiotic Resistance in Alluvial Groundwater of an Irrigated Agricultural Region with Dairies, 44 J. ENVTL. QUALITY 1435, 1435 (2015) [Exhibit 143]; Tucker Burch et al., Fate of Manure-Borne Pathogens during Anaerobic Digestion and Solids Separation, 47(2) J. ENVTL. QUALITY 336, 336 (2018) [Exhibit 144]; Laura M. Bexfield et al., Hormones and Pharmaceuticals in Groundwater Used as a Source of Drinking Water Across the United States, 53 Envtl. Sci. & Tech 2950, 2950-51, 2958 (2019) [Exhibit 145]; see also SCOTT A. BRADFORD ET AL., U.S. DEP'T AGRIC. (2008), REUSE OF CONCENTRATED ANIMAL FEEDING OPERATION WASTEWATER ON AGRICULTURAL LANDS, https://www.ars.usda.gov/arsuserfiles/20360500/pdf_pubs/P2194.pdf [Exhibit 146]; Yernar Amangelsin et al., The Impact of Tetracycline Pollution on the Aquatic Environment and Removal Strategies, 12 ANTIBIOTICS 15, https://pmc.ncbi.nlm.nih.gov/articles/PMC10044355/ [Exhibit 147]; Diana Yates, U. Illinois, Team Determines How Estrogens Persist in Dairy Farm Wastewater (June 5, 2012), https://news.illinois.edu/team-determines-how-estrogens-persist-in-dairy-farm-wastewater/ [Exhibit 148]; Muhammad Adeel et al., Environmental Impacts of Estrogens on Human, Animal and Plant Life: A Critical Review, 99 ENV'T INT'L 107 (2017), https://pdf.sciencedirectassets.com/271763/1-s2.0-S0160412016X00104/1-s2.0-S0160412016304494/main.pdf [Exhibit 149]; Edward F. Orlando et al., Endocrine-Disrupting Effects of Cattle Feedlot Effluent on an Aquatic Sentinel Species, the Fathead Minnow, 112(3) ENVTL. HEALTH PERSPECTIVES 353, 356 (2004) [Exhibit 150]; Joan A Casey et al., Industrial Food Animal Production and Community Health, 2 CURRENT ENVTL. HEALTH REP. 259, 266 (Sept. 2015) [Exhibit 151]; Fabienne Wichmann, Diverse Antibiotic Resistance Genes in Dairy Cow Manure,

proposed Expansion Project does not consider impacts from any pollutants other than nutrients. The potential for adverse water quality impacts from other pollutants must be weighed in an EIS, especially because waters adjacent to the Expansion Project area are already impaired by E. coli and other pollutants associated with mega-dairy operations.[219]

B. The EAW Downplays Water Quality Threats Posed By Clay-Lined Basins

Riverview's plan to store manure and process wastewater from the proposed expansion in clay-lined basins is likely to cause significant environmental impacts that warrant consideration in an EIS. A growing body of evidence demonstrates that clay liners are insufficient protection against feedlot contaminants leaching to the subsurface.[220] As Riverview is well aware, designing and upkeeping a clay liner to comply with a 1/56 inch per day permeability standard is complicated by clay's tendency to crack during freeze-thaw cycles.[221] In Minnesota, such cycles are common due to extreme seasonal temperatures. Further, though feedlot operators frequently point to compliance with permeability limits as evidence that clay liners prevent pollution from reaching groundwater, these same operators are rarely willing to conduct groundwater monitoring capable of substantiating their claims. Indeed, the EAW does not contemplate that Riverview will conduct any monitoring to detect whether its clay liners are continually performing as designed. Clay lines, without monitoring, provide no assurance that Riverview's lagoons will not contaminate groundwater,[222] and clay liners absent monitoring is an insufficient mitigation[223]

Failure to impose discharge monitoring requirements is particularly concerning at the Expansion Project site because groundwater within the vicinity of the dairy is hydraulically connected to the Pomme de Terre River.[224] Even if Riverview is able to maintain compliance with the permeability limit, the proposed lagoons are so large that they will leach substantial amounts of pollution over the lifetime of the

https://doi.org/10.1128/mbio.01017-13 (2014) [Exhibit 152]; EPA, National Pollutant Discharge Elimination System Permit Regulation and Effluent Limitations Guidelines and Standards for CAFOs 44-45 (Dec. 2000) [Exhibit 153]; JoAnn Burkholder et al., Impacts of Waste from Concentrated Animal Feeding Operations on Water Quality, 115(2) ENV'T HEALTH PERSPS. 308, 308 (Feb. 2007) [Exhibit 154]; Roberto Picetti et al., Nitrate and Nitrite Contamination in Drinking Water and Cancer Risk: A Systematic Review with Meta-Analysis, 210 ENVT 'L R ES . 112988 (July 2022), https://www.sciencedirect.com/science/article/pii/S0013935122003152 [Exhibit 155]; Daniel F. Gomez Isaza, Living in Polluted Water: A Meta-analysis of the Effects of Nitrate and Interactions with Other Environmental Stressors on Freshwater Taxa, 261 Environmental Pollution (2020) [Exhibit 156]; Jason Semprini, Early Prenatal Nitrate Exposure and Birth Outcomes: A Study of Iowa's Public Drinking Water (1970-1988), 4 PLOS Water (2025) [Exhibit 157].

[219] Riverview's EAW for West River Dairy, supra note 17, at 29-30.

[220] See David J. Erickson, CPG PG, Response to Riverview, LLP Application for the Herberg Dairy 1, 3-6 (2025) [Exhibit 158, hereinafter "Erickson Report"] (hydrologist report evaluating water pollution risks from another Riverview mega-dairy proposed for construction in North Dakota).

[221] See Memorandum of Britt Siddoway, PE, to Dakota Resource Council, Re: Abercrombie Dairy Manure Storage Ponds 1&2 – Assessment of Permitted Design w/ Regards to Modern Industry Practices (July 1, 2025) [Exhibit 159] (expert report assessing clay-lined lagoon designs that Riverview proposed to construct at a dairy in North Dakota); American Engineering Testing, Report of Geotechnical Exploration and Review, Herberg Dairy 8 (Nov. 21, 2024) [Exhibit 160] (engineering report prepared for another Riverview-owned dairy in North Dakota); see also Noah Rudko et al., Development of a Point-Source Model to Improve Simulations of Manure Lagoon Interactions with the Environment, 325 J. Env't Mgmt. 1, 9 (2023) [Exhibit 161] ("The effects of manure sealing that might reduce leakage rates as earthen structures age are offset by processes such as freezing and thawing cycles, or wetting and drying.").

[222] *See Food & Water Watch v. EPA*, 20 F.4th 506, 517 (2021) ("Without a requirement that CAFOs monitor waste containment structures for underground discharges, there is no way to ensure that production areas comply with the Permit's zero-discharge limit.").

[223] *Citizens Advocating Responsible Dev. v. Kandiyohi Cnty. Bd. of Comm'rs*, 713 N.W.2d 817, 834-35 (Minn. 2006).

[224] *Riverview's EAW for West River Dairy, supra* note 17, at 35.

Expansion Project.[225] Pollution that leaches to the subsurface is liable to contaminate not only soil and groundwater surrounding the basins, but also the Pomme de Terre River via subsurface hydrological discharges. MPCA must require that Riverview install synthetic liners with leak detection—as it has agreed to do for its Abercrombie Dairy in North Dakota[226] —to protect against subsurface discharges and the environmental hazards caused by such discharges. Additionally, MPCA must further investigate the interconnection between the basin sites and surface waters in the Pomme de Terre River basin before making a decision on the proposed Expansion Project.

C. The EAW Underestimates Water Quality Threats From Stormwater Management

If Riverview is permitted to store its waste in basins that are designed to—and will—leach pollutants to the subsurface, then its stormwater storage plans are seriously flawed. Of note, Commenters are limited in their ability to assess impacts that would result from Riverview's stormwater management because the facility's Stormwater Pollution Prevention Plan[227] was not included in materials made available for public comment. Nevertheless, at least one problem is evident from the EAW materials that were made available. Riverview plans to install a drain tile system to "control seasonal subsurface saturation" near the 35.2 acres of liquid manure storage basins where Riverview proposes to store nearly 150 million gallons of additional liquid manure.[228] This subsurface water will be diverted to one of the on-site storage basins and then released directly into the environment via a series of drainage ditches that ultimately flow to the Pomme de Terre River.[229]

Riverview's repeated claims that this stormwater is "clean"[230] are belied by their plan to construct the manure basins out of permeable (i.e. leaky) clay. Water that seeps into the ground surrounding the basins will be exposed to pollutants—including nitrates, dangerous pathogens, and pharmaceuticals that breed antibiotic resistant bacteria—that inevitably leach from the basins. Though the EAW makes vague references to "treatment" of this stormwater (an unnecessary step if the water were truly clean, as Riverview claims), but provides no details that allow Commenters or any other members of the public to evaluate the effectiveness of such treatment. This alone provides a sufficient justification for a harder look at the environmental impacts of the proposed expansion in an EIS.[231]

D. The EAW Does Not Disclose Or Evaluate Runoff Risks From Tile Drained Fields

All of the Expansion Project's manure application sites are also within the Pomme de Terre River watershed. The EAW does not consider how leaks from the hoses it uses to pump waste to these fields could impact water quality, nor are there monitoring requirements to ensure any such leaks are discovered and stopped in a timely manner.[232] But even if the hoses remain intact, the proposed expansion would substantially increase loads of contaminated runoff flowing from crop fields to the Pomme de Terre River and its tributaries. Extensive tile drainage installed on agricultural fields in the

[225] Erickson Report, *supra* note 220, at 4 (explaining how seepage adds up to significant pollution plumes over time, even when clay-lined basins meet low permeability standards).
[226] Email Exchange between Naomi Miranowski, Citizens for Responsible Growth and Riverview LLP (Oct. 2025) [Exhibit 162].
[227] *See Riverview's EAW for West River Dairy, supra* note 17, Attachment 22 at 12 (confirming that MPCA received the Stormwater Pollution Prevention Plan and other supporting materials not made available to the public on December 11, 2025).
[228] *Riverview's EAW for West River Dairy, supra* note 17, at 27.
[229] *Id*. at 27, 39.
[230] *Id*. at 15, 17, 27, 34, 36, 37, 38, 39.
[231] *See* Minn. R. 4410.0300 ("The purpose of parts 4410.0200 to 4410.6500 is to aid in providing that understanding through the preparation and public review of environmental documents.")
[232] *See* Cami Koons, *DNR Monitoring Hog Manure Spill and Clean Up in Carroll County* (Oct. 15, 2025), https://iowacapitaldispatch.com/briefs/dnr-monitoring-hog-manure-spill-and-clean-up-in-carroll-county/ [Exhibit 163] (describing manure spill from leaking hose).

area exacerbate runoff risks.[233] Notably, Riverview admits that it has not complied with the requirement to identify all tile inlets on the proposed manure land application sites.[234] The additional runoff caused by the expansion combined with subsurface leaching from the manure storage basins is likely to significantly increase cumulative impacts on the watershed. These impacts need to be fully assessed and disclosed to the public in an EIS before MPCA makes a decision about Riverview's expansion application.

V. MPCA MUST ORDER AN EIS TO ANALYZE THE CUMULATIVE EFFECTS OF THE EXPANSION PROJECT'S MANURE ON WATER QUALITY

The EAW is also incomplete because, in violation of the Minnesota Rules, it fails to analyze the Expansion's cumulative potential effects on water quality from manure application. The EAW avoids any true analysis of the effect of applying manure from an additional 11,000 dairy cows in the Pomme de Terre River watershed, a region that already has numerous feedlots and impaired waters. To comply with MEPA, MPCA cannot simply proclaim that the Expansion Project will have no cumulative effects on water quality—it must take a hard look at the potential for significant environmental effects. Thus far, it has not done so.

A. The EAW Shows That The Expansion Project Will Add Over 113 Million Gallons Of Liquid Manure To A Watershed Already Containing Impaired Waters

Riverview expects its additional 11,000 dairy cows to produce a truly extraordinary amount of manure—113,619,000 gallons of liquid manure and 15,400 tons of solid manure each year.[235] Combined with the existing feedlot, the expanded facility is expected to produce 202,744,000 gallons of liquid manure and 26,400 tons of solid manure each year.[236] This is far greater than the amount of waste produced by all the people in Minneapolis, Rochester, and Minnetonka combined.[237] That waste, of course, is treated, and ultimately discharged as clean water that meets water quality standards. Not so for Riverview's waste. Riverview intends to transfer the majority of the manure generated by the Expansion Project to 16,500 acres of non-Riverview owned or leased fields in Horton, Darnen, Synnes, and Scott townships within Stevens County, and on fields in Fairfield and Hegbert townships in Swift County. Notably, the Expansion Project is not the only large feedlot in this part of Stevens County. There are over 90 registered feedlots within the general area of the Expansion Project that also generate manure that needs to be managed, typically through land-application.[238]

The 113 million gallons of liquid manure will be added to an area where surface waters are already contaminated with the kinds of pollutants found in manure runoff. The Expansion Project is situated

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[233] *See Riverview's EAW for West River Dairy, supra* note 17, at Attachment 7a ("All land impacted by the Project Site is currently in crop production and the majority of it is pattern tiled.").
[234] *See Riverview's EAW for West River Dairy, supra* note 17, at 1-2 (mandating that Riverview attach to its EAW maps that show all tile inlets and other sensitive receptors on its land application sites and within a mile of the Dairy); *id* at 44 ("Many of the fields in the MMP belong to third-party farmers who will receive the transferred manure and are responsible for manure application on their land. For those parcels, the location of all tile drains is not easily identifiable by the Proposer.").
[235] *Riverview's EAW for West River Dairy, supra* note 17, at 8; Emily Payne, *Plan for Largest Dairy in Minnesota History Raises Water and Pollution Concerns*, SENTIENT MEDIA (Apr. 1, 2026), https://sentientmedia.org/plan-for-largest-dairy-in-minnesota-history/ [Exhibit 164] (reporting that "Riverview's expansion would more than double its liquid manure storage capacity in Morris, from 102 million gallons to 250 million gallons").
[236] *Riverview's EAW for West River Dairy, supra* note 17, at 8.
[237] *See* Ron Fleming & Marcy Ford, Human Versus Animals-Comparison of Waste Properties (2001), http://clucnorthfork.org/wp-content/uploads/2012/06/Human-versus-AnimalsComparison-of-Waste-Properties.pdf [Exhibit 165] (finding 20 dairy cows produce approximately the same waste as 1,000 humans); Minnesota State Demographic Center, Our Estimates, https://mn.gov/admin/demography/data-by-topic/population-data/our-estimates/ (listing the 2024 population of Minneapolis as 435,233 residents, Rochester as 124,220 and Minnetonka as 56,162 residents).
[238] Riverview's EAW for West River Dairy, supra note 17, at Attachment 14.

within the Muddy Creek Subwatershed within the Pomme de Terre River Watershed. The fields identified to receive manure from the Expansion Project are located in the Muddy Creek Subwatershed, the Middle Pomme de Terre River Subwatershed, and the Dry Wood Creek Subwatershed. Since at least 2011, MPCA has known about the substandard water quality in this region of the Pomme de Terre River Watershed. The cause of this is clear: fewer natural landscape features and more intensive agriculture.[239] This region of the Pomme de Terre River Watershed has the most stretches of impaired waters and the highest nutrient concentrations and turbidity levels.

The Expansion Project is situated in the lower part of the Pomme de Terre River Watershed and the lower portion of the Muddy Creek Subwatershed, suggesting that the nearby waterways are already impacted by downstream effects from agricultural activities in the watershed's northern region. Additionally, many of the manure-accepting fields are near the Expansion Project or about 10 miles north of it, which will further increase phosphorus downstream in the watershed, particularly in the Lower Pomme de Terre River Subwatershed.[240] The EAW merely suggests that farmers who receive manure to be spread in areas near surface water with already phosphorus-polluted waters will follow the Feedlot Permit rules for land application, with testing every 4 years.[241] But even if all recipients do follow the permit rules, those rules do not attempt to eliminate all water pollution from land application of manure. Some pollution will certainly occur, and there is no consideration in the EAW for the downstream effects on the already polluted water.

Additionally, E coli is present at high levels in multiple reaches of water in the Pomme de Terre River Watershed.[242] Increased concentrations of E. coli in rivers and streams are primarily caused by animal waste, with sewage overflows and stormwater also contributing.[243] Over a decade ago, MPCA noted that Muddy Creek was one of two reaches where tests showed elevated concentrations of E. coli.[244] Studies of this area revealed a correlation between precipitation and E. coli concentrations, suggesting that runoff from manure spread on agricultural fields is largely to blame.[245] In this part of the state, MPCA estimates that a 49% reduction in E. coli is needed to meet water quality standards.[246]

The Lower Pomme de Terre River Sub Watershed has similar issues to the Muddy Creek Sub Watershed. The quality in this region is compromised by high turbidity and bacteria.[247] Turbidity is caused by suspended particles and large algal blooms, resulting in murky waters that can degrade water quality and harm aquatic life. These large algal blooms may be related to the high phosphorus levels in the watershed.[248]

Additionally, substantial evidence shows that water quality degrades progressively downstream within a watershed.[249] Although the Expansion Project is situated in the southern portion of the broader

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[239] MPCA, Pomme De Terre River Watershed Monitoring and Assessment Report 1 (June 2011), https://www.pca.state.mn.us/sites/default/files/wq-ws3-07020002b.pdf [Exhibit 166, hereinafter "2011 Pomme de Terre WRAPS"].
[240] Riverview's EAW for West River Dairy, supra note 17, at 47-8.
[241] Id. at 46.
[242] Pomme de Terre TMDL, supra note 192, at 32-39
[243] Id.
[244] Minnesota River Basin 2010 Progress Report: Pomme de Terre River Watershed, https://mrbdc.mnsu.edu/sites/mrbdc.mnsu.edu/files/public/progress/pdf/9.%20Report%20-%20Pomme%20de%20Terre.pdf [Exhibit 167]
[245] Id.
[246] Pomme de Terre TMDL, supra note 192, at
[247] 2011 Pomme de Terre WRAPS, *supra* note 239, at 45.
[248] *Id*. at 55.
[249] Pomme de Terre WRAPS, *supra* note 186, at 80.

watershed, it lies in the northern section of the Lower Pomme de Terre River Sub Watershed, meaning its pollution will inevitably flow downstream and further burden already impaired waters relied upon by downstream users. Yet the current EAW fails to meaningfully account for these downstream impacts. The EAW ignores the cumulative and compounding increases in nitrate and phosphorus pollution, overlooks the broader context of intensive regional agricultural activity, and minimizes the significant additional pollution that an Expansion Project would contribute. This omission understates the true environmental harm and risks, allowing further degradation of already vulnerable water resources

B. The EAW Does Not Adequately Address The Cumulative Effects Of Manure From All Feedlots In The Region

Minnesota Rules require than an agency consider "cumulative potential effects" in determining whether a project has the potential for significant environmental effects.[250] This means the agency must analyze "the effect on the environment that results from the incremental effects of a project in addition to other projects in the environmentally relevant area that might reasonably be expected to affect the same environmental resources, including future projects."[251] As the Rules note, even projects that are individually minor can create significant cumulative effects over time.[252]

The EAW, however, contains only a superficial and incomplete cumulative effects analysis regarding manure application in an already impaired watershed. The EAW recognizes that there is the potential for cumulative potential effects from "overlapping manure application and excess water usage."[253] The concern about manure over-application, however, is waived away entirely by pointing to the number of acres local producers have made available to receive the Expansion Project's manure.

This is an entirely insufficient analysis. For one, it wholly ignores on-the-ground data from this region of the state that reveals 73% of fields received an over-supply of manure,[254] with nearly 60% of fields receiving manure at nitrogen rates averaging 166 pounds per acre, well-beyond the recommended rate of 100 to 140 pounds per acre.[255] Since Riverview intends the Expansion Project's manure to be applied at fields owned or controlled by others, Riverview will not be able to guarantee that farmers follow best management practices or apply at agronomic rates. Thus, the analysis does not seriously consider that waters in the Pomme de Terre River watershed are already impaired, and that runoff from an additional 113 million gallons of liquid manure that will be applied each fall will almost certainly worsen the impairments already present in the watershed. Manure runoff is well known to contaminate surface waters with nitrate, phosphorus, ammonia, and fecal coliform bacteria (like E.coli), which can make water undrinkable, harm fish, cause algal blooms, and destroy aquatic habitats.[256] More than half of all Minnesota's surface waterbodies do not meet basic water quality standards, and non-point source pollution, like manure runoff from feedlots and fields, is responsible for about 85% of water pollution.[257]

The EAW also makes no attempt to examine how the combination of manure from the Expansion Project and manure from the approximately 96,300 animal units in the Pomme de Terre River

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[250] Minn. R. 4410.01700, subp. 1.
[251] Minn R. 4410.0200, subd. 11a.
[252] *Id.*
[253] *Riverview's EAW for West River Dairy, supra* note 17, at 70.
[254] Pomme de Terre WRAPS, *supra* note 186, at 58.
[255] *Id*. at 59.
[256] Mary Berg & Miranda Meehan, North Dakota State University, Environmental Implications of Excess Fertilizer and Manure on Water Quality (Oct. 2017) [Exhibit 168].
[257] Sarah Graddy, Environmental Working Group, EWG Investigation: Manure Overload Threatens Water in Minnesota's Farm Country (May 28, 2020), https://www.ewg.org/release/ewg-investigation-manure- overload-threatens-water-minn-farm-country [Exhibit 169].

Watershed will affect water quality. While the EAW provides a map that identifies nearly 100 feedlots in the general area,[258] the EAW provides no other information about these nearby feedlots—such as how much manure they produce, where farmers apply that manure, and whether there is overlap with the fields receiving Riverview manure. Since manure cannot be cost-effectively transported far away, the manure from all these nearby feedlots is likely to be applied nearby. For a proper cumulative effects analysis, the EAW must examine "other projects in the environmentally relevant area that might reasonably be expected to affect the same environmental resources."[259] Here, that means other feedlots and how adding 113 million gallons of manure will impact an area where, presumably, farmers already allow a large amount of manure to fields. But the EAW failed to analyze other feedlots.

The contribution to already significant environmental degradation from the existing dairy is "significant when viewed in connection with other contributions to the cumulative potential effect."[260] The draft EAW itself fails to analyze many of the cumulative impacts, but publicly available information in the form of many agency studies over many years demonstrates the potential for significant environmental impacts on water quality from the addition of an enormous industrial feedlot in an already heavily impacted watershed. This must be studied in a detailed EIS that seriously considers alternatives before MPCA can permit the proposed project.

VI. MPCA MUST CONSIDER THE IMPACT THE EXPANSION PROJECT WILL HAVE ON THE DAIRY MARKET AND NEARBY ECONOMIES

Pursuant to Minn. R. 4410.1700 2a (A), MPCA should order an EIS and include within the scope of the EIS an assessment of the impacts the Expansion Project—in the context of larger expansion and consolidation trends—has on the dairy market and rural economies. MEPA requires RGUs to take "a 'hard look' at all the problems involved."[261] Although the EAW form guides the preparation and completion of an EAW, the assessment of environmental impacts is not limited by what the form asks. Rather, the assessment must consider all potentially significant environmental effects, even if not explicitly asked about in the EAW form.[262] Here, that includes assessing the effects the Expansion Project will have on the dairy market and the local economy.

The numbers are striking. In the last two decades, Minnesota has lost nearly 75% of its dairy farms,[263] even as the number of milk cows in Minnesota has remained relatively stable. Far fewer dairy farms exist now than before, but the average size of a Minnesota dairy farm has exploded.

Riverview is leading this charge to expand. According to MPCA's feedlot database, Riverview owns 15 dairy operations totaling more than 133,000 cows, with an average of nearly 9,000 cows per feedlot.[264] By comparison, the average dairy herd in Minnesota is approximately 280 cows,[265] meaning that the

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[258] *Riverview's EAW for West River Dairy, supra* note 17, at 24, Attachment 14.
[259] Minn. R. 4410.0200, subd. 11a.
[260] Minn. R. 4410.1700, subp. 7 (B).
[261] *Citizens Advocating Responsible Development v. Kandiyohi Cty. Bd. of Comm'rs*, 713 N.W.2d 817, 832 (Minn. 2006) (quoting Reserve Min. Co. v. Herbst, 256 N.W.2d 808, 825 (Minn. 1977)).
[262] *See In re Denial of a Contested Case Hearing Request & Modification of a Notice of Coverage Under Individual National Pollution Discharge Elimination System Feedlot Permit No. MN0067652*, No. A19-0207, 2019 WL 5106666, at *4-8 (Minn. App. Oct. 14, 2019) (concluding that MPCA's decision not to assess GHG emissions in a feedlot EAW failed MEPA's hard look requirement).
[263] United States Dep't of Agric. *Historical Highlights:* 2022 and Earlier Census Years, https://www.nass.usda.gov/Publications/AgCensus/2022/Full_Report/Volume_1,_Chapter_1_State_Level/Minnesota/st27_1_001_001.pdf [Exhibit 170].
[264] MPCA, *Feedlots in Minnesota*, https://gisdata.mn.gov/dataset/env-feedlots.
[265] Land Stewardship Project, *Flooding the Market: How Dairy Consolidation is Drowning Minnesota's Farmers & Rural Communities* (Apr. 23, 2026), https://landstewardshipproject.org/wp-content/uploads/Milk-Flood-C-4-23-26.pdf [Exhibit 171].

average size of a Riverview feedlot is roughly 500 times larger. As a result of this consolidation, nearly 50% of milk cows in Minnesota are confined in the largest 8% of farms.

Consolidation impacts pricing and the ability for smaller dairies to access markets. Most dairy farmers sell milk to regional cooperatives or processors, using a federal pricing system based on marketwide supply and demand.[266] Mega-dairies like Riverview monopolize the market which, they may argue, allows for efficiencies that (at least initially) drive down costs. But monopoly agribusinesses are contrary to public policy and the health of the rural economy. Small dairies cannot compete in a monopolized business environment. Moreover, dairies selling milk to cooperatives or processers typically have a limited number of potential buyers (often just one) in their region.[267] Because milk is perishable and uneconomic for long-distance travel, dairies are constrained from accessing a cooperative or processer unless it is close to the farm.[268] As production becomes more consolidated, research shows that the number of buyers shrinks, limiting the geographies where dairies can sell milk.

Consolidation also impacts rural economies. A 1995 University of Minnesota study examined the impact of dairy farming on the community near Green Isle, Minnesota.[269] The study showed that, between the 1970s and 1990s, the number of farmers serving the local creamery dropped from 1,400 to 960 and larger farms started dominating the area. Economic and social activity in Green Isle plunged; between 1979 and 1989, retail sales dropped by over 80 percent and institutions like the public dance hall and the grade school permanently closed.[270] This is consistent with more recent assessments that conclude having more dairy farms is associated with a more positive economic and socioeconomic environment than higher dairy sales.[271]

These forces have impacted Minnesota's rural landscape. According to Minnesota Attorney General Keith Ellison, "when you hear about giant producers who are going to increase production drive prices even further down what it really means is that we are running small dairy producers out of business."[272] When a small dairy closes, Minnesota loses more than a supply of milk. "The closing of small dairy farms has contributed to the diminishing of small towns across greater Minnesota. Each closure has meant less demand for local mechanics, fewer students in the public schools, fewer farmers shopping at the local hardware store, fewer buyers at the local tractor dealer."[273]

Given Riverview's dominance in the Minnesota dairy market and its current effort to expand an existing facility to become the State's largest ever feedlot, MPCA's environmental review must consider how the Expansion Project will impact the dairy market and local economies. The EAW's silence on this issue means that it has "entirely failed to consider an important aspect of the problem."[274] Importantly, these consolidation efforts are not separate from environmental review.[275] A production model centered on

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[266] *Id.*
[267] *Id.*
[268] *Id.*
[269] Patricia Weir Love, *The Impact of Changes in Dairy Farming on a Local Economy: A Case Study* (May 1995) [Exhibit 172].
[270] *Id.*
[271] C. D. Dechow, *Short Communication: Farm and Socioeconomic Characteristics of the Top 100 Dairy Farm Counties in the United States*, J. DAIRY S CI . (2011), https://doi.org10.3168/jds.2010-3909
[272] *Greener Pastures, Small Dairies are Disappearing. Here's why it matters* (May 4, 2026), https://www.youtube.com/watch?v=CP0bAjjyEP4 at 3:39 – 3:50.
[273] Karen Tolkkinen, *Let's Reconsider Allowing Massive Dairies in Rural Minnesota*, Minn. Star Tribune (May 3, 2026), https://www.startribune.com/tolkkinen-lets-reconsider-allowing-massive-dairies-in-rural-minnesota/601798066.
[274] *Citizens Advocating Responsible Development v. Kandiyohi Cty. Bd. of Comm'rs*, 713 N.W.2d 817, 832 (Minn. 2006).
[275] Minn. Stat. § 4410.1200(E) (requiring EAWs to include "major issues sections identifying potential environmental impacts and issues that may require further investigation before the project is commenced") (emphasis added); *id.* § 4410.2300(H) (requiring an EIS to assess the "[e]nvironmental, economic, employment, and sociological impacts" for the proposed project).

fewer, larger operations concentrates manure generation, land-application pressure, air emissions, water demand, truck traffic, and energy use at particular sites and in surrounding communities. The EAW fails to evaluate whether the Expansion Project would further entrench this consolidated production model and whether that concentration would cause or contribute to significant environmental effects requiring further review.

Consolidation in industrial farming and agribusiness presents very significant economic and social repercussions for rural families and communities. Regulators can scrutinize large agribusiness to ensure the marketplace is fair through anti-trust laws.[276] But in Minnesota, MEPA also requires state agencies to consider these economic and social impacts before a project is approved. Because the draft EAW wholly fails to address this aspect of the problem, MPCA must order an EIS which will include an inquiry into Minnesota's dairy industry and the economic and social impacts consolidation, driven by Riverview, is having on the State.

CONCLUSION

To comply with Minnesota law, an EIS must be conducted to fully analyze the GHG emissions expected from the Expansion Project, their effects on climate change, and potential mitigation measures that could be used to reduce those effects. The EIS must also consider the water quality impacts attendant from appropriating over 200 million gallons of water per year from an aquifer hydrologically connected to the Pomme de Terre River. Additionally, an adequate plan to protect water quality from the massive amount of manure the Expansion Project will add to the Pomme de Terre River Watershed is required. The analysis must include a full assessment of the cumulative effects of applying so much additional manure to fields in a region where surface waters are already impaired with agricultural pollutants. Finally, the EIS must assess the Expansion Project's impact on the Minnesota dairy market.

Given all the missing and incomplete information in the EAW, MPCA currently cannot make an informed decision regarding the Expansion Project's potential for significant environmental effects. Accordingly, the undersigned organizations ask that MPCA order an EIS, so that the full effects of what would be Minnesota's largest CAFO can be fully reviewed.

Respectfully submitted,

Minnesota Center for Environmental Advocacy

The Climate Change & Animal Agriculture Legal Initiative, part of the Law, Environment & Animals Program at Yale Law School*

Land Stewardship Project

FarmSTAND

Food & Water Watch

CURE

**Yale affiliation provided for identification purposes; position not endorsed by Yale University or Yale Law School*

Priscilla Wood **Letter 1290**

[276] U.S. Dep't of Justice, *Acting Attorney General Blanche Announces Antitrust Investigations on Meatpacking Operations* (May 4, 2026), https://www.justice.gov/opa/video/acting-attorney-blanche-announces-antitrust-investigations-meatpacking-operations.

A mistake was made by scheduling the public informational meeting in too small of a venue. I was an hour early and there were less than 10 scattered seats available. Ground water is a finate resource and there are already other large water usage industries in Steven's County. More and more farm land is being tiled which quickly drains rain water off the field so it is no longer seeping into the ground to replenish the ground water.

Extreme weather events are becoming more common due to climate change. Was there any reported manure over flow from the pit when Morris was hit with 16" of rain?

Stephanie Gausman **Letter 1291**

This expansion will put to much stress on the water table and other environmental impacts that will not be good.

Char Zinda **Letter 1292**

Water is not a renewable resource. It is the new gold for our lifetime and for our children and grandchildren. It affects much more than Riverview. Ease at the very least require an Environmental Impact Assessment Study. It is like dotting your I's and crossing your t's. It is you that we depend on.

Jamalea Martelle **Letter 1293**

My name is Jamalea Martelle, and I am writing in support of requiring the Minnesota Pollution Control Agency to conduct a full Environmental Impact Statement (EIS) for Riverview LLP's proposed West River Dairy Expansion.

I have had the privilege of experiencing this landscape through time spent with my husband and his family along the Pomme de Terre watershed and surrounding lands. Through waterfowl hunting, whitetail deer hunting, and time spent outdoors in this region, I have created lasting memories and developed a deep appreciation for the ecological value of this watershed and the wildlife it supports.

These experiences have also allowed me to witness the growing pressures placed on these landscapes over time. The Pomme de Terre watershed and nearby wetlands are vital habitat for migratory birds, deer, and countless other species that rely on these increasingly fragmented areas for survival. Protecting these lands and waters matters not only for conservation, but for the future generations who deserve the opportunity to experience and connect with these places the same way we have.

Given the unprecedented size of this proposed CAFO, the enormous water demand, and the proximity to already impaired waterways and protected wildlife areas, I believe a full Environmental Impact Statement is necessary. Minnesotans deserve a transparent and comprehensive review of the potential impacts to groundwater, surface water, wildlife habitat, local farmers, and rural communities before any decisions are made.

An EIS is a reasonable request for a project of this magnitude. It is a responsible step toward ensuring long-term protection of Minnesota's land, water, wildlife, and rural communities.

Thank you for taking the time to consider my comments.
Jamalea Martelle

Peter Kennedy **Letter 1294**

An Environmental Assessment Worksheet for a Confined Animal Feedlot Operation of this size is insufficient and an Environmental Impact Statement must be ordered.

The EAW is largely prepared with information provided by the petitioner and their contractors and is only focused on the CAFO in question. This casts the permitted activity in the best possible light and glosses over any negative impacts. An in independent assessment that includes this CAFO, the other CAFOs in the area and the impaired waterways in the affected watershed must be performed. The amount of water that is requested alone should trigger an EIS not to mention the nitrogen rich manure that will be applied through the watershed. The manure is applied largely in the fall when it has the greatest potential to leach nitrates into surrounding wells and waterways before it can be utilized by crops 6 months later in the summer.

No one is against progress, but when industrial agriculture progresses to this size then it needs to be regulated just like any other industry. Thank you.

Johanna Knorr **Letter 1295**

I am submitting the following comments on the West River Dairy Expansion Environmental Assessment Worksheet as both a resident of Morris and a lifelong dairy farmer. I have read the complete EAW, attended the MPCA's public information meeting on April 27, 2026, and reviewed several of the comments that have been submitted.

After reading the EAW, I appreciated the thorough, project-specific data and research that were compiled. I also noted that the Feedlot EAW template was updated in December 2024 and is more detailed and comprehensive than previous versions of the worksheet. I have been following several recent MPCA reports related to feedlots, and I believe it is important that this project be evaluated within the framework of these broader policy developments.

Compatibility with Minnesota's 2025 Nutrient Reduction Strategy (NRS)

Since 2014, many stakeholders—including the MPCA—have been working to improve water quality both locally and downstream. The 2025 Minnesota Nutrient Reduction Strategy (NRS) provides progress updates, establishes future goals, and outlines approaches for continued improvement. I would specifically like to highlight the following statement from page 158:

> "For the 2025 NRS, these best practices were reconsidered based on updated science and an assessment of their effectiveness, their potential to affect large acreages, and the multiple benefits they provide."

The West River Dairy Expansion incorporates three best practices identified in the NRS as having high total phosphorus (TP) reduction efficiencies.

1. In-Field Nutrient Management

Section 12.B.5.c.2 of the EAW identifies the use of precision knife-injection systems for liquid manure application. This practice is identified in the NRS as having a 35% TP reduction efficiency.

It is also important to recognize that the approximately 13,200 acres receiving annual manure application from West River Dairy will displace a comparable number of acres that are currently receiving commercial fertilizer. Manure application under this project will be closely regulated by the MPCA through a permit-required Nutrient Management Plan (NMP), including application rate limitations, timing restrictions, required setbacks from sensitive features, and mandatory cover crops or other best management practices (BMPs).

Commercial fertilizer sources, by comparison, are not typically subject to the same level of site-specific oversight. While I trust that farmers in my community are generally doing their best to responsibly

manage fertilizer use, it should be acknowledged that fields receiving manure are among the most closely regulated agricultural fields in the area.

2. Continuous Living Cover (Alfalfa and Cover Crops)

Section 18.B.1 of the EAW describes that the project will generate demand for approximately 2,200 acres of alfalfa. As of 2022, "other crops and hay" accounted for roughly 7% of all crop sales in Stevens County (USDA). While alfalfa is currently a minority crop compared to grains and oilseeds, the addition of a dairy operation that provides a stable, local market will incentivize increased acres of alfalfa production.

Conservation crop rotations, including alfalfa, are estimated to provide a 30% TP reduction efficiency.

The Draft Feedlot Permit (Section 18.4) requires that manure land-applied from June through September, and potentially through October 14, have a cover crop established within 14 days of application. Section 12.B.5.a.2 of the EAW identifies September 1 through November 15 as the primary manure application period, and Section 6.F.3 states that 13,200 acres will receive manure annually.

Based on this timing and permit structure, approximately 60% of application acres will require cover crops—equating to roughly 8,000 acres of new cover crops planted annually. Cover crop implementation is estimated to provide a 29% TP reduction efficiency.

3. Drainage Water Recycling

Section 12.B.4.b.5 of the EAW describes how the project will reduce sediment and nutrient runoff through stormwater pretreatment using sedimentation basins. The NRS estimates this practice has an 85% TP reduction efficiency.

In addition, Section 12.B.3.b of the EAW indicates that rainwater generated at the site will be captured and recycled for on-site use. This aligns well with the "multiple benefits" framework of drainage water recycling described in the NRS.

Cost and Public Benefit Considerations

The NRS estimates on page 154 that statewide adoption of best practices could cost taxpayers between $700 and $850 million per year if fully publicly funded. The practices proposed as part of the West River Dairy Expansion require no public funding. As a Minnesota taxpayer, I value that these privately funded practices will provide public water-quality benefits both locally and downstream.

Similarly, the 2026 Minnesota Climate Action Framework identifies the following priorities (page 54):

- Increase soil organic carbon and reduce erosion
- Manage fertilizer and manure to reduce emissions
- Manage farmland for multiple benefits
- Improve climate resilience through multi-purpose water storage and management
- Develop markets for climate-benefiting products

The practices described above—precision nutrient management, continuous living cover, and drainage water recycling—align closely with these stated priorities with no direct cost to Minnesota's taxpayers.

Context Within the Ongoing Feedlot Rulemaking Process

The MPCA initiated updates to Minnesota Rules Chapter 7020 in March 2025. Approximately one year later, priority areas within the rulemaking scope were identified. While final rule adoption may take several more years, the West River Dairy Expansion appears positioned to meet or exceed the

anticipated direction of the updated rules through requirements already included in the Draft Individual Feedlot Permit and practices described in the EAW. The relevant potential rules fell into 2 categories:

1. Land Application of Manure

The following requirements are addressed under the Individual Feedlot Permit:

- Transferred manure provisions
- Nitrogen BMPs
- Manure Management Plan applicability
- Visual field monitoring
- Recordkeeping requirements
- Application rate and location restrictions dictated by the MMP
- Manure sampling requirements dictated by the MMP

Regional zoning requirements are still under development; however, the EAW does not identify the project or receiving fields as being located in vulnerable groundwater areas.

2. Technical Standards

The Individual Feedlot Permit and EAW address the following technical standards:

- Manure storage capacity requirements
- Feed storage design and operation standards
- Livestock access to surface waters (not applicable, as this is a total confinement facility)
- Locational restrictions relative to sensitive areas (none identified)
- Enhanced manure storage design standards, including increased clay liner thickness and additional construction notifications

Presence of Existing Similar Operations

The proposed expansion would result in the largest dairy operation in Minnesota, a fact that has been cited in calls for preparation of an Environmental Impact Statement (EIS). However, size alone does not equate to environmental impact.

I have visited dozens of dairies across the country for personal, academic, and professional reasons. In my experience, herd size is not correlated with either animal care or environmental performance. Smaller farms are not inherently “better,” nor are larger farms inherently “worse.” Environmental outcomes are driven by the combination of regulatory standards and the integrity of ownership and management.

Minnesota has extensive regulatory requirements, as demonstrated by the hundreds of pages of documentation in this EAW, and is actively expanding oversight through rulemaking. The EAW did not identify any significant environmental impacts that would warrant preparation of an EIS.

Comparing similar projects does not fall within the formal scope of this EAW, but it seems relevant that comparable operations exist. The original West River Dairy, constructed in 2004, was one of the largest feedlots in the state at that time and has operated successfully and in compliance for over 20 years. This pattern has been repeated in other Riverview LLP dairy projects throughout Minnesota—large-scale facilities that have functioned with regulatory compliance and demonstrated environmental responsibility and operational integrity.

Conclusion

Based on the information presented in the EAW and the Draft Feedlot Permit, the West River Dairy Expansion is consistent with Minnesota's published environmental initiatives, including the Nutrient Reduction Strategy, the 2026 Climate Action Framework, and the known scope of the Animal Feedlots Rulemaking process. The project proactively incorporates many of the practices that Minnesota's agricultural community and state agencies should be encouraging to improve water quality.

For these reasons, I urge acceptance of the EAW as published, without requiring preparation of an Environmental Impact Statement.

Thank you to the MPCA for your work both in reviewing this project and providing Minnesota with the framework to evaluate projects and work together to protect Minnesota's air, water, land, and climate.

References

Minnesota Climate Change Subcabinet. (2026). Minnesota Climate Action Framework 2026 [PDF]. https://climate.state.mn.us/sites/climate-action/files/cc-mn4-04.pdf

Minnesota Pollution Control Agency. (2025). The first decade of the Minnesota Nutrient Reduction Strategy: 2014–2024 (Document No. wq-s1-87a) [PDF]. https://www.pca.state.mn.us/sites/default/files/wq-s1-87a.pdf

U.S. Department of Agriculture, National Agricultural Statistics Service. (2024). County profile: Stevens County, Minnesota (2022 Census of Agriculture) [PDF]. https://data.nass.usda.gov/Publications/AgCensus/2022/Online_Resources/County_Profiles/Minnesota/cp27149.pdf

U.S. Department of Agriculture, Natural Resources Conservation Service. (2026). Minnesota Nutrient Reduction Strategy (NRS) update: FY26 Minnesota State Technical Committee briefing [PDF]. https://www.nrcs.usda.gov/sites/default/files/2026-04/MN%20STAC%20FY26%20Minnesota%C2%A0Nutrient%20Reduction%20Strategy%20%28NRS%29%20Update.pdf

Travis Moser **Letter 1296**

Dear Commissioner Kessler and Commissioner Petersen:

We are residents of western Minnesota, eastern North Dakota, and eastern South Dakota, representing generations of farmers, business owners, and communities writing to share our strong support for Riverview's proposed West River Dairy expansion and to offer our perspective as you consider the project's path forward.

Many of us have spent our lives working this land, growing crops, raising livestock and building our livelihood here. We understand firsthand the importance of protecting our natural resources while also sustaining the farms, families, and local economies that depend on them. That balance matters deeply to us, and it is why we support this project.

Riverview is not new to our communities. They have a long track record of operating with care for the land, respect for animals, and a genuine commitment to the people and rural communities where they live and work. We have seen their approach up close: investing in environmental stewardship, partnering with local farmers, and contributing to the long-term vitality of the region.

The proposed West River Dairy expansion has undergone extensive and rigorous review. The Environmental Assessment Worksheet (EAW) and feedlot permit application together include nearly 900 pages of detailed technical analysis, developed over more than three years in coordination with state

agencies. The project is subject to oversight from multiple agencies, including the MPCA, DNR, and MDH, ensuring a comprehensive evaluation of groundwater, surface water, air quality, and natural resources.

In addition, the farm will operate under an individual NPDES feedlot permit – one of the most stringent and site-specific permits in Minnesota – and includes enhanced environmental protections that go beyond baseline requirements. Riverview has also taken proactive steps to reduce impacts, including voluntarily cutting permitted groundwater use in half and incorporating stormwater capture and reuse into the project design.

Based on what we know and what has been studied, we believe the current environmental review process is thorough, science-based, and appropriate for this project. An Environmental Impact Statement (EIS) should be reserved for situations where the evidence clearly demonstrates it is necessary. In this case, we are confident the existing process provides a full and careful evaluation.

For our communities, this project is also about the future, supporting family farms, creating economic opportunities, and strengthening our rural areas for generations to come. Riverview's model of working with neighboring farmers and investing locally reflects the kind of agriculture we want to see continue and grow.

We appreciate the seriousness of your roles and the responsibility you carry in reviewing projects like this. We respectfully encourage you to rely on the extensive environmental review already underway and the strong record of stewardship demonstrated by Riverview.

Thank you for your time and consideration.

Sincerely,

Travis & Rita Moser, Spring Valley Farms
Mike Yost, Yost Farm Inc
Michael Yost, Yost Farm Inc
Jim Radermacher, Yost Farm Inc
Kevin Lundberg, L&A Partnership
Cory Ahrends, Swift Pumping
Anthony Anker, Swift Pumping
Dustin Walsh, Walsh Farms
Jackson Walsh, Walsh Farms
Marc Stevens
Megan Horsager
Marcus Goldenstein
Scott Ruiter, Ruiter Farms
Nate Hultgren, Hultgren Farms
Randy Pothen, Pothen Farms
Matt Claussen, Claussen Farms
Stan Claussen, Claussen Farms
Thomas Claussen, Claussen Farms
Richard Walsh
Jim Kanten, Kanten Farms
Brett Petersen, Petersen Farms Inc
Nathan Collins, Collins Family Farms
Kent Bosch, CK Bosch Farms
Eric Boike, Boike Farms
Douglas Finstrom, Finstrom Farms
Erik Finstrom, Finstrom Farms
Cameron Adams, Skaurud Grain Farms
Gregory Anderson, Skaurud Grain Farms
Oloff Bergh, Skaurud Grain Farms
Rickie Brunner, Skaurud Grain Farms
Phillip Earle, Skaurud Grain Farms
Jacobus Esterhuizen, Skaurud Grain Farms
Adriaan Faber, Skaurud Grain Farms
John Gall, Skaurud Grain Farms
Jacob Geldenhuys, Skaurud Grain Farms
Marco Griebenauw, Skaurud Grain Farms
Edward Kriel, Skaurud Grain Farms
John McArthur, Skaurud Grain Farms
Joseph McArthur, Skaurud Grain Farms
James Menge, Skaurud Grain Farms
Matthew Miller, Skaurud Grain Farms
Richard Mizzell, Skaurud Grain Farms
Marissa Munsterman, Skaurud Grain Farms
Jim Murn, Skaurud Grain Farms
Dustin Nelson, Skaurud Grain Farms
Kelby Opsahl, Skaurud Grain Farms

Ross Opsahl, Skaurud Grain Farms
John Palm, Skaurud Grain Farms
Nicholas Pederson, Skaurud Grain Farms
Gerhardus Prinsloo, Skaurud Grain Farms
Stephanus Prinsloo, Skaurud Grain Farms
John Rothschadl, Skaurud Grain Farms
Louis Daniel Scheepers, Skaurud Grain Farms
Cory Skaurud, Skaurud Grain Farms
Evan Skaurud, Skaurud Grain Farms
Kathleen Skaurud, Skaurud Grain Farms
Kelly Skaurud, Skaurud Grain Farms
Perry Skaurud, Skaurud Grain Farms
Vicki Skaurud, Skaurud Grain Farms
Shaun Syverson, Skaurud Grain Farms
Grant Visser, Skaurud Grain Farms
Kenneth Winter, Skaurud Grain Farms
Steve Lacey, Lacey Ridge Farms
Jaylene Lacey, Lacey Ridge Farms
Brian Lacey, Lacey Ridge Farms
Deb Lacey, Lacey Ridge Farms
Natasha Lacey, Lacey Ridge Farms
Blake Steenblock, Spring Valley Farms
Paul Adams, Paul Adams Farms
Travis Miller, Mill Farms
Jessica Miller, Mill Farms
Greg Halubok, Summit Farms
Alicia Halubok, Summit Farms
Madison Yaggie-Schuler, Children's Discovery Center
Tanner Davison, Champion Farms
Frank Davison, Champion Farms
Kelsey VanOverbeke, Associate Agronomist
Nate Summerville, Summerville Electric
Dylan Summerville, Summerville Electric
Anthony Anker, Swift Pumping
John Habedank
Bradan Krump, Krump Brothers Farms
Randy Rittenour, JLR Farms
Janelle Rittenour, JLR Farms
Jerry Loxtercamp, Jerry's Pumping
Todd Klein, TAKCO Inc
Boone Carlson, Carlson Ag
Allen Yaggie, Allen Yaggie Farms Inc
Jesse Morgan, Christine Morgan Farms
Scott Hagy
David Heil
Scott Hennen
Brent Koehl
Keith Koehl
Lucas Koehl, Doubletree Farm
Levi Koehl, Doubletree Farm
Kurtis Koehl, Doubletree Farm
Kyle Koehl, Doubletree Farm
Derek Koehl, Doubletree Farm
Adam Koehl, Doubletree Farm
Randall Gorder
Trent Prestegord, Prestegord Farms
Tom & Stephanie Borgen, Borgen Farms
Michael Porter, MJP Trucking
Joel Rinke, Rinke Farms & Triple J Seed
Jake Rinke, Rinke Farms & Triple J Seed
James Rinke, Rinke Farms & Triple J Seed
Brian Rinke, Rinke AG
Steve Fridgen, Steve Fridgen Farms
Richard Jonhson, Johnson Farms
Adam Lichtsinn, Adam Lichtsinn Farms
Craig Lichtsinn, Adam Lichtsinn Farms
Steve Rinke, SR Farms
Mitch Frisch, Wheaton Resident
Paul Frisch, Frisch Farms
Tom Frisch, Frisch Farms
Travor Timm, T&T Cattle
Trent Timm, T&T Cattle
Kyle Bessler, Bessler Farms
Lee Sebek, Sebek Farms
Ron Kohl, Kohl Farms
Dillon Lien, Lien Farms
Shane Rein, Rein Construction
Derek Hansen, DC Trucking & Tree Services
Mitch Bodin, Bodin Construction
Brian Vig, Vig Livestock & Grain
Linn Vig, LVFI Farms
Gus Buss, Proper Welding & Fabrication
Brandon Gieser, Gieser Farms
Steven Steiner, Steiner Livestock
Renny Tank, Tank Farms
Jake Doyle, Puck Application
Justin Gaukler, Gaukler Farms
Jason Medhaug, Medhaug Farms
Jerry Nelson
Denver Nickeson, Nickeson Harvesting
Lonnie Jones, JNL Harvesting
Paul Mund, MG Harvesting
Nathan Koehl, CRK Partners

Tyler Scott, CRK Partners
Andrew Steiner, CRK Partners
Benjamin Koehl, CRK Partners
Byron Koehl, CRK Partners
Kaleb Koehl, CRK Partners
Taylor Gramm, CRK Partners
Arvin VanEps, CRK Partners
Brady Koehl, CRK Partners
Andrew Yost, CRK Partners
Mitch Koehl, CRK Partners
Clark Koehl, CRK Partners
Coby Backman, CRK Partners
Kevin Koehl, CRK Partners
Marciano Gonzales Garcia, CRK Partners
Megan Wulf, Spring Valley Farms
Lane Wulf, Spring Valley Farms
Jerry & Kedron Nohl, Spring Valley Farms
Fabian Hernandez, Spring Valley Farms
Greg Reuter, Spring Valley Farms
Hein Enslin, Spring Valley Farms
Jon Moser
Kurt & Savannah Wulf, Spring Valley Farms
Lowell & Karen Moser, Spring Valley Farms
Eric Meischner, Spring Valley Farms
Brent Evink, Spring Valley Farms
Eric Zeltwanger, Spring Valley Farms
Emmit Wulf, Spring Valley Farms
Reed Wulf, Spring Valley Farms
Carlos Hernandez, Spring Valley Farms
Craigan Wulf, Spring Valley Farms
Ed Wilkinson, Wilkinson Farms
Chad Malone
Kirk Aughenbaugh, Aughenbaugh Farms
Alan Aughenbaugh, Aughenbaugh Farms
Matt Aughenbaugh, Aughenbaugh Farms

Ronald Visser **Letter 1297**

Ronald Visser

Go on a tour! Riverview does them on every dairy. This is the best way to fully understand the dairy operation.

What you will see is:

A great cow environment-the barns are designed with cow comfort as top priority. The cows are calm when milking. They have access to feed, water, and a bed all day.

A great employee culture-the team is professional, hardworking and loves the cows.

A clean site-the farm is well organized, kept clean and well maintained.

A great manure plan-the manure lagoons are covered to control odor and to keep precipitation and manure separate; the lagoons have plenty of storage capacity-14 months. You might see manure injected into the soil after harvesting in the fall.

No rodents-the clean facility along with a pest control program keeps rodents in check.

Very few flies-the clean facility, constant air flow in the barn and a fly control program limit the flies.

My parents built a new 60 cow tie-stall barn in 1973 when I was 3 years old. I've been told that our county had 175 dairy farms at the time. 7 milk processors competed for our milk. Today, none of those farms have dairy cows. The entire dairy infrastructure (processing, veterinarians, nutritionists, consultants, ag lenders-dairy, equipment dealers/repairs, etc.) is gone. I have watched a similar transition in the far north of Minnesota, all of North Dakota and Black Hill area in South Dakota. Very few dairy farms remain in these areas, and the infrastructure is far away or gone. Milk processing left drove most of this.

I have spent my entire life in the dairy industry. I have witnessed the transition from tie-stall barns to larger free-stall barns in the Midwest. Most of the traditional cow regions in the Midwest and Northeast

are now a blend of both. This trend will continue as small tie-stall barns get replaced with larger free-stall barns. The dairy infrastructure here is good.

The dairy industry has had regions in Idaho, Texas, Indiana, South Dakota and Kansas where the dairy infrastructure took off or is taking off. The harsh reality is that these new pockets of dairy rarely include the addition of small dairy farms. What we have currently in the United States dairy industry (and Global) are traditional cow regions, areas that are losing and areas that are gaining.

Riverview plays a huge role in maintaining a healthy dairy infrastructure in Minnesota. The dairy industry in Minnesota is stronger because of Riverview. Making it more difficult, or impossible, for Riverview, or any other dairy operation, to obtain permits to operate in Minnesota will result in the movement of dairy infrastructure and the dairy industry somewhere else. Making it less difficult for Riverview, or any other dairy operation, to obtain permits to operate in Minnesota will result in the movement of dairy infrastructure and the dairy industry into Minnesota.

The dairy industry is no different than any other industry as it relates to the environment. We have become better stewards of the land through knowledge and regulations. You can still find people or businesses that have complete disregard for the environment. The next level for me is those that are willing to follow the rules. Most farmers that I know are above these levels as they do their best to be efficient and follow practices that are positive for the environment. The next level for me is doing things to improve the environment that add cost to their business. The ultimate level is where you can find Riverview. The environmental impact is considered in every decision that they make, often resulting in additional costs and reduced efficiency.

I would like to see the dairy industry grow in my home state of Minnesota. I live a mile from a Riverview site. I breathe the air and drink the water from my well. Yes, I appreciate the protections in place for our environment. The rules need to be in place and verified for the first two levels mentioned in the previous paragraph. We don't need additional regulations for those like Riverview at the ultimate level. We do need to explore ways to make it easier (or an option) to grow for those "good farmers" at level 3 or 4 above. I don't see that right now in Minnesota. I do see our neighboring states provide this opportunity.

Riverview plays a huge role in supporting other agriculture infrastructure and other agricultural industries in Minnesota as well. The farmers next to the dairy benefit in many ways: manure as fertilizer for improved soil health, additional cropping options with corn silage and alfalfa haylage, and use of machinery and labor during forage harvest and manure application. This reaches further with the use of by-products from corn and soybean processing as food sources for dairy cows.

The additional cows proposed as part of this expansion are not introducing anything new or untested. Riverview has extensive experience managing operations of this size safely and responsibly. The current Environmental Assessment Worksheet (EAW) process is doing exactly what it is intended to do—evaluating potential impacts and ensuring environmental protections are in place. Based on the proven track record of Riverview and the safeguards provided through the EAW process; this expansion does not warrant a full Environmental Impact Statement (EIS). The existing environmental review process already provides adequate protection for Minnesota's natural resources while allowing responsible agricultural operations to move forward. Riverview Farms has shown that agricultural growth and strong environmental stewardship can go hand in hand. I respectfully encourage the MPCA to consider their outstanding environmental record and support the proposed West River Dairy expansion. Thank you for your time and consideration, and for the important work you do to protect Minnesota's environment.

A concerned Minnesota resident **Letter 1298**

Minnesota's First and Largest Proposed Livestock Facility

Demand for Environmental Impact Study

P A R T O N E — T H E T H E M E

Minnesota Has Never Seen Anything Like This. That Is Precisely the Point.

Minnesota dairy farming is woven into the identity of this state. On a typical Minnesota dairy in 2025, a family averages fewer than the average 280 cows. They know their herd. They know their neighbors. They know the watershed. They have made generations of careful decisions about how much to take from the land and how much to give back.

What Riverview, LLP is proposing is not a larger version of that farm. It is not a bigger barn or an extra milking parlor. What Riverview is proposing is a facility that would house 18,855 dairy cattle, totaling 26,397 animal units, in a single location. That is nearly double the size of the next largest livestock operation in the entire state of Minnesota. It is more than 60 times the size of the average Minnesota dairy. It would be, from the day it opens, the largest livestock facility Minnesota has ever seen.

> *This is not a farm expansion. This is the industrialization of Minnesota agriculture at a scale this state has never confronted and is entirely unprepared to regulate without a comprehensive Environmental Impact Study.*

And here is what we know with certainty, backed by decades of peer-reviewed science: at this scale, in this concentration, the environmental consequences of a dairy operation are categorically different from what an average family operation of the average 280 cows produces. The water impacts are different. The air quality impacts are different. The public health risks are different. The threat to neighboring farms and rural communities is different.

Minnesota's families, farmers, rural residents, schoolchildren, and people who draw their water from the aquifers and streams of the affected watershed deserve to know what those differences are before the facility is built. Not after. Not once have the wells been drawn down, and the manure lagoons have been constructed, and the 26,000 animal units are in place, and the consequences have become irreversible.

The demand before you today is the most modest, reasonable, legally grounded request that can be made in the face of a proposal this large: conduct a full Environmental Impact Study before a single shovel breaks ground.

P A R T T W O — T H E S T O R Y O F T H E E V I D E N C E

What the Science Tells Us — And Why Scale Changes Everything

The evidence in this matter is not drawn from a single study, a fringe journal, or an advocacy organization. It represents the convergent findings of dozens of independent, peer-reviewed scientific studies conducted across the United States, Europe, Asia, New Zealand, and Latin America. Wherever researchers have examined what happens when dairy operations reach mega-scale, they have found the same patterns. What follows is the story that evidence tells, about water, health, the land, and the communities that depend on all three.

Chapter One: Scale Is Not Just a Number, It Is a Threshold

To understand why 26,397 animal units in one place is qualitatively different from the average 280 cows on a family farm, consider the arithmetic of waste. A single dairy cow produces approximately 120 pounds of manure per day. Riverview's proposed facility, with 18,855 dairy cattle, would generate on

the order of over one million pounds of manure every single day, waste that must be stored in lagoons, applied to fields, and managed in a watershed that has never absorbed anything remotely close to that volume.

The science of nutrient loading is precise on this point. As dairy intensity expands in a watershed, phosphorus loads, the primary driver of toxic algal blooms, have been shown to increase by as much as 91%.[Waller et al., 2021] Studies measuring stream water quality downstream of dairy CAFOs found dissolved nitrogen concentrations eight times higher downstream than upstream during manure application periods. [Sousan et al., 2021] Manure lagoons, which a facility of this size would require at a massive scale, have been documented contributing between 6% and 12.6% of a region's total groundwater nitrogen load while occupying just 0.8% of the land surface. [Baram et al., 2014] Now multiply those impacts by the difference between an average 280- cow farm and an 18,855-cow facility.

Chapter Two: The Groundwater Threat Is Documented and Severe

Minnesota's rural communities depend on groundwater. The families, farms, and small towns near the proposed facility draw their drinking water from wells. Those wells tap the same aquifer system that a facility of this scale would draw upon and potentially contaminate.

The science is unambiguous about what mega dairies do to groundwater. Nitrate concentrations beneath dairy operations have been measured at an average of approximately 64 mg/L, nearly three times the EPA's maximum contaminant level of 10 mg/L for drinking water. [Harter et al., 2002] In California's Central Valley, a region with significant experience with large dairy operations, dairies are identified as major contributors to domestic well contamination. [van der Schans et al., 2009]

And contamination is not limited to nitrates. Groundwater near dairy operations has been found to contain sulfonamide antibiotics [Batt et al., 2006], steroid hormones transported from waste lagoons to depths exceeding 30 meters [Arnon et al., 2008], antibiotic-resistant bacteria and genes [Meyer et al., 2024], and PFAS, the "forever chemicals", documented in groundwater near large livestock operations. [Wang et al., 2025] These are not isolated findings. They are a consistent pattern that repeats wherever mega dairy operations and aquifers intersect, and Minnesota's aquifers would be no exception.

Critically, the research documents that groundwater contamination from intensive livestock farming can have legacy effects with lag times exceeding 20 years.[Kim et al., 2021] The full consequences of today's permitting decisions may not fully appear in Minnesota's water supply for two decades. By the time the harm is visible, the facility will be entrenched, the contamination will be established, and the opportunity to prevent it will be gone.

Chapter Three: The Surface Water and Watershed Damage

Minnesota's lakes, rivers, and streams are not just ecological assets; they are cultural and economic ones. The state's identity, its tourism economy, its fishing heritage, and its agricultural water supply all depend on the quality of surface water in its watersheds.

The nutrient loads from a facility of 26,397 animal units, the manure, the runoff from feed storage, and the effluent from milking operations would enter Minnesota's watershed through multiple pathways. The science documents what happens when those loads arrive. Phosphorus and nitrogen fuel eutrophication: the systematic suffocation of aquatic ecosystems by algae that strip oxygen from the water, killing fish, generating toxic blooms, fouling drinking water sources, and degrading the ecological function of lakes and rivers for generations.

Pathogens follow the same runoff pathways. E. coli O157:H7, Cryptosporidium, Giardia, and fecal coliforms enter waterways through manure runoff and field applications [Mohammed et al., 2023;

Mausbach et al., 2025], creating direct risks for downstream communities. Pharmaceutical residues, such as estrogens, NSAIDs, and antibiotic compounds, are routinely detected in surface water runoff from manure-amended fields at concentrations sufficient to cause endocrine disruption in aquatic organisms. [Havens et al., 2020; Hill et al., 2021] Minnesota's fishing culture and recreational water economy have no margin for this.

Chapter Four: The Human Health Evidence Is Not Speculative

The people who would live within one to two miles of this proposed facility farm families, rural residents, schoolchildren, elderly neighbors face documented health risks that accumulate with proximity and time.

Air quality monitoring at homes within a quarter mile of industrial dairy operations found ammonia concentrations eight times higher and cow allergen concentrations sixty times higher than at homes three miles away. [Williams et al., 2011] Children with asthma demonstrate measurable declines in lung function on the day after elevated CAFO emissions events. [Loftus et al., 2020] Adults with COPD experience acute lung function drops exceeding 20% following ammonia spikes from nearby operations. [van Kersen et al., 2020] Residents within 1.5 miles show significantly higher rates of asthma, allergies, and persistent lung function decline. [Schultz et al., 2019]

In regions with high livestock density, physicians document higher rates of pneumonia and other infectious diseases among nearby residents. [Hooiveld et al., 2016] A 2026 study across three U.S. states found higher cancer incidence in counties with greater CAFO density. [Son et al., 2026] And the antibiotic resistance threat driven by the documented presence of up to 21 classes of veterinary antibiotics in dairy-associated watersheds [Lee et al., 2020] represents one of the most serious emerging public health threats of our time. A facility producing at the scale proposed here would be a significant driver of that threat in Minnesota's environment.

Chapter Five: What Riverview Has Already Done Elsewhere

We do not need to speculate about how Riverview, LLP behaves when its operations reach a scale that strains the surrounding environment. We have a documented case study. In Arizona.

On December 31, 2025, just months ago, Riverview, LLP entered into a formal Settlement and Release Agreement with Arizona Attorney General Kristin Mayes. The Attorney General had invoked her authority under Arizona's public nuisance statute based on expressed concerns that Riverview's existing groundwater pumping in the Sulphur Springs Valley of Cochise County constituted a public nuisance. The settlement's own recitals acknowledge that groundwater levels in the Valley "continue to decline" and that Valley residents' domestic wells "no longer reach the aquifer." Arizona's own water resources agency found conditions serious enough to designate the affected basins as Active Management Areas, a designation reserved for regions facing critical groundwater depletion.

The result: before Riverview could proceed, the state of Arizona extracted $11 million in remediation commitments, $5.5 million to an independent charitable fund for residents and schools affected by groundwater decline, and $5.5 million administered directly for those closest to Riverview's irrigation wells. Five Valley schools were specifically identified as needing emergency water access assistance. Riverview also committed to removing 2,000 acres of irrigated farmland from production over 15 years.

> *Riverview paid $11 million in Arizona to address what its existing operations already did to that state's groundwater — before adding a single animal. Minnesota is now being asked to permit a facility nearly double the size of anything that state has ever seen, with no comparable assessment of what it will do here.*

To be precise: Riverview denies liability in the Arizona matter. The settlement is not a legal admission. But the Attorney General of the State of Arizona with the full resources of her office found the evidence of groundwater harm serious enough to pursue formal legal action under the state's public nuisance statute That is not a fringe claim. That is the considered legal judgment of a state's top law enforcement officer about Riverview's existing operations. And now Riverview is asking Minnesota to permit a facility that, by its own application, would be the largest livestock operation this state has ever seen.

P A R T T H R E E — T H E S I G N I F I C A N C E

Why This Matters: Minnesota Does Not Get a Second Chance

Some harms can be remediated. You can clean a spill, relocate a facility, adjust a management practice. Aquifer depletion, watershed contamination, and the destruction of rural communities are not those kinds of harms.

When an aquifer is drawn down beyond recovery within a human lifetime, the water does not return. Wells that took families years to install become useless. The agricultural economy of a region, built across generations, can be permanently compromised. Nitrate contamination once established in a groundwater system can persist for decades, affecting the neurological development of infants, the health of elderly residents, and the viability of neighboring farm operations. Studies document legacy contamination effects with lag times exceeding 20 years. [Kim et al., 2021] By the time the full damage is visible, the facility will be entrenched, the permits will be issued, and the opportunity to prevent harm will be a memory.

The economic consequences for Minnesota's rural communities would be profound. A 26,397- animal-unit facility doesn't just compete with family dairies for water it competes with them for land, for local labor, for community identity. The research is clear that mega dairy operations tend to reduce total employment per unit of output relative to smaller farms, concentrate land ownership, weaken local supply chains, and generate community tension that undermines the social fabric rural areas depend upon. The average 280-cow farm that has sustained Minnesota's dairy heritage for generations cannot compete on the same terms as a facility that is 60 times its size and externalizes its environmental costs onto the surrounding community.

And the threat is not merely to this one watershed, or this one community, or this one permitting decision. This is the first proposed livestock facility of its kind in Minnesota. If it is permitted without a rigorous Environmental Impact Study, if the precedent is established that a 26,000-animal-unit facility can be sited and built without a comprehensive, independent, public assessment of its consequences, then every future applicant for a comparable facility will point to this decision as the standard. The precedent set here will shape Minnesota's agricultural and environmental landscape for a generation.

> *An Environmental Impact Study is not a weapon against agriculture. It is the mechanism a responsible state uses to ensure that its most consequential decisions are made with eyes open — not discovered in hindsight.*

P A R T F O U R — T H E C R E D I B I L I T Y Q U E S T I O N

If the Science Is Wrong, Why Won't They Let Us Check?

Riverview and its advocates will argue that the science is overstated. That their operation is well-managed. That they use the best available technology. That an Environmental Impact Study is unnecessary, burdensome, and punitive. That this is just opposition to progress dressed up as environmental concern.

Consider that argument carefully because embedded within it is a question they have not answered and do not want you to ask:

> *If this facility poses no significant environmental risk to Minnesota's water, air,land, and communities a rigorous, independent Environmental Impact Study willprove it. So why fight one?*

The Environmental Impact Study process is not a presumption of guilt. It is a neutral scientific and regulatory assessment. It requires independent experts, not the company's consultants, not the company's attorneys, not the company's hired engineers, to evaluate the projected impacts on groundwater, surface water, air quality, public health, and community welfare. If Riverview's facility truly poses no significant harm, the Environmental Impact Study will say so. The permit will be granted with public confidence and legal protection.

The only reason to oppose an Environmental Impact Study is if you fear what it will find.

The Efficiency Argument Is Incomplete

Riverview will point to its conservation practices, and some of them are genuinely meaningful. The 2025 Arizona settlement documents center-pivot systems, low-energy precision application, and variable-frequency drive pumps. These are real technologies with real water efficiency benefits.

But there is a critical distinction that efficiency arguments consistently obscure: per-unit efficiency gains do not offset the aggregate impact of scale.[Rotz et al., 2024; Han et al., 2024] A facility that uses 15% less water per cow but concentrates 18,855 cows in a single location draws dramatically more water from the aquifer system than any collection of smaller farms that those cows would otherwise replace. The manure volume is not reduced by efficiency technology, it is concentrated. The ammonia emissions are not eliminated; they are concentrated. The pathogen load in runoff is not neutralized it is concentrated. Concentration is the variable that an Environmental Impact Study must evaluate. It is also the variable Riverview does not want evaluated.

The Regulatory Gap Problem

The research literature on CAFO oversight is striking in its consistency across states and decades. Federal databases on the number and location of CAFOs are incomplete.[Chugg et al., 2021] Permitting rates are low even for large operations. Inspection rates have declined sharply since 2011. Most compliance monitoring relies on operator self-reporting the very operator with a financial interest in favorable findings. [Glibert, 2020; Moran, 2022] State preemption laws in many jurisdictions block local governments from imposing stricter standards than the state minimum, creating what researchers call "regulatory vacuums" that leave communities with no meaningful recourse. [Moran, 2022]

Minnesota has never permitted a facility of this scale. It has no track record with a livestock operation of 26,397 animal units, no established monitoring infrastructure calibrated to impacts of this magnitude, no regulatory precedent for enforcing against a facility that dwarfs anything that has come before. The Environmental Impact Study is not just about understanding the facility's environmental impacts it is about determining whether Minnesota's regulatory framework is even equipped to manage them, and what additional protections would be required before a permit could be responsibly granted.

The Arizona Track Record Cannot Be Dismissed

Riverview will argue that Arizona is a different state, a different climate, a different hydrogeology. And that is true as far as it goes. Arizona's desert aquifers face different pressures than Minnesota's.

But the Arizona settlement does not prove a specific quantity of harm in Minnesota. What it proves is something more fundamental: that at the scale Riverview operates, the company's activities can deplete

groundwater to the point where a state Attorney General pursues formal public nuisance litigation, where domestic wells go dry, where schools require emergency water assistance, and where $11 million in remediation is required before anyone agrees to stop investigating.

That is a pattern of conduct. It occurred with Riverview's existing operations not with a proposed expansion. Minnesota is now being asked to permit a facility the applicant itself describes as nearly double the size of the next largest livestock operation in the state. The Arizona experience is not a disqualifier. It is, precisely, the reason an Environmental Impact Study is necessary.

The Environmental Justice Dimension

The communities that bear the greatest burden from mega dairy operations are consistently documented to be rural, lower-income, and in many cases, communities of color or Indigenous communities with the least political capacity to demand accountability. [Driscoll & Theis, 2020; Hudlet-Vazquez, 2025; Tulbure et al., 2024] Rural Minnesota families are not corporations. They cannot hire hydrogeologists, retain legal teams, or absorb the cost of a failed well while litigation proceeds. They depend on the regulatory process on the Environmental Impact Study to ensure their government is looking out for them before the damage is done, not after.

When we ask why Riverview opposes a full Environmental Impact Study, part of the honest answer is this: the people who bear the cost of getting this wrong are not the people deciding to build. That asymmetry between who profits and who pays is precisely the asymmetry that environmental review processes were designed to address.

P A R T F I V E — T H E C A L L T O A C T I O N

The Demand Is Reasonable. The Stakes Are Not.

We are not here to end dairy farming in Minnesota. Agriculture is the backbone of this state's economy and identity. Minnesota's dairy farmers, the real ones, the average 280-cow operations that have sustained rural communities for generations, deserve a future. And that future is not served by permitting a single corporate facility that is 60 times their size to externalize its environmental costs onto the land, water, and communities those farmers share.

What we are asking for is not extraordinary. It is not punitive. It is not a backdoor attempt to block development. We are asking for what the law provides, what the science demands, and what any reasonable observer looking at a proposed 26,397-animal-unit facility that would be the first and largest of its kind in Minnesota would recognize as the minimum due diligence owed to the people of this state.

Is it so much to ask for a full Environmental Impact Study conducted independently, reviewed publicly, and completed before a single permit is issued and a single shovel breaks ground?

Minnesota's environmental and community interests.

The Legal and Moral Standard

Environmental review processes exist because Minnesota and the federal government made a foundational decision: when an action is large enough to cause significant environmental consequences, the public has the right to know what those consequences will be before the decision is made, not after.

A facility of 26,397 animal units, the first of its kind in Minnesota, nearly double the next largest operation in the state, 60 times the average dairy, proposed by a company that is already paying $11 million in remediation for groundwater impacts in another state, is precisely the kind of action this standard was designed to address.

The burden in this proceeding does not fall on Minnesota's farmers and families to prove that this facility will cause harm. The burden falls on the applicant to demonstrate, through a rigorous and independent process, that it will not.

> *Minnesota has never faced a livestock facility of this scale. It will never get a second chance to make this decision correctly. Require the Environmental Impact Study.*

We are asking you to require what the law contemplates, what the science demands, and what Minnesota's rural communities deserve: a full Environmental Impact Study before the largest livestock facility in this state's history is permitted to become a permanent feature of Minnesota's landscape.

The family farmers whose livelihoods border this proposed site, the parents whose children will breathe the air within two miles of 26,000 animal units, the neighbors whose wells draw from the same aquifer those Minnesotans cannot afford for you to get this wrong.

Require the Environmental Impact Study. Demand the full picture. Do not let the largest environmental decision Minnesota's agricultural communities have ever faced be made in the absence of the information they are owed.

SCIENTIFIC CITATIONS REFERENCED IN THIS ARGUMENT

All citations correspond to peer-reviewed scientific literature. Full bibliographic details are available in the accompanying Environmental and Health Impact Summary.

Arnon et al., 2008: Transport of testosterone and estrogen from dairy-farm waste lagoons to groundwater. Environmental Science and Technology. https://doi.org/10.1021/es800784m

Baram et al., 2014: Assessing the impact of dairy waste lagoons on groundwater quality using a spatial analysis of vadose zone and groundwater information. Journal of Environmental Management. https://doi.org/10.1016/j.jenvman.2013.11.008

Batt et al., 2006: Occurrence of sulfonamide antimicrobials in private water wells in Washington County, Idaho, USA. Chemosphere. https://doi.org/10.1016/j.chemosphere.2006.01.029

Chugg et al., 2021: Enhancing environmental enforcement with near real-time monitoring: Likelihood-based detection of structural expansion of intensive livestock farms. International Journal of Applied Earth Observation. https://doi.org/10.1016/j.jag.2021.102463

Driscoll & Theis, 2020: "Not in our water!": Environmental resistance in rural Wisconsin. Journal of Rural Studies. https://doi.org/10.1016/j.jrurstud.2020.08.018

Glibert, 2020: From hogs to HABs: impacts of industrial farming in the US on nitrogen and phosphorus and greenhouse gas pollution. Biogeochemistry. https://doi.org/10.1007/s10533-020-00691-6

Han et al., 2024: Industrialization Mitigates Greenhouse Gas Intensity in China's Dairy Sector yet May Prove Insufficient to Offset Emissions from Future Production Expansion. Environmental Science and Technology. https://doi.org/10.1021/acs.est.4c03768

Harter et al., 2002: Shallow groundwater quality on dairy farms with irrigated forage crops. Journal of Contaminant Hydrology. https://doi.org/10.1016/S0169-7722(01)00189-9

Havens et al., 2020: Occurrence of estrogens, androgens and progestogens and estrogenic activity in surface water runoff from beef and dairy manure amended crop fields. Science of the Total Environment. https://doi.org/10.1016/j.scitotenv.2019.136247

Heederik et al., 2007: Health effects of airborne exposures from concentrated animal feeding operations. Environmental Health Perspectives. https://doi.org/10.1289/ehp.8835

Hill et al., 2021: Dairy manure as a potential source of crop nutrients and environmental contaminants. Journal of Environmental Sciences (China). https://doi.org/10.1016/j.jes.2020.07.016

Hooiveld et al., 2016: Doctor-diagnosed health problems in a region with a high density of concentrated animal feeding operations. Environmental Health: A Global Access Science Source. https://doi.org/10.1186/s12940-016-0123-2

Hudlet-Vazquez, 2025: Interconnected forms of violence of CAFOs and indigenous peoples' rights in Yucatan. Elgar Concise Encyclopedia of Animal Law. https://doi.org/10.4337/9781803923673.00064

Kim et al., 2021: Shift of nitrate sources in groundwater due to intensive livestock farming on Jeju Island, South Korea. Water Research. https://doi.org/10.1016/j.watres.2021.116814

Lee et al., 2020: Characteristics of veterinary antibiotics in intensive livestock farming watersheds. Science of the Total Environment. https://doi.org/10.1016/j.scitotenv.2020.142375

Loftus et al., 2020: Estimated time-varying exposures to air emissions from animal feeding operations and childhood asthma. International Journal of Hygiene and Environmental Health. https://doi.org/10.1016/j.ijheh.2019.09.003

Mausbach et al., 2025: Molecular Tracking of Fecal Indicator Bacteria and Protozoan Parasites in Mixed-Use Watersheds. Water, Air, and Soil Pollution. https://doi.org/10.1007/s11270-025-08342-y

Meyer et al., 2024: Do animal husbandry operations contaminate groundwater sources with antimicrobial resistance: systematic review. Environmental Science and Pollution Research. https://doi.org/10.1007/s11356-024-31899-w

Mohammed et al., 2023: The potential risk associated with foodborne pathogens in a watershed: Escherichia coli O157:H7 in dairy cattle. Journal of Environmental Quality. https://doi.org/10.1002/jeq2.20494

Moran, 2022: Pretextual Preemption: The Modern Weaponization of Preemption in the Regulation of Concentrated Animal Farming Operations. University of Pennsylvania Law Review.

Rotz et al., 2024: Fifty years of environmental progress for United States dairy farms. Journal of Dairy Science. https://doi.org/10.3168/jds.2023-24185

Schultz et al., 2019: Residential proximity to concentrated animal feeding operations and allergic and respiratory disease. Environment International. https://doi.org/10.1016/j.envint.2019.104911

Son et al., 2026: Density of animal feeding operations, including concentrated animal feeding operations (CAFOs), and cancer incidence: A county-level ecological study across three U.S. states. Environmental Research. https://doi.org/10.1016/j.envres.2026.124298

Sousan et al., 2021: High-frequency assessment of air and water quality at a concentration animal feeding operation during wastewater application to spray fields. Environmental Pollution. https://doi.org/10.1016/j.envpol.2021.117801

Tulbure et al., 2024: Earth Observation Data to Support Environmental Justice: Linking Non-Permitted Poultry Operations to Social Vulnerability Indices. GeoHealth. https://doi.org/10.1029/2024GH001179

van der Schans et al., 2009: Characterizing sources of nitrate leaching from an irrigated dairy farm in Merced County, California. Journal of Contaminant Hydrology. https://doi.org/10.1016/j.jconhyd.2009.06.002

van Kersen et al., 2020: Acute respiratory effects of livestock-related air pollution in a panel of COPD patients. Environment International. https://doi.org/10.1016/j.envint.2019.105426

Waller et al., 2021: Shifts in precipitation and agricultural intensity increase phosphorus concentrations and loads in an agricultural watershed. Journal of Environmental Management. https://doi.org/10.1016/j.jenvman.2021.112019

Wang et al., 2025: Study on groundwater PFAS pollution near large livestock farms in Guangdong-Hong Kong-Macao Greater Bay Area. Environmental Chemistry and Ecotoxicology. https://doi.org/10.1016/j.enceco.2025.10.022

Williams et al., 2011: Airborne cow allergen, ammonia and particulate matter at homes vary with distance to industrial scale dairy operations. Environmental Health: A Global Access Science Source. https://doi.org/10.1186/1476-069X-10-72

Settlement reference: Settlement and Release Agreement, State of Arizona ex rel. Attorney General Kristin Mayes v. Riverview, LLP, effective December 31, 2025. Riverview expressly denies liability. The Arizona settlement is not an admission of fault or unlawful conduct and pertains to Riverview's existing Arizona operations, not the proposed Minnesota facility.

Logan Visser **Letter 1299**

My name is Logan Visser and I am an employee of Visser Trenching, a construction company serving agricultural operations in Minnesota like Riverview. I am writing in support of their proposed West River Dairy expansion in Stevens County.

Through our work in the agricultural sector, we depend on a strong and stable livestock industry. Operations like Riverview's create consistent economic activity that supports local jobs, drives investment, and allows businesses like ours to grow and reinvest in our communities.

The proposed expansion represents a meaningful economic benefit to the region. It will generate demand for local vendors, support both construction and long-term employment, and contribute to the vitality of rural communities that rely on agriculture.

From our direct experience, Riverview is a professional and reliable partner that contributes positively to the communities where it operates. Their presence strengthens the local economy and supports a broad network of agricultural and service-related businesses.

Projects like this are essential to maintaining a competitive and sustainable rural economy in Minnesota. Continued investment in agriculture ensures that local businesses can continue to provide jobs, services, and economic stability close to home.

No EIS is needed as the state environmental review process is rigorous and very sufficient. I respectfully encourage your support and approval of this important project.

Overall I believe that without projects and developments in the agricultural industry such as this one, the local economy is at a deficit.

Sincerely,
Logan Visser

Max Lundgren **Letter 1300**

Thorough review is absolutely essential before any project! We have a gold standard, stick to it! No shortcuts!

Glen Visser **Letter 1301**

My name is Glen Visser and I am the owner of Visser Trenching a Excavation and service company serving agricultural operations in Minnesota like Riverview. I am writing in support of their proposed West River Dairy expansion in Stevens County.

Through our work in the agricultural sector, we depend on a strong and stable livestock industry. Operations like Riverview's create consistent economic activity that supports local jobs, drives investment, and allows businesses like ours to grow and reinvest in our communities.

The proposed expansion represents a meaningful economic benefit to the region. It will generate demand for local vendors, support both construction and long-term employment, and contribute to the vitality of rural communities that rely on agriculture.

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Projects like this are essential to maintaining a competitive and sustainable rural economy in Minnesota. Continued investment in agriculture ensures that local businesses can continue to provide jobs, services, and economic stability close to home.

No EIS is needed as the state environmental review process is rigorous and very sufficient. I respectfully encourage your support and approval of this important project.

Sincerely,
Glen Visser

Sandra Fernow **Letter 1302**

My name is Sandra Fernow. I am a current resident of Morris, and have been for the past 10 years. I have two kids, age 8 and 5, who were born at the local hospital, and now our family has come to call this place home. I may not be a farmer, but I do have a career in housekeeping, so I care about ensuring the community has a clean, safe environment to thrive in. I waited until after I had attended the MPCA public comment meeting at Old No One Southside on April 28th to submit my comment. I have to inform you that I was one of the last to enter the room before the doors were closed for the extent of the public comment meeting, and I had arrived about 15 minutes early. I was guided to standing-room-only, from where I had a vantage point of the main entry door. There were waves upon waves of concerned citizens who attempted to come to the meeting to be better informed, and/or to make their concerns, questions, or whatever else be heard, and their entry to the venue was denied due to the Southside being at capacity. I watched some friends, some community members, and more I didn’t recognize, have their whole body demeanor sink as they heard the news that they were not allowed to enter the “public” comment session. I won’t forget their faces. This experience left me frustrated, and I believe it revoked some of the voice of the community and other farmers, and effectively silenced their concerns or potential opposition to the proposed expansion. Even now, amongst the public comment period board, there are many submissions stating “No EIS needed, I support West River expansion” type

of a generic comment; it makes it feel like that same moment, of filling the space in a similar manner so it's harder to see the worries people may have surrounding this.

An old college acquaintance of mine first messaged me in September of 2025, directing me to a video on some of the less-than-ideal impacts that Riverview had done to the community in Arizona; this video was put together by Perfect Union, and posted April 25, 2025 on their Instagram. The first example in the video, an Arizona resident, had their well run dry due to Riverview's over-usage of groundwater there, so the resident had no running water in their home for 6 months. This person had hoped to pass their house down, a stability for generations, but feared they could no longer do so due to the manner in which their land was impacted. I saw an article from January of this year, that Riverview reached an agreement to reduce groundwater usage and pay $11 million to affected residents in AZ over 20 years; but is money enough to repair damage to our natural world? Does money paid after-the-fact undo damages which dictate how we leave the land for our children? At what point are we crossing the line here, away from being farmers and into something more reminiscent of resource miners, extracting the land and exchanging it for the all-mighty dollar? Are there things which could be done unto our local land out here, thanks to decisions made by investors, which could be irreversible?

These sort of questions is why I think we need an Environmental Impact Statement.

I'm concerned about Water Quality, as a recent story from Minnesota Public Radio described in their headline, "Nitrate is quietly polluting rural drinking wells. How researchers are working to help." I may live in town, but have daydreamed about buying property somewhere out of town for more room to garden and enjoy nature's bounty, so I'm concerned about rural groundwater quality. Groundwater pollution is especially difficult to filter, needing expensive equipment a lot of people probably can't afford. I worry that surface water could be polluted as well, impacting local hunters and outdoors-people who want to enjoy what western MN has to offer. The manure runoff from factory farms can have a big impact on putting nitrates in water. I think the community should be able to achieve a sense of security, in having detailed and clear answers to the many questions they may have. CAFOs (or Concentrated Animal Feeding Operations) are notorious for contaminating water with nitrates, and I have real concern that a massive operation such as this could potentially pollute our area in a way that impacts our precious resources for years, and generations, to come.

Ground water and surface water contamination is a greater risk with factory farm style projects of this size, and I'm concerned about our water resources being negatively impacted with such a massive expansion. The types of pollutants associated with potential spills concern me, because of their environmental impact to wildlife in the form of algae blooms, and the increased risk of cancer rates associated with nitrates. I know fisherman friends who have shared Snapchat videos to their story while out at the lake and along the Pomme de Terre watershed near here, and possibly north of town, which depicted algae of an unnatural color along the shore line. Another concern I have for stability of the land is for future generations out here, because Blue Baby Syndrome is caused by drinking from nitrate-contaminated water wells. I worry, also, as a "townie" here, about how well our own municipal water facility is capable of filtering out harmful pollutants. We do have a reverse osmosis system in our home, but the option we chose has monthly payments, and not everyone can afford luxuries like water filtration systems within their home. Many in our town are also renters, who may not find it feasible to have their own RO system, or are limited to the water fill up station at places like Willie's grocery store, which is dependent on the local water supply as well. I'm ultimately concerned about the future of this community, if we are allowing a major expansion at this scale, and the implications it could have for people down-stream from this operation, or for the people who are connected to the aquafer below this massive expansion, or in the areas which the "fertilizer" is applied. Even in application of the manure to

fields, which in a way is just a bunch of micro-spills, I am concerned about potential for water to run off of the fields, and contaminate area waterways of both surface and groundwater.

I have also heard from one of the smaller time farmers, that Riverview had a manure spill near Pennock, MN, and this was supposedly not reported for a full week. Supposedly there was no environmental contamination indicated from that 2025 spill, but I remain concerned that there could be things unreported, or issues to be had in not having a baseline to compare data to if a spill occurs, or things could be cleaned up before a spill was fully reported, so the scale of a spill could potentially be underreported. This contamination would be difficult to undo or remedy, once it occurs. As I said, I have already heard from friends who fish in the area along the Pomme de Terre water shed, that there were noxious algae blooms in area waterways in the last several years. I am concerned that a project of this size may go up, before we even have baselines of data to compare anything to, to monitor the effects of the expansion over time. I believe we need more accurate data than is currently the standard, in order to protect the environment from the people who are "farming" on it and straining the land for what they view it is worth.

To couple the risk of the pollution of the waterways, with the increase risk of abnormally dry times and increased water demand on local supply that this project would cause, it makes this project expansion seem like it could potentially cause more harm than good. I know that in the last several years, there have been summers filled with Red Flag Warnings, abnormally dry to moderately dry periods of drought, and there has been some cause for concern in the arid climate of the Great Plains steadily creeping eastward, potentially now swallowing Morris up with it. This type of climate shift may be hard to come to terms with, but I think it gives cause for concern that a proposed expansion of this size could get its fingers deep in the watershed, thus jeopardizing the safety and security of the residents and others who call west central MN home. There are more who live out here than the cows "churning" a profit for their investors, but this expansion would ensure there are more cows than people here.

The effect this expansion could have on small family farms is potentially irreversible. I just today saw a news article from MPR news titled, "Agriculture is changing. To protect farmers from stress, mental health support has to change, too," which was written by Tadeo Ruiz Sandoval and Molly Castle Work. This article described the immense stress that small farms have in the face of the current turbulent economy. With the proposed expansion of Riverview's operations in Morris, I fear for the small-time farmers who may "go under" because the influence of flooding the market with this many cows may be "the straw that broke the camel's back" and negatively impact those who gave their testimony at the MPCA public comment meeting at Old No One Southside on April 28th. Riverview wanting to expand from 7,885 to 18,885 cows has small family farms worried about what the future holds for their farm.

With Riverview having so much capital, I wonder also how they have been influencing the housing market in town in Morris. I have seen recently a home was for sale, then swooped quickly off the market, where now a truck with "Riverview" on the side is parked. This could be a good thing on the surface, or could be a more complicated thing at the heart of it. If Riverview is able to purchase properties, they could then rent them to employees, setting terms for rent and making even more profit as an entity. By purchasing homes right when they enter the market, I fear that other people and families in this town may struggle to then become homeowners themselves, due to not being able to put as big of a downpayment on a potential home purchase in comparison to those associated with Riverview. Morris has an abundance of renters, and I wonder how much their ease of access to evolving to the level of homeownership is impacted through this potential pattern in rapid property buy-ups.

And while Riverview may not own all the land which they interact with, I fear they still have the "air of a monopoly" due to the amount of influence they have upon farmland which they contract with; they may

not own all the acres, but in a way they do, by having the ultimate say on what cover crop is planted and what is used to fertilize via their cow-barn liquid excrement. I heard that this liquid manure is tested once a year? Well, I don't think testing this liquid manure once a year is enough, because I imagine there could be some variations over the course of the year which could impact testing results.

One of my acquaintances, her husband works for Riverview tending the cows. They are from Mexico. She said they treat the cows better than their workers at times. They are very strict with timing of operations. My acquaintance is fearful that if the company might have something go wrong, that potentially people will blame the low-level workers, before they find any fault in the owners and investors of the company.

Situations like the overly-packed MPCA meeting are problematic; there were community members who were born and raised in Morris area, who were unable to attend the meeting due to capacity constraints. From comments I have read on local Facebook posts online, people became very frustrated that Hispanic/people of color (who potentially may not be proficient in English or may not have attended the meeting to make a public comment) were there "in their stead", and thus occupying seats where other genuine concerns could have been sitting. Moments like this impact the resiliency of our community, because I believe there could be an increase in racial prejudice and racial stereotyping or profiling, due to someone reporting that they had attempted to speak with the Hispanic members of the audience, and were apparently greeted with "No English". This issue has me feeling frustrated, because my Mexican acquaintance whose husband works for Riverview, said she had wanted to attend the meeting to maybe see more people in the community, and to learn more about the scope of the project and impact it could have; she wants to maybe have a baby of her own, and needs to know if she should invest in a water filter for her home to protect her family, and she voiced concern about how the community may view her, and welcome her (or not) depending on the way this proposed expansion situation unfolds.

This sort of social impact is something that could be better understood, if an EIS were to be conducted. An EAW is small potatoes, compared to the in-depth analysis that this community deserves before this project is pushed through.

There is also the major recent concern, of having so many animals housed in a relatively small areas; given the recent hantavirus sensationalism in the news, I am now worried about what it means for the community in Morris to have so many animals in close quarters. Would an increase in capacity at the facility put the surrounding area at an increased risk of pathogens to spread or mutate in close quarters? What measures are in place to prevent and plan for this biological aspect of the project? Is there adequate confidence that a sufficient plan is in place if something were to go wrong, to prevent us from being a new "Ground Zero"?

I am not voicing that I am for or against this project, but I do have legitimate concerns regarding a project at this scale. It's great if it works, but I worry about what happens if or when it doesn't go according to plan. This is the only home my kids have ever known, and I would appreciate getting a sense of potential impact on the community and our area at large, and maybe even beyond, if this project proposal were to be granted. If this project pollutes the water, or air, or wrecks roads in the area, that is an issue I need to be addressed. How can we mitigate these potential impacts, and what sort of plan is in place, if these impacts are realized in our community, or by those who are downstream? I don't want to focus on potential jobs created by this expansion, or impact on taxes (although my worry for an increased burden on tax-payers is also real), I care most about our fundamental rights to have access to clean water and to retain our freedoms to accessible clean water, and to have ethical land management which considers the community at large, wildlife who doesn't

have a voice to defend itself, and the state of Minnesota as a whole. I'm concerned about how much manure waste a facility of this size would have, what land this waste would be applied to, and how much of a risk there is for runoff to pollute our precious water ways, which could in turn impact local families, local wildlife, and the future of the land in west central MN and beyond, due to the precedent this facility will set. We need a thorough Environmental Impact Statement. The risks to the ecology of the area are too great to not conduct an EIS. How would this sort of precedent established by the project impact the way that other future operations are scaled up?

The only people who were advocating for a "more streamlined, faster" process of these proposals and project fulfillment, were the ones who stood to profit from it. What's to come of the people, who are stuck in the area which they call home, after this area becomes altered in ways they struggle to voice, due to a project which was pushed through too hastily?

I request that an Environmental Impact Statement be completed, to ensure all necessary factors are considered, and controls in place to mitigate the potential risks of this project. I need to be assured that I have an answer that I can depend on, through scientific data and rigorous analysis of all facets of the proposal.

Sam Visser **Letter 1303**

My name is Sam Visser and I am an employee of a family owned excavation company. Riverview has helped our business grow and taught us new ways to achieve our goals. Anytime we are on the farm you can always guarantee two things great attitudes from all the employees and a super clean work environment. So our company never has a problem with going to help them out with what ever is needed.

I feel that Riverview also has a big impact to the surrounding communities. The farmers have an opportunity to sell their crops locally right to the dairy which saves on trucking and on guessing what the markets are going to do. They have apartments in small towns that brings new customers into small businesses. They have even taken on high school students as interns who might be interested in doing something in that career field!

Riverview has brought so much growth and opportunity into our community and we are grateful for that.

Joe Stroman **Letter 1304**

My name is Joe Stroman and I operate my family farm which is located 2 miles from the existing West River Facility. I am the 6th generation to live and work here, and 2026 marks 150 years of family ownership of our farm since it was homesteaded in 1876.

I am very familiar with Riverview's operation. I have family members who work for them. I have toured both their main barn and the West River barn. I've sold silage to them in the past and I've also worked on one of their silage harvesting crews. What people say is true: Their barns are clean and professionally run, and their employees all seem happy to work there.

That being said:

After reviewing the Environmental Assessment Worksheet, I believe there are some issues that need to be addressed.

My first issue of concern is wind erosion due to numerous consecutive corn silage crops. While documentation shows that runoff erosion is minimal, It seems that wind erosion is not being monitored.

In fact, wind erosion isn't mentioned once in the entire EAW document. We have many days throughout the fall, winter and spring where the wind exceeds 30 mph and large amounts of topsoil can be observed blowing off of Riverview's silage fields while adjacent fields remain intact. Corn silage harvest removes at least 90% of above ground biomass, and even if the maximum rate of manure solids are applied afterwards and a cover crop is planted, it doesn't come close to replacing what was removed. Riverview usually grows silage corn for a number of years, followed by a perennial alfalfa crop as a resting period. This is described numerous times in the EAW as a "crop rotation". This is not a crop rotation, it is a decade-long alternation of two cash crops and a cover crop that never exceeds vegetative state. The continuous removal of biomass, followed by intensive tillage, plus a lack of biodiversity from consecutive corn crops results in a loss of soil structure and rapid degradation of the A-horizon. When topsoil blows off of fields it typically collects in road and drainage ditches. Numerous studies have been conducted where blown topsoil has been shown to have very high concentrations of nitrogen, phosphorous and potassium. Wind erosion potential of continuous silage ground and mitigation practices thereof is something that should be required in an Environmental Assessment Worksheet. If not, an Environmental Impact Statement should be required to determine the potential impacts of these practices.

Another concern that I have is the socioeconomic impact of an operation this size, which is not covered in the EAW, and is often ignored in public discourse. While Riverview does provide opportunities to other farmers in the form of buying silage and selling manure, many smaller farm operators within the West River Dairy footprint are of the opinion that Riverview's competitive presence in the local land market has caused a false inflation of land values. If Riverview is interested in a piece of farmland, they will pay top dollar, and landowners are aware of this fact. Most farmland tenants can't compete with Riverview's offers or bids if and when their rented ground comes up for sale, which decreases their acres of production, leading to a loss of opportunity for future generations to step into their family business. This has become very evident in the small communities surrounding Morris, who must work diligently to keep businesses and schools open in spite of a declining population. I am aware that the consolidation of agriculture in this area isn't solely caused by Riverview. However, observing many other rural communities where Riverview doesn't have a presence may lead one to believe that they are a catalyst. An argument could be made that the West River Expansion already has a sufficient land base to operate with, and has no need to buy more land. That very well could be true, under the assumption that there will be no further expansions. Anyone who possesses the gift of hindsight can see how that plays out. In 2003, Riverview held a public meeting to discuss the proposed construction of the original West River Dairy facility, their second barn at the time. My father, Keith Stroman, stood up and asked why they were more than doubling the size of their dairy enterprise with the simple question: "Why are you doing it?" One of the owners responded, "It's for our kids." This was a good enough answer for Keith, as he was structuring his own farm operation so that I could someday step in. Fast forward 23 years, and they've built a dozen more barns just in the state of Minnesota alone. I'm not convinced that this is a one and done project, and I'm also not convinced that this is being done to safeguard job security for someone's kids.

I believe that Riverview has every right to do business in Stevens County, but when the industrial scale of their expansion has the potential to impact an entire community, there needs to be industrial scale accountability.

I've deliberated making this comment since the opening of the comment period, because I feel like it will put a target on my back. I know many other people who won't be making a comment or voicing their opinion because they fear social or professional repercussions. This ties back to the socioeconomic effects that I mentioned above.

In closing, I don't believe the Environmental Assessment Worksheet addresses all of the potential impacts of the proposed expansion, environmental or otherwise. Riverview has the personnel, resources and most of all, ambition to do their due diligence and complete an Environmental Impact Study.

Rick Metzger **Letter 1305**

Dear Commissioner Kessler:

I grew up on a small farm in southwest Minnesota. Prior to joining Riverview, I spent my entire career in agricultural finance working with farm and agribusiness operations of every scale across the United States. I am also a Riverview employee and partner who came to this company because of its culture of opportunity. I want the record to reflect what that actually means: I am a farm kid who did not have a clear path back into production agriculture through my own family. I found that path at Riverview. And now my son is working here too. From the outside, people see a large dairy operation. From the inside, this is a story about what happens when passionate people who love agriculture are given an opportunity to build something together. That is the story this expansion is about.

I have reviewed a substantial amount of the comments submitted on this project and would like the MPCA to take note of something: the support record includes a substantial number of named local and regional businesses, contractors, equipment suppliers, ag lenders, and employers who have written substantively about the economic activity Riverview generates for them and their communities. Supporters also consistently speak to firsthand knowledge of Riverview's environmental stewardship, its nutrient management practices, its commitment to operating above minimum regulatory requirements, and its track record of compliance on this very site. The opposition contains virtually no businesses at all. The people with direct economic experience alongside this operation, and direct observation of how it operates on the ground, appear to overwhelmingly support it.

The MPCA is a science-based regulatory body. I am asking you to hold this comment record to that standard. What follows is my attempt to do the same.

Opposition comments suggest this project is somehow detrimental to Minnesota's farm economy. The record says otherwise. This project comes at a moment when the national dairy industry is signaling extraordinary confidence in future demand: U.S. dairy processors invested a record $11 billion in new processing capacity between 2025 and 2028, per-capita dairy consumption reached a record 661 pounds per person in 2023, U.S. dairy exports continue to grow, and U.S. milk production is projected to grow by 15 billion pounds by 2030. The market is not asking whether dairy should grow. It is asking where. West River Dairy is part of that answer. The demand exists for farms of every scale that choose to meet it.

It is also worth discussing what “large” actually means in today's dairy industry. Virtually every new dairy built in the United States over the past ten years has been constructed at 5,000 to 12,000 cows or larger. West River Dairy's proposed scale is significant by Minnesota standards. By the standards of modern dairy investment nationally, it is competitive and rational.

In my work in agricultural finance, I have heard the same observation consistently from lenders, peer groups, and industry professionals across the country: Riverview is frequently cited as a model for people development, operational management, animal welfare, and environmental stewardship. Their facilities are among the most sought-after in the United States for industry tours. I share that not to advocate for the company that employs me, but because that external, unsolicited recognition from professionals who evaluate dairy operations for a living is relevant context for this permit decision. The existing West River Dairy site has operated at this location for years with a strong compliance record.

This permit is not for an untested proposal. It is an expansion of something the record shows already works.

On environmental matters: first and foremost, managed manure application is not a threat. It is a tool. Under a nutrient management plan with soil testing, calculated application rates, and state oversight, it is agronomically sound practice that improves soil health, builds organic matter, and reduces dependence on synthetic inputs. Minnesota farmers have used manure as a fertility resource for generations, and the agricultural community broadly understands its value when managed properly. The permit conditions governing this operation require exactly that level of management. The concerns raised about runoff deserve to be evaluated against the actual permit requirements, not against a worst-case scenario untethered from how regulated operations work.

On the trajectory of agriculture broadly: tractors are larger and more capable. Genetics are more productive. Milking is automated and more frequent. These are not threats to agriculture. They are the result of American innovation, and they are the same forces that made Minnesota dairy competitive globally.

On water specifically: some opposition comments argue that Minnesota cow numbers have declined while simultaneously arguing that this operation uses too much water. Those two positions are in direct tension. If Minnesota still had the same total cow population distributed across thousands of smaller farms, system-wide water consumption would be comparable or higher. Consolidated operations are measurably more efficient on a per-cow and per-unit-of-output basis. That is not an assertion. It is an engineering and agronomic reality that the permit record supports.

The Environmental Assessment Worksheet for this project has been completed. An individual feedlot permit with specific, enforceable conditions will govern this operation. The categories of concern raised in opposition comments, water quality, manure management, stormwater design, and watershed protection, are all addressed within the existing regulatory framework. No commenter has identified a specific material question that the EAW failed to address and that only an EIS could answer.

One comment suggested that Riverview's resistance to an EIS implies something negative to find. That is an inversion of how permitting works in a system that must presume compliance with applicable laws, unless evidence suggests otherwise. The question is whether the existing process has left specific material questions unanswered. It has not. And the standard is whether there is the potential for significant environmental effects. There is not.

Applying a never-before-used standard to this operation would also send a signal to every agricultural investor considering Minnesota: that regulatory certainty here is conditional, and that scale alone is sufficient grounds for extraordinary review regardless of designs, plans, applicable regulations, and compliance record. That signal would have consequences well beyond this permit decision.

There is something worth saying plainly at the close of this letter. Rural Minnesota is not dying because of farms like this one. Farms like West River Dairy are among the reasons rural Minnesota's future is bright. They bring jobs and families and economic activity that ripples outward through every business and institution in the region. They give farm kids another place to build a life in the communities they grew up in.

The factual record supports this permit. The EAW has been completed. The permit process is sufficient. The economic case is documented. The environmental concerns raised in public comments are addressed within the existing regulatory framework, and no specific gap has been identified that would require an EIS to fill.

I recognize that many people who submitted comments have genuine concerns about their community and their environment. Those concerns are valid and deserve a rigorous process. That process exists and has been followed here. What the concerns do not warrant is a heightened standard that the record does not justify.

I respectfully ask the MPCA to issue this permit. The existing review process is sufficient. An EIS is not warranted. This project, and the people whose futures depend on it, deserve the opportunity to move forward.

Respectfully submitted,
Rick

Jeff Beckman **Letter 1306**

It concerns me that when we concentrate this many animal units in a single area that there is the potential for issues. While I understand their ability to handle these farms, It's important to remember that when we concentrate the farms, we lose small farms, and when we lose small farms we lose communities. If this project is allowed to move forward, I believe it will affect our rural areas in a way that will not be seen for years. Therefore, it is important to fully understand the effects on the loss of other dairy's in the state that this project would be replacing.

I believe when we look at all the facts and exam the options there are other ways that the good of all people can be achieved. Understanding that we need to consider the water and the waste issues, it is important to study it in more depth. Thank you for considering this and requiring a more in depth study.

Erica Boyum **Letter 1307**

Dear Commissioner Kessler:

I am writing in strong support of the proposed West River Dairy Expansion in Synnes Township, Stevens County, and to respectfully urge the MPCA Commissioner to issue a negative declaration on the need for an Environmental Impact Statement. Both my husband and I grew up on dairy farms in Minnesota. We are passionate about agriculture, passionate about dairy, and passionate about building sustainable opportunities and livelihoods for generations to come. We are raising our family here, living right on the Pomme de Terre River, and we have found our personal and professional home with Riverview. I am the fourth generation in my family to work in dairy, and it is my sincere hope to pass that opportunity on to my children. Riverview has made that possible — and this expansion is part of that same story. Farming sustainably and responsibly is not an abstract value to me; it is a daily commitment. I truly believe that Riverview cares for people, animals, and the environment in the best way possible, and the record before the MPCA reflects that. The Environmental Assessment Worksheet is thorough, the permit structure is adequate, and an EIS is not warranted.

Peter Louwagie **Letter 1308**

Living my entire life in the dairy industry i have seen tremendous growth in farm size and we are getting to the point of industrialization not farming. At the proposed size of this dairy I believe there are many things that could result in a disaster along the line of the large dairy in Texas suffering a fire on killed the majority of the cows and had a effect on the national milk supply. There is many possibilities of biosecurity going wrong with the scope of an operation this size and causing a disruption of the short shelf life of diary products.

Concentrating this size of operation in one location i believe is not good for the people of Minnesota. A strong viable dairy industry is i believe very important to this state.

As the industry farm operations increase to industrial size maybe the state legislature has to consider in spending public dollars on research and promotion a worth while invastment

Alisha Livengood **Letter 1309**

My name is Alisha Livengood. I have lived in Morris for 33 years. I graduated high school here and continue to live here as we raise our family. Riverview continuously invests in our community, provides opportunity and growth, and holds strong values. I support the West River Dairy expansion. No EIS is needed as Riverview has already provided information required to move forward with an expansion. Thank you for your time and consideration.

Alisha Livengood

Rebecca Pedersen **Letter 1310**

There is more than just the environment at issue here. The dairy cattle live heart-breaking lives in these factory farms. If MN can save beagles from a neighboring state, I think we can try to help the cattle here...along with our environment. We know that weather and ethical issues often cross state lines and impact lives at great distances from our State. Thank you for requesting we pause and give more thought to all of the issues involved. You are correct, our water, climate and communities are counting on us...as well as the animals with whom we share our lives on a daily basis. What world do we want our children inherit from us? What care and concern and compassion are we modeling for them?

Willis Mattison, Izaak Walton League of America **Letter 1311**

Dear Mr. Peterson,

Thank you and the Minnesota Pollution Control Agency staff for inviting comments on the draft West River Dairy Expansion Environmental Assessment Worksheet (EAW) and for holding a public meeting in Morris, Minnesota on April 28th.

Based on the history of past Riverview projects and confined animal feeding operations (CAFOs) in general, our review of the draft EAW for this exceedingly large expansion and the applicable criteria we have concluded that an environmental impact statement (EIS) is warranted. We find the draft EAW itself deficient in a lot of ways, but we do not call for its revision. Instead, the information we do find in the draft EAW is more than sufficient justification for moving forward into a full EIS.

Our comments in support of that conclusion are grouped according to the four specific criteria shown in Minnesota Rules 4410.1700, subpart 7. The MPCA, as the Responsible Governmental Unit (RGU) must consider these criteria when determining if a project has the potential for significant environmental effects and therefore warrants an Environmental Impact Statement (EIS):

1. Type, extent, and reversibility of environmental effects;
2. Cumulative potential effects;
3. Degree of mitigation by ongoing public regulatory authority, and;
4. Anticipation and control of effects from other studies.

Below is our summary outline with our comment topics listed as lettered subheadings under each of the four criteria. Following this summary is a more detailed discussion on each topic.

Comment Summary as Outline of Topics Covered

Criterion 1 - Type, extent, and reversibility of environmental effects -

A. EAW vastly under sizes the environmentally relevant area (ERA)
B. EAW fails to acknowledge that polluted groundwater may not be reversible
C. Effects on ground and surface water quantities and flows don't add up;
D. Potential ground water contamination by leachate from manure pits and basins is not quantified
E. Contamination by manure seepage to perimeter tile draining shallow groundwater from under manure pits delivered to storm water basin is unaccounted for
F. A report in EAW minimizes future low flow probability in Pomme de Terre River and is misleading and inconsistent with climate trends stated elsewhere
G. Crop land used for manure spreading may need containment to avoid runoff reaching surface waters
H. The EAW fails to identify potential increases in antibiotic resistance and/or the potential zoonotic infections effects of large CAFOs.

Criterion 2 - Cumulative potential effects

A. Deliberate under sizing the environmentally relevant area cannot be used to avoid impact overlap and claim impacts are not cumulative
B. EAW does not properly characterize past, present and future environmental conditions of the environmentally relevant area
C. EAW fails to account for impacts of feedlots in the impacted areas whether owned or operated by proposer or not.
D. EAW minimizes or ignores proposed project incremental contribution to cumulative potential effects
E. EAW describes purposeful avoidance of potential mitigation offered by "green infrastructure" as part of intentional project design
F. EAW fails to identify impaired waters as evidence of past and present projects

Criterion 3 - Degree of mitigation by ongoing public regulatory authority

A. The EPA has found MPCA's existing feedlot rules and permits to be inadequate
B. MPCA will not have strengthened feedlot rules in time to control this project
C. Local ordinances and county feedlot officers are ineffective
D. Federal Clean Water Act authority remains delegated to the state MPCA
E. MPCA may be in violation of MEPA which prohibits permitting polluting activity when less polluting alternatives exist
F. MPCA fails to extend its authority over pollution caused by manure delivered to other farmers and landowners
G. MPCA has failed to adopt nitrate standards for surface and groundwaters.

Criterion 4 - Anticipation and control of effects from other studies

No other EIS has been prepared on a feedlot of this size in the project area or similar setting
B. Compliance with TMDL goals for areas surface waters are not acknowledged
C. Other studies have found large feedlots degrade local economies and community health
D. Economic impacts are not included in EAWs but can be addressed in an EIS

Detailed Discussion of Each Topic

Criterion 1 - Type, extent, and reversibility of environmental effects – The RGU must examine the nature of the impacts, how widespread they are, and whether they can be undone.

A. EAW vastly under sizes the environmentally relevant area (ERA).

The EAW claims the area impacted by the project can be limited to the exact area of the feedlot site, the areas where manure will be spread and a one-mile radius around the off-site wells.

> *"The Environmentally Relevant Area (ERA) for the Project has been delineated to ensure that environmental effects from other projects do not overlap. The ERA is defined as the oversized Project Boundary, all idenƟfied manure applicaƟon fields designated for the Project and ExisƟng Facility, and a one-mile radius surrounding the off-site water-supply well (Attachment 20).*

This claim cannot be supported. Project impacted air, water and soils move freely across these property boundaries and are carried far beyond them, down rivers into aquifers that move and across neighboring properties and into other counties. Climate impacts are global in scale. Surface water impacts are regional and can exceed the bounds of the Pomme de Terre watershed into the Minnesota River. Therefore, the impacts of this exceeding large feedlot project on this larger more realistic and environmentally relevant scale are potentially significant and justify an EIS.

B. EAW fails to acknowledge that polluted groundwater may not be reversible

The potential for manure storage area leakage and field applied manure seepage below the crop root zone into groundwater is likely under the many thousands of acres proposed for this project. Despite the project's inclusion of extra thick clay liners under the manure storage pits, these liners can still be expected to leak up to 100 gallons per acre per day (one fifth of the allowable leakage rate). Manure application (along with commercial fertilizer) to farm fields has been shown to create the potential for seepage into groundwater even when applied at agronomic rates. Agronomic application rates are not designed to prevent excess nutrients or other farm chemicals from reaching groundwater, instead they are designed to maximize production with the least amount of application.

Once contaminated, groundwaters are extremely difficult if not impossible to clean. Drinking water sourced from groundwater may be treated to remove some contaminants but this is not a reversal of the original contamination.

C. Effects on ground and surface water quantities and flows don't add up

The expansion would use 287.5 million gallons per year, almost as much as the city of Morris, population 5,100. The project relies on two well water fields, one on site and one off site that are limited in available supply, either by impact on low river flows or excessive drawdown of aquifer levels. A back up storm and well water storage pond is planned to serve as a temporary water supply in when well extraction limits kick in. No calculations are supplied in the EAW to assure the backup will suffice during extended drought periods lasting several months if not years. An EIS will be required to estimate the probability and frequency at which the project operators may request emergency exemption from well pumping limits to keep their livestock alive. Depopulating such an enormous feedlot in a time of drought is impractical. Such an exemption places other well users and the river at risk for serious water shortages. This alone is a potential for significant impact warranting an EIS to evaluate available alternatives including the no-action alternative.

D. Potential ground water contamination by leachate from manure pits and basins is not quantified

At the public meeting in Morris on April 28th of this year, MPCA officials admitted that manure pit leakage, even at the reduced rates afforded by thicker clay liners, would likely reach groundwater. The MPCA dismissed these impacts as not being significant because "receptors" of this contamination (understood to be private or public wells) were far enough away. These estimates are subject to internal

speculation and discussion with the project proposer but have not been made public. The basis for these estimates and the factors contributing to estimate uncertainties should be presented in an EIS and thus subjected to third party scrutiny.

E. Contamination by manure seepage to perimeter tile draining shallow groundwater from under manure pits delivered to storm water basin is unaccounted for

The draft EAW states:

> "To control potenial seasonal subsurface saturaion near the LMSAs, a drain-tile system will be installed around the perimeter of the LMSAs at an elevaion below the LMSA liners. The clean seasonal subsurface water from the perimeter tile system will drain into a nearby stormwater basin, where it combines with Project stormwater.

MPCA acknowledges and allows (permits) manure storage ponds to leak and this leachate is most certain to find its way into the perimeter drain-tile system. The project should not be designed to dispose of manure contaminated seepage in this tile system in a stormwater system. The stormwater system is oversized but still can be predicted to need discharge during wetter years. The EAW form fails to address the need for wastewater treatment in section 12.B.1. C as follows:

> "12.B.1.c. If the wastewater discharge is to surface water, identify the wastewater treatment methods and identify discharge points and proposed effluent limitations to mitigate impacts. Discuss any effects to surface or groundwater from wastewater discharges, taking into consideration how current Minnesota climate trends and anticipated climate change in the general location of the project may influence the effects."

The RGU's entry here is that this treatment requirement is "Not Applicable" which is interpreted to mean no wastewater discharge is planned. An EIS would need to resolve this contradiction/omission and either describe total containment of contaminated manure pit leachate which would seem impractical or the proposed treatment of this wastewater, possibly by land irrigation or other means.

F. A report in EAW minimizes future low flow probability in Pomme de Terre River and is misleading and inconsistent with climate trends stated elsewhere

> "Riverview LLP requested Moore Engineering Inc. (Moore) to evaluate discharge flows from Pomme de Terre River (River) in Appleton, MN. Moore assessed historic data from USGS Gage #05294000 to determine the percentage of time the flow in the River was less than three specified flow parameters. Historically, the trend of the Rivers minimum discharge has increased. This is most evident after 1991, as can be seen on Figure 1. Between 1931 and 1991, average minimum flow was approximately 8.5 cfs. After 1991, the average minimum flow increased to 50 cfs.

In the climate impacts section of the EAW, river flows are predicted to continue decreasing as average temperatures increase. These inconsistencies are confusing to the public and should be clarified in an EIS.

G. Crop land used for manure spreading may need containment to avoid runoff reaching surface waters:

The EAW states:

> "Increased precipitation may cause the loss of some acres of cropland due to saturation of low spots within fields or localized flooding after rain events. New drainage or water impoundment systems may need to be developed by landowners to handle increased volumes of stormwater

in fields. If these structures are built on any of the manure application fields, they would take land out of crop production to convert to water management structures. With a contingency of over 3,000 additional manure application acres beyond what is needed each year, there is abundant operational flexibility if some portions of the fields are no longer available due to weather condition impacts.

This is a very important revelation that has potential for significant future effects that are a direct result of this project. If 3,000 acres of prospective manure application fields have known drainage issues that will not be identified and remedied until after some future rain events this should be a red flag. Rainstorms that are increasing in frequency and severity due to climate change and cause localized flooding should not be relied upon as the trigger for corrective action. Surface or groundwater pollution is likely to have already happened. Simply eliminating these areas from future manure application after the drainage problem has been experienced will not prevent this pollution. Here, the EAW can serve its true function and trigger an EIS that can explore this issue more thoroughly and evaluate alternatives that would avoid predictable pollution.

H. The EAW fails to identify potential increases in antibiotic resistance and/or zoonotic infections effects of large CAFOs.

A report in 2020 by the Natural Resources Defense Council[1] (NRDC), reveals that US cattle producers use more than 40% of all medically important antibiotics—those that are also used in human medicine—sold for use in US livestock, and use them three to six times more intensively than many of their European counterparts.

NRDC says this overuse of antibiotics is a strategy used by the beef industry to offset heightened disease risks in feedlots, where cattle are routinely fed antibiotics to prevent disease whether or not they are ill, a practice that the World Health Organization discourages and that the European Union will no longer allow starting in 2022. The reports also argues that there is little transparency or accountability in the beef industry regarding its use of medically important antibiotics, and little urgency to rectify the problem.

"Many infectious disease and antibiotic resistance experts believe such use is improper and helps contribute to reservoirs of drug-resistant bacteria on farms that can spread easily to humans through consumption of meat, exposure to soil or water contaminated with manure containing antibiotic-resistant pathogens or contact with animals. They also worry that it reduces the effectiveness of antibiotics that are needed to fight infections in people."

A 2023 report in the Journal of Dairy Science[2] states:

"Antibiotics are used in the dairy industry mainly to treat mastitis, respiratory illness, lameness, and enteric diseases (Andrews, 2000; Dodd and Booth, 2000; Alliance to Save Our Antibiotics, 2016). Some of the antibiotics used are particularly important in treating human infections; therefore, their continued use in dairy cattle is predicted to have dangerous implications for human and animal health (Alliance to Save Our Antibiotics, 2016). One of the main uses of antibiotics in dairy cattle is "dry cow" treatment, which involves a long-acting intramammary antibiotic infusion given to cows between lactation cycles, with the intention of treating existing infections and preventing new infections (Dodd and Booth, 2000). Blanket dry cow therapy (BDCT) involves the prophylactic

[1] **Report slams beef industry for overuse of antibiotics** - Chris Dall | News Reporter | CIDRAP News June 26, 2020 Antimicrobial Stewardship

[2] Factors influencing dairy farmers' antibiotic use: An application of the COM-B model - Journal of Dairy Science Volume 106, Issue 6, June 2023, Pages 4059-4071

antibiotic treatment of every cow at drying off to prevent infection; BDCT has historically has been used in mastitis control (Biggs, 2017). As this involves giving antibiotics to all cows, even those who are not infected at drying off, BDCT has been linked to the threat of AMR development (Brunton et al., 2012; Higham et al., 2018).

With regard to zoonotic infection risks on large dairy farms, a 2017 article by Michigan State University[3] states that:

"People that work with dairy cattle can be at risk of becoming infected with a zoonotic disease. However, families of employees and people in close contact with dairy personnel can be at risk too. The compliance of preventive measures protects not only people in direct contact with animals, but also people in their homes. Prevention is especially important if there are children under 5 years old, elderly or people with weak immune systems in the families of the dairy personnel, since they can get sick more easily and could have more severe symptoms of the disease.

Contracting a zoonotic disease not only has consequences on the health and wellbeing of the person affected, it also impacts the normal operation of a dairy farm. In times when the work force is very limited, producers cannot afford to have a valuable worker off the farm due to a preventable disease."

Because these issues are highly complex, were not addressed at all in the EAW and because research has shown the overuse of antibiotics and failure to employ proper and consistent biological safeguards in feedlots can present significant threats to human health that may not be reversable, an EIS is warranted to fully inform the public and inform the permitting of an industrial scale livestock facilities like the one proposed.

Criterion 2 – Cumulative potential effects – The RGU must consider whether the project's impact is significant when added to other past, present, and reasonably foreseeable future projects, including those by other entities.

A. Deliberate under sizing the environmentally relevant area cannot be used to avoid impact overlap and then claim impacts are not cumulative

As was previously referenced above the EAW states:

"The Environmentally Relevant Area (ERA) for the Project has been delineated to ensure that environmental effects from other projects do not overlap. The ERA is defined as the oversized Project Boundary, all identified manure application fields designated for the Project and Existing Facility, and a one-mile radius surrounding the off-site water-supply well (Attachment 20). **The established ERA for the Project avoids cumulative potential effects** (CPE) as detailed in Item 21." (bold added for emphasis).

This is a conspicuous but unacceptable attempt to avoid having to disclose effects that are most certainly cumulative. The project is not proposed for a pristine, isolated island, it will be situated in an already degraded environment, part of which is caused by the existing feedlot that is being expanded. And degradation by the landscape having been converted to agriculture is evidence of past effects. If the air and water in the vicinity are not clean and the native ecosystems are not fully functioning, this project's impacts must be added to these "past and present" actions and then added to the impacts of reasonably foreseeable actions. The incremental degradation attributable to this project is certainly greater than most but it cannot escape its cumulative significance by simply declaring it does "overlap"

[3] **Prevent Zoonotic Diseases on your Dairy Farm -** Paola Bacigalupo Sanguesa, Michigan State University Extension - November 29, 2017

with other "projects. These cumulative effects should be more honestly and accurately assessed by preparing an EIS.

B. EAW does not properly characterize past, present and future environmental conditions of the environmentally relevant area

The existing dairy and other farming operations are near the Pomme de Terre River, which flows into the Minnesota River. State testing has found E. coli in the Pomme de Terre watershed, as well as nutrients that can lead to algae blooms. Already, several sections of the river do not support aquatic life or human recreation. The river starts out clean but gets more and more polluted as it passes through farmland. TMDLs have been prepared to document the problems directly associated with animal agriculture in several streams and wetlands in the vicinity and the remedial measure needed to restore them to the fishable and swimmable condition required by law. A fair determination of the cumulative effects of this project requires the effects of all past, present and future projects be accurately characterized so this project's impacts can be added to them. An EIS is the appropriate tool for correcting this oversight in the EAW and informing the MPCA and the public as to whether a permit can be issued.

C. EAW fails to account for impacts of feedlots in the potentially affected areas whether owned or operated by proposer or not.

As stated in our comments above, Riverview owns and operates numerous other large feedlots, many of which in the same watershed as the proposed expansion. And other smaller feedlots not owned by Riverview are identified in maps included in the EAW. These feedlots are also in the same watershed and potentially are affecting the same wetlands, groundwater, habitat and air quality. Quantifying and accounting for the collective impacts of these existing livestock operations is usually beyond the scope and purpose a of an EAW. The EAW must identify and locate these feedlots but does not need to quantify their impacts. This is an appropriate function of an EIS.

D. EAW minimizes or ignores proposed project incremental contribution to cumulative potential effects

By declaring the environmentally affected area of the project so narrowly, as described above, the proposer attempts to side-step the need to acknowledge the incremental addition of the project to the effects of its own operations and those like it in the vicinity. This error should be corrected and the incremental impacts quantified in an EIS.

E. EAW describes purposeful avoidance of potential mitigation offered by "green infrastructure" as part of intentional project design

The EAW states:

> "The Project is not proposing to incorporate typical green infrastructure or planting trees at or around the Project site due to the negative effects they bring to the dairy cows. Common green infrastructure includes landscaping features such as trees, shrubs, and standing water that attract insects. In turn, this attracts birds and/or other animals. The United States Department of Agriculture (USDA) recommends incorporating enhanced biosecurity features into new dairy operations to avoid unwanted diseases. West River Dairy Expansion measures included designing the facility to minimize livestock exposure to birds and further prevent disease transmission, such as Highly Pathogenic Avian Influenza."

Landscaping with trees, shrubs, pollinator friendly plants near constructed ponds could provide aesthetic mitigation for the adverse effects of the enormous built infrastructure proposed in this project while providing a modicum of natural habitat for birds, insects and many other forms of important

wildlife. As described above, this entire region has had its wildlife populations of all kinds, decimated by loss of these types of habitats. While this biosecurity practice may be recommended by the USDA, alternatives to these environmentally harmful biosecurity measures should be evaluated with an EIS.

F. EAW fails to identify impaired waters and loss of biodiversity as evidence of past and present projects

The writers of the EAW miss an opportunity to utilize comments from other agencies to document how past projects have degraded several aspects of the environment in the vicinity of this project.

The DNR letters and emails attached to the EAW identified several areas with high potential for restoration very near the project and recommended the project include plans to implement designs to prevent surface runoff or invasive species from damaging these areas:

> "The Minnesota Biological Survey (MBS) considered several areas very near the proposed project for Sites of Biodiversity Significance that did not meet the minimum biodiversity threshold for statewide significance. Despite being Below the statewide threshold, these areas may have conservation value at the local level as habitat for native plants and animals, corridors for animal movements, buffers surrounding higher quality natural areas, or as areas with high potential for restoration of native habitat. **As such, indirect impacts from surface runoff or the spread of invasive species should be considered during project design and implementation.**

The project, as presently designed, does not specify any special designs or alternative measures intended to effectively avoid these impacts. This is an appropriate function of the EIS and underscores the need for that higher level of review that we support.

And the DNR identified several areas of high biological significance near the project largely due to bird populations, but mollusks and plant species were also mentioned:

> Ecologically Significant Areas • Three lakes near the proposed project area have been identified as Lakes of High Biological Significance. These are Gorder Lake, Clear Lake, and an unnamed lake in T124N R43W Section 13. Lakes of Biological Significance were ranked as Outstanding, High, or Moderate based on unique plant and animal presence. These lakes received their rank largely due to their bird populations.
>
> Elktoe (Alasmidonta marginata), a state-listed threatened mussel; Small white lady's-slipper (Cypripedium candidum) and prairie mimosa (Desmanthus illinoensis), both state-listed plant species of special concern
>
> • To benefit all of the above rare species and features, we recommend that manure application rates and timing be carefully determined to ensure that nutrient input does not exceed the ability for crop nutrient uptake on the fields where it is applied.
>
> The Environmental Assessment Worksheet should address whether the proposed project has the potential to adversely affect the above rare features and, if so, it should identify specific measures that will be taken to avoid or minimize disturbance. Sufficient information should be provided so the DNR can determine whether a takings permit will be needed for any of the above protected species."

Here the DNR recommends the EAW establish whether the proposed project has potential to affect these species but it does not. While buffers are shown around manure application fields near wetlands and water courses no analysis is provided to assure these buffers are sufficient to avoid or minimize the effects the DNR is concerned about. An EIS should be prepared to answer the question the DNR poses in

order to inform the Department whether a takings permit will be needed. The EAW did not and likely could not provide this level of analysis.

The EAW reveals specific water body impairments near the project that included Lake Hattie had a nutrients TMDL plan approved in 2015 and the Pomme de Terre River identified turbidity (2002) and fecal coliform (1994) impairments. Muddy Creek has excessive E. Coli (2020) while Dry Wood Creek has listed impairments for dissolved oxygen (2012) benthic macroinvertebrates bioassessments (2012) Turbidity (2010) E. Coli (2010) with TMDL plans approved for all impairments in 2015.

The proposed project can be predicted to exacerbate these impairments given the EPA's finding that the state's feedlot rules are ineffective for protecting water quality (see item 3-A below). These impairments are, as evidenced by the TMDL plans prepared for them, significant and in need of reduced loading primarily from improper handling of livestock wastes in their respective watersheds. An EIS is necessary to explore alternative methods for land application of livestock wastes from this facility as part of the remedial actions called for in the TMDLs

Criterion 3 - Degree of mitigation by ongoing public regulatory authority – The RGU evaluates if existing, specific regulatory permits or processes can effectively mitigate the environmental impacts.

A. The EPA has found MPCA's existing feedlot rules and permits to be inadequate

The Minnesota Division of the Izaak Walton League of America on the advice of the Prairie Woods Chapter in Detroit Lakes joined with the MCEA, Trout Unlimited and the Minnesota Well Owners Organization (MnWOO) and others in signing a petition to the U.S. Environmental Protection Agency (EPA) that successfully convinced the EPA that the MPCA's current rules and permit requirements for feedlots were inadequate to protect water quality and the human environment as required by the Federal Clean Water Act. The EPA instructed the MPCA to revise or amend their rules and write more effective permits. While the MPCA is in the process of making these improvements, the proposed project is subject to the very same existing rules the EPA found inadequate.

The petition to EPA did focus on karst and sand plain regions of Southeaster and Central Minnesota but similar alluvial sands exist in the areas in and around Stevens County where manure application fields have been identified for this project.

While this fourth criterion is primarily intended to require identification of regulatory authority in place that could mitigate potential environmental impacts it can also function to identify shortcomings of existing regulations. That is precisely the situation we have here. There is no more compelling argument for ordering an EIS on this and any other large feedlot proposed in Minnesota than this finding by the highest environmental authority in the nation, the U.S. Environmental Protection Agency.

B. MPCA will not have strengthened feedlot rules in time to control this project

As stated in item 3-A above, the MPCA's rules and permit requirements for feedlots are in the process of being improved to satisfy the EPA and the public that they will adequately protect water quality. However, those improvements have not yet been made. Yet the MPCA has proceeded to draft an EAW and a prospective permit for this project under these decidedly inadequate rules.

In a footnote to a table showing depths to groundwater under the projects manure application fields the EAW states:

> **The Proposer has agreements with landowners for manure application covering over 16,500 acres. Depth to groundwater will vary throughout these acres.* ***There are no rules prohibiting manure application onto high water table soils.*** *The Proposer uses and exceeds BMPs for manure application and follows all state rules and local ordinances. (bolding added for emphasis)*

This declaration (in bold) by the project proposer demonstrates how feedlot operators can take advantage of the agency's overly lax feedlot rules to apply manure where shallow water tables are vulnerable.

The MPCA's moving this project forward to this point may be required by laws intended to streamline the permitting process. But by ordering an EIS on this and any other feedlot seeking a permit in the interim, the MPCA has the choice of forestalling inadequately designed feedlots from being constructed and operated until more adequate rules are in place. While not the intended purpose of the document, an EIS can serve as an effective guide in crafting rules and permit conditions that meet the EPA's requirements and fulfil the goals of the Clean Water Act. This in effect, would declare a moratorium on large feedlot permits until such time as the rules are deemed adequate to protect the state's water quality.

We request the MPCA respond to this proposition by exploring their own and possibly the Environmental Quality Board's statutes and rules to assure the Agency has the authority and willingness to temporarily hold permits in abeyance for this purpose.

C. Local ordinances and county feedlot officers are ineffective

Here again, we apply this criterion to demonstrate the lack of regulatory authority at the local county or township level to mitigate identified environmental effects not otherwise addressed by state or federal rules. The Izaak Walton League's experience in Becker County and other rural counties has demonstrated local governments reluctance to effectively control water pollution from feedlots through local land use ordinances. In fact, these counties defer to the MPCA on these matters insisting that they control land use conflicts through ordinances, but they do not and will not control water pollution from these activities.

D. Federal Clean Water Act authority remains delegated to the state MPCA

While the EPA did find the MPCA feedlot rules inadequate the federal agency has not revoked the state's authority to continue issuing permits under the existing rules while the state's feedlot rules are undergoing amendments. Thus, citizens cannot depend on the federal government to prevent feedlot pollution.

E. MPCA may be in violation of MEPA which prohibits permitting polluting activity when less polluting alternatives exist

Minnesota Statutes 116D.04 (the Minnesota Environmental Policy Act or MEPA) in Subdivision 6 – Prohibitions states:

> *"No state action significantly affecting the quality of the environment shall be allowed, nor shall any permit for natural resources management and development be granted, where such action or permit has caused or is likely to cause pollution, impairment, or destruction of the air, water, land or other natural resources located within the state, so long as there is a feasible and prudent alternative consistent with the reasonable requirements of the public health, safety, and welfare and the state's paramount concern for the protection of its air, water, land and other natural resources from pollution, impairment, or destruction. Economic considerations alone shall not justify such conduct."*

Given that the EPA has officially notified the MPCA, the petitioners and the public (including Riverview Farms that the agency's feedlot rules are inadequate to protect water quality it is likely that if the agency does proceed to issue a permit for the project it will, in this federal agency's opinion, cause the pollution, impairment or destruction expressly prohibited by this section of MEPA when and if the project is constructed and operated as planned.

We agree with the EPA and also believe that this project will cause or is likely to cause pollution, impairment, or destruction of the air, water, land or other natural resources located within the state and that feasible and prudent alternatives to the issuance of this permitting action by the state exist including the no action (no permit) alternative. And, as MEPA states; any economic hardship such permit denial may inflict on permit applicants shall not be used to justify issuance of a permit for this or other similar projects.

Should the MPCA choose to issue this, or other large animal feedlot permits before it has properly amended its feedlot rules, we assert that such state agency action would be in violation of this prohibition section of MEPA.

In its response to these comments, we request the MPCA address this assertion and explain to us and the public why they should be considered in violation of MEPA in this situation.

F. MPCA fails to extend its authority over pollution caused by manure delivered to other farmers and landowners

MPCA feedlot permit writers and enforcement staff admit they have not attempted to extend permit conditions for land application of manure to secondary users. This means these secondary users have been knowingly allowed complete immune from compliance with the permittees manure management plan. This is an obvious failing of the MPCA's current feedlot rules and permits or the agency's enforcement policy.

The MPCA should not issue feedlot permits or approve manure management plans that allow this loophole that has significant potential for adverse effects on water quality. An EIS may be useful for exploring the jurisdictional options and authority the MPCA has or may need to close this loophole.

G. MPCA has failed to adopt nitrate standards for surface and groundwaters.

The Minnesota legislature granted the MPCA the authority and resources to develop nitrate standards to protect aquatic life uses for the state's surface waters and regulate non-fertilizer sources of nitrates (primarily manure) from large feedlots decades ago but the agency has not completed the necessary rulemaking to implement this authority.

An EIS for this project that calculates nitrate loading to area surface waters (and groundwater) from the project may help underscore the urgency for the agency and the Minnesota Department of Agriculture to complete the rulemaking in effective way to control manure borne nitrates from polluting both surface and groundwaters.

Criterion 4 - Anticipation and control of effects from other studies - The RGU considers if the effects can already be managed through other available environmental studies or previous EISs conducted for the project or area

A. No other EIS has been prepared on a feedlot of this size in the project area or similar setting

This is an important fact and should be considered support for preparing an EIS for this project. The food industry in general has avoided formal environmental scrutiny by local, state or federal governments. Scientific studies of this industry's impacts are widely available in literature, and the impacts are myriad and widespread. We believe the MPCA is capable of a thorough literature search for these studies to corroborate this assertion. But, to assist the agency we've attached a report prepared by the Prairie

Woods Chapter of the Izaak Walton League of America for Becker County's planned update of its comprehensive land use plan as it was dealing with a proposed CAFO in 2024. The report cites a number of environmental impacts identified by scientific studies.

The MPCA would be well justified in selecting this, the largest ever proposed CAFO in the state for the very first EIS.

B. Compliance with TMDL goals for areas surface waters are not acknowledged

C. Other studies have found large feedlots degrade local economies and community health

The following is taken from the abstract of Kelley J. Donham, et al article entitled: "*Community Health and Socioeconomic Issues Surrounding Concentrated Animal Feeding Operations*"[4].

A consensus of the Workgroup on Community and Socioeconomic Issues was that improving and sustaining healthy rural communities depends on integrating socioeconomic development and environmental protection. In workshop sessions the following recommendations were developed:

"Workshop Recommendations

Priority research needs.

Community health studies. *Although sufficient research supports actions to protect rural residents from the negative impacts of CAFOs on community health, additional research could be conducted to further delineate mechanisms of effects and impacts on susceptible subgroups. These areas include psychophysiologic impacts of malodor; impacts of malodor on mental health and quality of life; and respiratory impacts of bioaerosol mixtures, especially among asthmatics, children, and the elderly. Wider and more effective application of community-based participatory research will be important to advance research in these areas.*

Sustainability of livestock production.
Federal funding for agricultural research should be reoriented to promote innovation in sustainable livestock production.

Translation of science to policy.
Requirements for issuing permits for CAFOs should include increased protections for health and the environment including the following:

- **CAFOs should be sited and issued permits on the basis of total animal density allowed in a given watershed as determined by the carrying capacity.**
- **Environmental impact statements should be mandated for all new CAFOs. These should include environmental health, social justice, and socioeconomic issues.**
- **Decisions to issue permits for CAFOs should be considered in public meeting and decided at the local level.**
- **CAFOs should be regulated using standards applied to general industry based on the level of emissions and type of waste handling.**
- **Permits for manure storage basins should require bonding for performance and remediation.**
- **The current state of knowledge of community impacts of CAFOs warrants support for the American Public Health Association recommendation for a moratorium on all new CAFO construction."**

[4] Environmental Health Perspectives • VOLUME 115 | NUMBER 2 | February 2007

D. Economic impacts are not included in EAWs but can be addressed in an EIS

Dr. John Ikerd, who holds a PhD in Agricultural Economics, now retired from University of Missouri-Columbia, in a Freshwater Futures May 15, 2024, webinar presentation entitled "Economic Fallacies of CAFOs", presented the following conclusions from multiple studies:

- **2008 Review: Reams of research dating to the 1940's show local economies suffer economically and socially from industrial agriculture;**
- **2001 Study: Many CAFO counties are forced to raise taxes to offset increased costs of repairs to rural roads and bridges;**
- **2008 Study: Lower income, greater income inequality, more poverty, less active "Main Street", fewer stores, and less retail trade in CAFO counties;**
- **2015 Study: Property values up to 7 miles from CAFO lowered by 3.1% to 26%; properties next to CAFOs down 88%;**
- **2022 Study: Personal incomes dropped 8% from 1982 to 2017 in Iowa counties with most CAFOs. Other rural counties rose 41%**

Dr. Ikerd, in his own paper entitled: Economic Realities of CAFOs[5] draws the same conclusions and more. He includes an extensive list of reference publications that support his findings. Below are some excerpts from that paper on rural community impacts:

> *"Defenders claim that regardless of the need for CAFOs to meet the needs of consumers, CAFOs are necessary for the economic survival of many farming communities. They point specifically to community economic benefits from local investments in CAFOs, local sales of animals and animal products, and local employment in CAFOs and related local industries. However, decades of socioeconomic research and actual experience in CAFO communities reveal something very different. Whatever CAFOs contribute to local tax bases is more than offset by increased costs of maintaining rural roads and bridges that were not built to accommodate the heavy truck traffic associated with CAFOs. Also, local CAFOs operators typically source construction materials and labor from outside their local communities. Feeder animals, feed, and other supplies are shipped in from elsewhere. Even animal health care is typically provided by corporate veterinarians. Few of the economic benefits from CAFOs remain in local communities.*
>
> *The most frequent claim for community benefits is probably that CAFOs will increase local employment, which is sorely needed in many farming communities. However, the economic reality is that CAFOs employ far fewer people per dollar invested or unit of production than do the independent family farms they inevitably displace. The first research I personally did on this subject was an evaluation of CAFOs as a rural economic development strategy. I evaluated the employment implications of PSF's planned operation in north Missouri. My conclusion was that if PSF came into Missouri, their CAFOs would displace up to three independent Missouri hog farmers for every job they created.[26] CAFOs came to Missouri, and Missouri lost more than 90% of its independent hog producers. I doubt that the number of workers employed in CAFOs in Missouri exceeds more than one-third of the independent hog farmers they displaced. In the case of CAFOs, once livestock and*

[5] "Economic Reality of CAFOs and Rural Communities" - Dr. John Ikerd - University of Missouri - Prepared in May 2020 for discussion at screenings of the CAFO documentary film, Right to Harm, and other uses.

poultry production became specialized, previously diversified family farms became specialized producers of either livestock or crops.

Livestock and poultry were major sources of farm income that had made many diversified family farms economically viable. So, farmers who specialized in grain production were forced to farm more acres of land than before to maintain adequate family incomes. Larger crop and livestock operations meant fewer economic opportunities for farmers. With the industrialization of agriculture, the percentage of the U.S. labor force employed in agriculture dropped from 4.4% in 1970 to less than 1.5% in recent years. Even in the communities where they locate, CAFOs do not actually create jobs. They simply relocate and concentrate fewer lower-paying jobs in CAFO communities than had previously existed on family farms elsewhere.

In addition, this loss of farm families cannot be offset by people moving into rural communities from elsewhere. No one really wants to move to a CAFO community. A 2015 study reviewed thousands of assessed property values for residences located up to 7 miles distant from CAFOs. The review concluded: "Overall, the new studies confirm the [negative] valuation impacts reported in earlier studies, as they range from 3.1% to 26% losses depending on multiple factors, and that properties immediately abutting an AO [CAFO] can be diminished as much as 88%."

It takes people, not just production, to support rural communities. It takes people not only to buy farm supplies and equipment but also to shop on Main Street for cars, clothes, shoes, and haircuts. It takes people to send their kids to local schools, to attend local churches, and to serve on volunteer fire departments and local town councils. When independent family farmers are displaced by CAFOs, it's not just a matter of losing employment; it's a matter of losing the essence of what it takes to be a viable rural community."

After detailing our specific comments on the EAW above, it is important that we make some broader statements here about the deficiencies of Minnesota's environmental review process itself. The worksheets used to make preliminary determination on the potential significance of a project's environmental effects have evolved to be so focused on categorical details as to miss the big picture. The public who reads these lengthy EAWs gets lost in minute details and is never informed of the devastating, incrementally small but cumulatively significant destructions of nature that humans have committed.

The ecological setting for this massive, multifaceted food (milk) industry enterprise is one that has, over many decades, been incrementally degraded to such an impoverished level that the beneficial functions (services) original ecosystems once provided have been all but obliterated. These are the very services nature delivers for free that are essential for all life forms including humans. Pure clear air, clean and plentiful water, fish and wildlife once abounded here. Remnants of the tall grass prairie and wetland complex ecosystems that existed prior to its near total conversion to agriculture (dotted by small human communities) remain only in small insignificant patches here and there. This EAW hints at what the area used to be and in subtle ways justifies the projects contribution to the ecological destruction by explaining that the land is now only used for agriculture and therefore there is little measurable impact on the parts which remain in their "natural" state. That is to say that if natural attributes of our property have already been destroyed, our project's further contribution to that destruction can only be described as minimal or insignificant. Our proposed use is consistent with current land use. We find phrases like this used frequently in this and many other EAWs.

If the setting, the natural backdrop of this project was to be fairly described, it would have to disclose the plummeting populations of insects, birds, fish, reptiles, amphibians, fish and macroinvertebrates. It would have to describe soils that are no longer thriving ecosystems teeming with microscopic life forms

important to healthy crops or native prairie. This is known science but this and other EAWs avoid mention of it. Thus, the public largely remains unaware of the apocalyptic declines and a projects likely role in continued declines. Only when a species for which we have some measure of its population trend (which is few) reaches a near extinction level to we call attention to in in EAWs and that is because it is required by law. There is no requirement to acknowledge mass declines on most all other wildlife and plant populations that are rapidly nearing extinction.

It was astonishing but revealing that the project proposer (who we all understand is allowed to draft the EAW) claims that natural vegetation (trees and shrubs) that might provide habitat for birds on or around the area used for confinement buildings would have to be removed in order to prevent the potential for viral infections transmitted by some birds to reach their livestock. When mere vestiges of nature are pronounced a threat to a human enterprise and sanctioned in a government document such an EAW, there is something seriously wrong with the process. It no longer serves the serves the spirit or intent of Minnesota's Environmental Policy Act that authorizes the document.

This is a substantive comment on all EAWs in general, but also on this one in particular. So, we request that the MPCA respond to it in its record of decision.

The scope and scale of the project under review is not fairly represented in the EAW. Riverview Dairy is a very large food industry spread widely across the landscape in Minnesota and other states. The huge dairy operation is but a fraction of the entire corporate food enterprise that, when viewed as a whole, has tremendous potential and real impact. But current rules allow for segmenting incremental steps, whether large or small, into smaller parts.

We realize this may be allowed by current rules but nevertheless, nature responds (the environment is affected) according to natural rather than human law.

Karen Tolkkinen, a newspaper reporter put the subject project in its proper perspective, one not really allowed by environmental review because, as the EAW states below, the specific project is not presented as a phase or "stage" of any past, existing or future project, it's an expansion. And the proposer's existing facilities have already passed environmental muster so its impacts can no longer be counted.

The EAW states:

> "There are no past stages for the Project. The Existing Facility was permitted in August 2003 after undergoing environmental review and receiving a negative declaration on the need for an Environmental Impact Statement (EIS)."

In nature, serial impacts from a series of similar projects (especially large ones) in the same area add up. This by scientific definition is a "cumulative impact". But this is not definition allowed by Minnesota's environmental rules.

> "There are no planned future stages of the Project beyond what is described in this worksheet."

This statement above is also in the EAW and, for the moment it may be true. But do the public and the MPCA really believe that River View Dairy will not continue to expand and add more feedlots and even milk processing factories? EAWs are not allowed to speculate beyond what is not already in formal planning stages.

We refer to a more realistic assessment of the scope and scale of the no-less-than fourteen gigantic subcomponents of the larger project by the same owner. In Tolkkinen's recent Minnesota Star Tribune article she writes, *"the proposed expansion is the latest in a series of large dairies appearing in western Minnesota over the past two decades. Riverview's 13 dairy farms are located in Chippewa, Grant,*

Kandiyohi, Norman, Stevens, Swift, Traverse and Wilkin counties. A 14th in Traverse County, has been approved for 8,571 cows but not yet built."

The article goes on to say: "*The Existing Facility in Stevens County was permitted in August 2003 after undergoing environmental review (EAW) and receiving a negative declaration on the need for an Environmental Impact Statement (EIS). The Existing Facility operates under the NPDES General Feedlot Permit and has undergone the addition of an anaerobic digester (2008), dry manure solids storage (2010), and liquid manure storage (2014). Additionally, the Existing Facility has increased its animal unit capacity three times (2008, 2011, and 2018).*"

Our state government's tolerance (it is not the MPCA alone) for siloing a segment of what is obviously a much larger industrial enterprise, that shelters it from closer environmental scrutiny is a miscarriage of authority and a slow-moving environmental tragedy that is obvious to any student of the science.

It was one of the Izaak Walton League's early members, Aldo Leopold who aptly said:

> *"One of the penalties of an ecological education is that one lives alone in a world of wounds. Much of the damage inflicted on land is quite invisible to laymen. An ecologist must either harden his shell and make believe that the consequences of science are none of his business, or he must be the doctor who sees the marks of death in a community that believes itself well and does not want to be told otherwise."*

It is eminently and very possibly existentially regrettable that even our state agencies who accept and even produce flawed environmental assessments "do not want to be told otherwise".

These comments were prepared by Willis Mattison, professional ecologist, retired MPCA Regional Director now volunteering for the Izaak Walton League of America – Prairie Woods Chapter as chief science advisor. These comments are offered on behalf of the Prairie Woods Chapter with permission.

This concludes with our comments.

Ethan Bruer **Letter 1312**

Hello, my name is Ethan Bruer, I'm a life long resident and 5th generation farmer of Stevens county. Our family farm which started in 1884 is west of west river dairy 4 miles.

I've been reading most of these comments made and I also attended the public meeting in Morris. I'd like to point out a few things from an observation of mine. RiverView had people standing outside the Old No. 1 at 4:45pm for a meeting that was supposed to start at 6pm. Talk about stacking the deck. Lots of people in this community knew this was going to be a large meeting, yet the planned event space was exceptionally small for the masses that wanted to come and voice their views. Unfortunately many people were denied entry due to space. I'd suggest having a second meeting at a larger venue.

That being said, from what I've gathered are, if you're tied to Riverview in any way, employee, shareholder, family or any financial ties you're in favor of the expansion. Which stands to reason. But you need to look beyond on that and think what's good for the environment. Those who weren't, seemed to have genuine questions or concerns about the project. Almost each person who was in favor wrote a sermon on how great RiverView was followed by a softball lob of a question to the MPCA panel to tie it in at the end. Are we playing to emotion or are we going to look at facts, data and research? Data such as wind erosion, water, manure, nitrate runoff, all aspects that impact the environment and those around it.

With that said, I will say Riverview does a nice job keeping their facilities clean and well maintained.

I've debated writing a comment on this as I feel it puts a target on my back being a smaller farm in the area who cannot compete on such a scale as Riverview. We all know smaller farms are going away as years go by. But when that happens you don't have a community anymore. The more people and farms you have in a community the better it thrives. Not less when the "competition" is driven out. As a fifth generation farmer I want to pass this legacy and way of life down to my children. I just hope the resources, (land and water) are here for them and their kids. But with large a scale operation like Riverview it's hard to compete and be optimistic.

I'd suggest there needs to be an EIS done on this project. Something of this scale needs to have every component looked at. Whether it passes or not. There needs to be a standard or precedent for such large projects.

Thank you for you time
Ethan Bruer

Brett Boyum **Letter 1313**

The current EAW process is sufficient and thorough. There is no need for further EIS review.

Kody Livengood **Letter 1314**

I have been a resident in the Morris area for 18 years. After attending the informative and factual meeting that the MPCA hosted in Morris I am in strong support of the West River Dairy Expansion. The EAW is sufficient and there is no reason for an EIS.

Josh VanDerPol **Letter 1315**

I would request that you require an EIS. These Riverview sites are not farm scale, but industrial scale. They need to regulated at the highest possible level to protect our shared environment and water resources. The amount of water pulled from the ground is very concerning for anyone on the same aquifer. The size that they are if something goes wrong with manure application or storage it would be disastrous.

Mike Odello **Letter 1316**

I implore you to require an EIS for this project. This appears to be an unprecedented size of operation in our region. We don’t know what the impacts can be or how far-reaching they may be. Bringing jobs to the area is not a bad thing at all. My concern lays more in how our groundwater and farmland will be impacted. Our agricultural output is staggering in the area. It could be tragic if that is impacted.

Thank you for your time and your concern.

Mike Odello
Morris Area Elementary Music
UMM

Kim Larson **Letter 1317 FP**

This MPCA Animal Feedlot Permit application for an increase of Animal Units (AU's) for Riverview LLP's West River Dairy, should be approved for the follow reasons:

The West River Dairy has demonstrated exemplary history (30 yrs) through the following:

#1, Strong neighbor relations-

Prior to Riverview's initial permit for West River Dairy, they made a point to address their intentions to the neighbors that were in close proximity to the proposed permit area. This discussion was personable and often took place over the neighbor's kitchen table.

#2, Impacted economy in the proposed permit area-

As demonstrated in the initial West River Dairy permit, Riverview makes a concerted effort to incorporate area contractors/suppliers for their construction expertize/materials. Once completed, it is the neighboring farmers that are impacted economically by the opportunities of supplying West River Dairy with higher returns on the diversity of forages needed to feed the animals, as well as the option to receive the natural fertility back to their fields.

#3, West River Dairy holds a "positive file" with the Minnesota Pollution Control Agency-

Riverview maintains a long standing record of working towards positive outcomes in a collaborative effort with MPCA in maintaining our area's environmental quality. The addition of the very large amounts alfalfa acreage in the five-seven mile radius of West River Dairy is an example of the very positive impacts that West River Dairy will continue to provide to the area's environment.

Thank you for the opportunity to provide this feedback,

Kim Larson

Kandiyohi County

Eric Klindt **Letter 1318 FP**

Public Comment for Riverview LLP West River Dairy

Hello I'm Eric Klindt from Campbell MN. I'm also a County Commissioner for Wilkin County.

I'm writing in support of Riverview Dairy. They came to our county in 2018 and have been nothing but great to deal with and work with. They go above and beyond what would be expected of the most state of the art Dairy's. I have seen first hand what they have done for the public and neighbors and they always have done what's right and in my opinion, I think they have done more than they should, but they have a set of ethics that are very high.

We have been waiting for another dairy that Riverview has been planning to build in our county for many years waiting for the permit from the state, I don't think it should take this long.

I'm in support of what Riverview is planning to build, and I don't think there should be any more restrictions for them to build what they already have built across the country. Look at what they have already done, take a tour, I guarantee you will be impressed.

I look forward to them building more in our county or region.

Thank you,

Eric Klindt

Thomas Claussen **Letter 1319 FP**

Riverview should be granted the permit for expansion. Riverview LLP facilities have had a positive impact on agriculture and the community. They provide another outlet for marketing our crops and we are able to utilize the manure as a great sustainable fertilizer for our growing crops. Their employees have children in our school systems and they are involved in volunteering at community and school events.

The sites that Riverview operates are among the cleanest livestock farms that you can find in the country. Having a business in our communities that is willing to invest and grow is a great opportunity that we should not ignore. Their farms have helped increase tax receipts at the local and county level that help government budgets.

Susan Frenzel **Letter 1320 FP**

We are living with global warming which is rapidly making weather events more extreme and more frequent. There will be an increasing number of extreme storm events. We're seeing them already, year round. It is no longer possible to swim in most MN waterways due to blue-green algae caused by feces runoff from MN land. It just takes a few flooding events per year to spread feces into waterways.

How will they keep the water table around the 19,000 cow feedlot free of nitrogen from manure? How will they keep the air clean and fresh for the neighbors? How will they dispose of the manure on an ongoing daily basis that won't burden the county with fecal waste? Can they disperse it beyond the county? Right now more than 5 tons of animal waste is generated for every man, woman and child in the U.S. per Dr. Michael Greger. You don't want that concentrated in one county.

And even though the MPCA's only concern is pollution, the State has a strong health interest in avoiding another pandemic. This is a comment site for the MPCA, so you'll see it as irrelevant that epidemiologists like Dr. Michael Osterholm believe we're due within a few years for a pandemic that could originate in industrial feedlots that could kill 1/3 of mankind. Pathogens swiftly become maximally lethal where animals are packed together skin to skin, according to nutritionist (originally epidemiologist) Dr. Michael Greger. Globally, corporations have copied our megafarm model, so the next pandemic is just as likely to originate overseas as in Minnesota. Wet markets, uber feedlots, endanger mankind to save a few pennies.

And cow milk isn't even that healthy, due to the pregnancy hormones in it. A huge Swedish nutritional study of tens of thousands of people over decades found that people who drank a cup of milk per day die at a higher rate than those who don't.

I've studied comparative religion 63 years, and it turns out 2 Messengers from God arose in Iran 200 years ago, Muslims, who fulfill the prophecies/requirements of the 9 major world religions for the ones who will bring world peace at "the end of time". The prophecies about pandemics that will kill 1/3 of mankind are yet to be fulfilled, even if Christ returned in Iran as a Muslim 200 years ago. MPCA can't prevent the raging pandemics that are coming, but at least you could stop them from starting here.

We're making dairy as cheap as possible through inhumane crowding of animals. Maybe we can make the burying of our children in the next, about 7 times worse than covid, pandemic cheaper by digging mass graves and omitting coffins and just tossing people in.

Until then, and it could be within 5 years, don't let corporations destroy the sweet, fresh air, and clear, clean water for the people who live in this county, because you know there will be extreme weather events thanks to fossil fuel use, and there will be escapes from the well-intentioned lined storage structures, or you wouldn't have inserted the escape clause about extreme weather events in your statement above.

Sue Frenzel **Letter 1321 FP**

1321 FP

But what I have to say shouldn't be muzzled because it applies to the dangers to Minnesotans of animal/poultry factory farm practices. And the MPCA is the government bureau with the oversight to regulate animal and poultry factory farms. So take my comment. And act to protect Minnesotans.

I note that the head of the MPCA when the MN public was just discovering 3M's PFAs pollution came to the MPCA from 3M. So perhaps the current leadership at MPCA is from the corporate animal factory farm sector, and they're in a position to try to hide from us the dangers they actually pose to us.

NYT best-selling nutrition expert, Dr. Michael Greger, started out as an epidemiologist. One of the world's leading epidemiologists is Dr. Michael Osterholm, at the University of Minnesota.

In 2020, Dr. Michael Greger published, "How to Survive a Pandemic," about the next pandemic, possibly as soon as within 5 years, that might be a bird flu pandemic, that he predicted would probably be generated in an animal/poultry factory farm. He went in detail in the book about why viruses and bacteria become extremely lethal when generated in a system where the hosts are packed body to body, in dark, airless enclosures. Yes, dark, airless enclosures, packed body to body, causes weight to be put on fastest for poultry, cutting meat production time in half.

Greger told us calves are weaned on cow blood, which is protein nutritious, rather than on milk, which farmers can sell. Cattle (beef and dairy?) are fed chicken manure, which doesn't affect the taste of the meat of the cattle butchered for meat. Cattle are fed highly subsidized corn and soybeans which causes e coli to be produced in their stomachs, and the e coli endangers the consumer when he eats hamburger.

The reason this is relevant to MPCA, pollution control, is that you are the government bureau that can green light or limit animal and poultry factory farms.

Stink, smell and shit aren't the only things you should be paying attention to. The likelihood of animal factory farms generating pandemics is in your wheelhouse, too, within your responsibity.

Dr. Michael Osterholm published a book in December 2025 called, "The Big One," about the upcoming pandemic which might take 1/3 of mankind's lives.

I couldn't bear to finish Dr. Greger's book or to get past a few chapters of Dr. Osterholm's book.

I advise you to talk with Dr. Michael Greger and to Dr. Michael Osterholm about how animal/poultry factory farms can be modified to minimize their generation of pandemics.

As a living being, I ask you to make the factory farms you regulate act humanely toward their living products.

Thomas Probst **Letter 1322 FP**

As a consumer of dairy products, I urge the MPCA to deny this permit. The proposed size of the project is simply too large, and will have profoundly negative effects on the area's groundwater, air and neighbors, not to mention the animals themselves.

As such, approving it would make a mockery of the stated mission of the MPCA.

Thank you.

Amy Kephart **Letter 1323 FP**

This is a terrible proposal. We need more small farms, family farms, not factory farms. As a consumer of dairy products, I urge the MPCA to deny this permit. The proposed size of the project is simply too large,

and will have profoundly negative effects on the area's groundwater, air and neighbors, not to mention the animals themselves.

As such, approving it would make a mockery of the stated mission of the MPCA.

Thank you

Rita Holland **Letter 1324 FP**

I had no idea that this type of factory farm is being proposed in the Morris MN area until I read the StarTribune article in the April 2nd edition.

Having grown up on a farm in northeast South Dakota, I know the damage that these "farms" inflict on our communities. There are so many environmental, ethical, and economic downsides to this proposal. 26000 cows in a confined area is simply wrong. This is about big ag damaging the prospects for smaller farms all across Minnesota. It's wrong on so many levels.

This needs to be reviewed at the very least, with the possible damage scrutinized at every turn. Stopping it is the very best outcome, and is your responsibility as the MPCA. Please live up to your name.

Heather Rykhus **Letter 1325 FP**

I would not be in favor of granting this proposal. I think the potential for negative impact on the environment is huge with disposal of concentrated manure. I also think the cows deserve more of a real life then being held in a factory farm.

Julia Pearson **Letter 1326 FP**

I am asking that there be a full environmental impact statement for this project. The size/number of cattle will inhibit and hurt smaller, family-owned operations. The water for environment and humans would be impacted. Plus - can't we put risk to people above the profit motive?

Laura Klein

To whom it may concern;

I am writing on behalf of many neighbors, friends, and family that live in Minnesota that strongly oppose factory farming in our state, particularly the expansion of factory farming. I oppose this because it has been shown to have a negative effect on the environment, water, soil, air etc. It puts neighboring Minnesotans at risk for disease and health issues related to the environmental impact. It also is not ethical to put animals in cramped, unsanitary conditions such as those in factory farms. Theres is also a global oversupply of milk right now. Out state doesn't need more factory farm milk, we need small organic farms that care deeply about the land, relationship with the ecosystem, neighbors, animals, and role in the community.

Heidi Hardner **Letter 1328 FP**

I'm concerned about the overall scale and that it's unprecedented in the state. How can we be confident about how the consequences of failure scale with volume at these new levels?

I'm also concerned about the words "except in an extreme storm event" and how different that will look with these huge volumes compared to what might happen at a small family farm.

I see that some commenters are very confident this particular business will do everything right. The permit can say certain things are required but why should we feel confident the operators can really meet those requirements when it's so far beyond what's be done so far? Weren't we just hearing about some insane number of chickens left to starve when a large chicken outfit went out of business? They were probably fulfilling some permitting requirements right up until they weren't around to be held accountable anymore. Their business was probably an economic boon to some farmers and communities right up until it wasn't.

I see that the chickens (1.6 million!) were not actually all in one location. Well, thank goodness for that! This kind of concentration means all the local environmental consequence eggs are in one basket. I see the words "permanent stockpiles" above there too... uh, there was nothing permanent about the chicken business and presumably these will be the largest ever permanent manure stockpiles in the state?

My understanding is the decision being made currently is just about whether there should be a more detailed environmental assessment.

Yes, yes there should. What would merit such a review if not a huge increase in scale like this? If this kind of increased concentration is actually a good idea, it will pass such a review.

Thomas Kalahar **Letter 1329 FP**

This is insane. As a former feedlot inspector for Renville Co. I find this a major threat to our water supply both surface and groundwater. Our surface and groundwater in the agricultural regions of the state are already badly degraded by the Ag industry. To add yet another threat is MPCA not doing their job to protect the citizens. All the water in this region is already degraded/impaired due to lack of regulation and influence by big Ag. For once due your job and defend the citizens and not corporate agricultural.

Kevin Van Winkle **Letter 1330 FP**

I am writing this letter from the perspective of a fellow Dairyman and grain farmer.

#1. Nutrient management, River View Farms are built with some of the highest standards i have seen, covered storage ponds to help mitigate odor, when you drive onto a Riverview Farm you do not get the odor of a livestock facility the only thing I smell is fresh feed being delivered to animals. They also catch all rain water from the facilities which is stored in fresh water ponds. All nutrients are injected into the soil which is used for crop production and replaces the use of commercial fertilizers that are spread on top of the ground. Also crops grown with animal waste tend to yield more per acre than commercial fertilizer which is better for the environment. So less commercial fertilizer means less petroleum used to produce that fertilizer which is better for the environment.

#2. Creating a market for locally grown feed. The corn and soybeans that are grown on Farmland in the United States are used for feed for animals or made into ethanol to replace gasoline as far as soybeans go they are crushed and processed into vegetable oil for humans and the byproduct is soybean meal which is used for animal feed. We do not use all the corn and soybeans that are produced in the United States, about 15 percent of the corn crop is exported and around 45 percent of the soybean crop is exported. So if a livestock facility is built in any given part of the US it creates a new local market for grain. This creates competition for that grain which leads to a better price for neighbors in the area that produce the grain. Also it means less transportation of grain around the world which uses less petroleum which is better for the environment.

#3. Food security for the US. As for most Americans we do not ever think about running out of food because US farmers are great at producing it efficiently and with environmental stewardship as a high priority. We as farmers love our animals and we love our land, we have a personal connection to them and will do anything to take care of them. I know River View has the same philosophy when it comes to their animals and the environment. Dairy Farming is very hard work and requires a special set of work ethics and commitment, with that said there is fewer and fewer of us out here willing to do this. So with fewer of us willing to tackle this type of lifestyle it requires a somewhat larger scale farm to supply high quality food for our fellow Americans. So if we do not allow some new facilities to be built to replace the dairy farmers that are retiring around the US we will eventually have a problem with food security.

Bob Lefebvre **Letter 1331 FP**

I have had the fortune of working with dairy farmers across the Country. The people at Riverview from top to bottom are the best in the industry. Care, integrity and innovation are words that describe the culture. Every person is passionate about producing wholesome food by caring for the animals, environment and their fellow peers. The same care and innovation goes into the planning of their facilities. And, they have an impeccable decades long track record.

The design and planning of the expansion exceeds standards. We also know from experience that the building and operation of the facility will also exceed standards. I urge MPCA to move forward expeditiously.

Francis Casey **Letter 1332 FP**

I've toured Riverview facilities and am amazed at the strong environmental stewardship from water protection to nutrient management plans. I'm a soil scientist and know the value of manure and the organic matter it adds to soil to build nutrition and soil health. The animals are very well treated, extremely healthy and happy. There are veterinarians and highly skilled workers taking care of the animals all day. The facilities were also very clean and in the heart of the operations there was no bad odors. This business cares for the community and as industry and revenue to the state.

Darlene Aragon **Letter 1333 FP**

Confining close to 19,000 cows in one site is incomprehensible to me. Sprawling industrial facilities like this jeopardize our natural resources, animal welfare, and public health. Facilities like this keep their cows pregnant for six years and then slaughter them when they've become no longer useful. This is just another way of destroying small dairies that lovingly take care of their animals and strive to proudly produce dairy products that are healthy and unique.

Ferolyn Angell **Letter 1334 FP**

Please conduct the essential Environmental Impact Study that clearly should be done for a project of this magnitude. As a citizen of Stevens County I am deeply concerned about potential further depletion and pollution of our regional water resources. I oppose the project in general and believe that the EIS will show that this is not a sustainable or viable project.

As the wife of someone who has worked in the farm fields of this region I find it alarming to see the degradation of the land here by family corporations that put profit before environmental protection. We already know that Riverview Dairy's operations in other parts of the country have caused serious problems for people in the communities that surround their dairies. Please require Riverview to prove that they can protect the people and environment of this region.

Thank you for doing the job of protecting the residents of Minnesota!

Marv Post **Letter 1335 FP**

Dear Commissioner Kessler and MPCA Staff,

My name is Marv Post. I am a dairy farmer from Volga, South Dakota, and former chairman of the South Dakota Dairy Producers Association. I am writing to express my strong support for Riverview LLP's proposed expansion of West River Dairy near Morris, Minnesota.

I have spent my career working alongside producers, processors, and policymakers to grow South Dakota's dairy industry, and I have seen firsthand what a growing dairy herd can do for a state, for an industry, and for the rural communities that depend on both.

What a Growing Dairy Herd Has Meant for South Dakota In the early 2000s, South Dakota had fewer than 80,000 dairy cows. Today that number is more than two and a half times that. That growth happened because producers, processors, and state leaders recognized that a growing milk supply is the engine that drives the entire dairy economy.

Every time we expand processing, we expand milk production. With our ability to grow corn, alfalfa, and all the raw ingredients needed to feed a dairy cow, the Upper Midwest is simply a very efficient place to do that.

In South Dakota, it's safe to say that our dairy infrastructure has come back. We would not have the infrastructure that supports dairy farmers of all sizes without a thriving dairy industry. We would not have processors who look at our state and say, "If we build it, they will fill it." That infrastructure — processing plants, trucking routes, feed suppliers, veterinary clinics, equipment dealers — exists because there is a growing, reliable milk supply to sustain it. And when that supply grows, every dairy farmer benefits, whether they milk 100 cows or 10,000.

The benefits extend to crop farmers too. Dairy manure has proven to be a valuable source of locally sourced fertilizer, and we have seen the basis for cash grain improve in recent years because of the demand for feed crops from dairy farms. Milk processing capacity has grown dramatically up and down South Dakota's I-29 corridor. These represent real plants, real jobs, and real communities that are stronger because of a growing dairy industry.

North Dakota's Dairy Industry

Next door, North Dakota experienced the opposite outcome. As cow numbers declined and milk supply dwindled, processors lost the volume they needed to justify their operations. When processors close, remaining farmers lose their market, which accelerates the decline further. Today, North Dakota is home to just 17 dairy farms with approximately 8,000 cows. I would not wish that outcome on any state.

The Upper Midwest is positioned to be a global leader in the dairy industry, but only if we encourage and allow our farmers to grow.

Environmental Stewardship Goes Hand in Hand with Growth

This project has undergone a detailed analysis through Minnesota's EAW process. The expansion will operate under an Individual NPDES Feedlot Permit requiring zero discharge of pollutants to waters of the state. Responsible manure management is well known to improve soil health and reduce the potential for nutrient runoff from croplands. The water supply appears to be robust and more than sufficient to sustainably supply the West River Dairy expansion. It appears that the applicant and the agency have considered and addressed all of the relevant areas of environmental protection.

Furthermore, the development of the Individual Permit demonstrates real leadership on the part of both the MPCA and Riverview, and a commitment by all parties involved to pursue growth in a responsible manner.

Conclusion

We want our neighbors in Minnesota to share in the optimism and success that a growing dairy industry has brought to South Dakota. The West River Dairy expansion is exactly the kind of project that makes that possible.

I respectfully urge the MPCA to follow the facts and the science in its review of this project. The environmental review is thorough. The regulatory safeguards are robust. This project deserves to move forward so that our industry can continue to grow in the Upper Midwest — responsibly, sustainably, and in a way that benefits producers, processors, communities, and the environment alike.

Thank you for the opportunity to provide this comment.

Marv Post

Kristine Hamm **Letter 1336 FP**

This feedlot proposal is too large. I have no faith any corporate farm will abide by current regulations nor will they care for the animals. This type of gigantic farm is bad for family farms and our environment. Our history of family farms is too important to ignore and allow big business have their way.

Robert Finley **Letter 1337 FP**

A project of this nature absolutely requires an Environmental Impact Statement (EIS). Not requiring one makes a mockery of all that has been done previously to protect our land and water resources from degradation.

Jeanne Norrgard **Letter 1338 FP**

I am writing to you at the MPCA as a concerned Minnesotan, born and raised in the land of 10,000 lakes, and proud of our environmental advocacy. I love our state and I am certain that you do, too. My public comment to all of you at the MPCA is this: As the Minnesota POLLUTION CONTROL Agency, caps added by me, if you don't outright deny Riverview LLP's expansion proposal, which I truly believe is the only environmentally responsible decision to make for our state, then the only alternate and responsible environmental decision left for you to make is for you to request an Environmental Impact Statement. Please, and I know I speak for countless thousands of your fellow Minnesotans, do the job that you are all there to do. This potential dairy feedlot expansion permit request is horrific for our state in so many ways, including for our lands, our waters, our air and our public health. Requiring an EIS would require Riverview LLP to justify and to prove to you and to all Minnesotans that increasing their feedlot capacity to a maximum total of 26,397 AU, ANIMAL UNITS (read living, breathing, suffering, milk-producing cows kept in close proximity in total confinement barns) while inconceivable to me, is environmentally sound; that spreading an unimaginable volume of manure onto our lands isn't a dire contamination threat to our lands, our waters, our wildlife, our air quality, our public health; that there is no risk of inadvertent manure spills onto our lands and into our groundwater, streams and lakes; that closely confining many thousands of animals for the entirety of their lives presents no risks of illness and disease to be spread amongst them or to their caregivers; that a mass casualty event such as mass illness requiring euthanasia has been contemplated, planned for and mitigated; that the environmental disaster implied by the ominous words "except in an extreme storm event" has also been planned for and mitigated;

...and I wish I knew the other environmental risks there are that I would cite today if I knew them. Instead, I must trust that you at MPCA know what these additional environmental risks are and that, with an EIS, you will hold Riverview LLP accountable to the highest standards of environmental protection that our state and we Minnesotans expect and deserve. We Minnesotans and our beautiful state are worth protecting. Thank you.

Shannon Nieland **Letter 1339 FP**

I hope that the MPCA recognizes Riverview's long history of doing right by the communities it's established in. Not only do they invest into communities through their support of agriculture education, community events, sports and employment, they also build operations that are sustainable. When it comes to pollution and manure seepage, I have seen no evidence of any case of water contamination at previous sites, and I would encourage the MPCA to examine their track record.

Many of the towns in West Central Minnesota are dead or dying, with little to no growth in businesses or recreation. In contrast, our community in Morris is growing and thriving—in large part due to companies like Riverview investing into it and supporting communities and families like mine.

Patricia Cole **Letter 1340 FP**

To Whom it May Concern,

I am writing to formally express my strong opposition to the proposed expansion of the Riverview dairy operation in Morris, Minnesota. As a concerned citizen who worked for over 40 years as a Registered Professional Engineer, I believe this project—which would become the largest livestock farm in state history—poses unacceptable risks to our local environment, our groundwater and the health of our community.

My primary concerns include:

Water Depletion: The facility is permitted to pump up to 226 million gallons of water per year. This massive appropriation rivals the consumption of the entire City of Morris (permitted for 300 million gallons) and threatens to deplete local groundwater and impact the Pomme de Terre River.

Nitrate Pollution: The collection and application of manure from such a massive number of animals significantly increases the risk of nitrates leaking into groundwater. Given Riverview's history of manure spills in western Minnesota, I am deeply concerned about the long-term safety of our drinking water, and the impact that will have on the cancer rates of those living in the area.

Inadequate Environmental Review: I join organizations like the Land Stewardship Project in calling for a full Environmental Impact Statement (EIS). The current Environmental Assessment Worksheet (EAW) is insufficient to address the unprecedented scale of this facility and its cumulative impacts on the region's land and water.

I urge the MPCA to deny the current permit and require a more rigorous environmental review to protect the health and resources of Stevens County residents. The impact of these large scale corporate farms and livestock enclosures on the health of our groundwater aquifers needs to be of concern to ALL Minnesotans.

Sincerely,

Patricia Cole

Jacqueline Colby **Letter 1341 FP**

Because of the environmental harm and increased animal suffering these large factory farms cause, I am adamantly against allowing these permits.

TJ Hennen **Letter 1342 FP**

I have lived with in 5 miles of the proposed expansion for most of my life. I am not concerned about Riverview as a company itself. I think that they a great asset to our community. However, I am concerned about is the true environmental impact of the proposed expansion. I believe that a full Environmental Impact Statement should be done prior to the expansion. Also, I have noticed that our water quality has gone down in past 15 years. What happens when our well goes dry? Who will pay for that?

Audrey Arner **Letter 1343 FP**

I am writing to formally request that the MPCA mandate a full Environmental Impact Statement (EIS) for the proposed West River Dairy expansion. As the largest livestock operation in Minnesota's history, the cumulative environmental risks—specifically regarding Contaminants of Emerging Concern (CECs)—far exceed the scope of the current Environmental Assessment Worksheet (EAW).

The Minnesota Department of Health (MDH) and the MPCA classify hormones as CECs. MDH data indicates that these substances already affect 90% of tested Minnesota lakes, and a U.S. Geological Survey study found the Mississippi River in Minnesota has the highest rate of "feminized" fish--male fish that develop female characteristics, such as eggs in their testes. The cause is attributed to endocrine-disrupting chemicals (EDCs) that act as estrogens, causing sexual disruption.

The scale of the West River Dairy expansion poses the following significant risks:

- Hormone Output: Pregnant and lactating cows produce large amounts of estrogen and related hormones. An 18,000-cow herd produces approximately 15 pounds of estrogen daily. Hormones are potent in very small concentrations. In addition, large dairies routinely use synthetic hormones to maximize lactation and control the cows' reproductive cycles, which further increases this biological load.

- Environmental Persistence: Estrogens in dairy wastewater are notably persistent and often fail to biodegrade under the anaerobic conditions found in manure storage lagoons.

- Public Health Implications: These hormones bioaccumulate in the food chain. Human exposure through contaminated drinking water is linked to impaired fertility, developmental malformations, and hormone-sensitive cancers.

- Private Wells: Rural residents relying on private wells are particularly vulnerable. No one monitors our wells for safety, so the full financial and health burden of testing and harm falls directly on us. Most municipal systems are incapable of filtering out these contaminants, so well owners are particularly disadvantaged by lack of regulatory oversight to keep our water safe. We deserve better. Our state prides itself on its water, pure water at that. If our water is no longer drinkable because others have profited from making it so, regulation and justice must prevail.

Having grown up along Shakopee Creek in the adjacent watershed to the proposed expansion, I have witnessed the degradation of local watersheds firsthand; the Shakopee is now a designated critical nutrient hotspot. Nearby is Dublin Dairy, one of Riverview LLP's 8000 cow dairies. Do we have CEC data for Shakopee Creek? A blueprint for protecting our water and preventing contamination may become apparent if we choose to look. Perhaps we have hardly begun to accurately assess the environmental

impact of dairies of this size, placing them ahead of CEC data collection and the safety of our drinking water.

If this expansion is green-lighted, hormones and endocrine disruptors will enter our water system at an unprecedented scale, affecting us all. Along with raising already elevated levels of nitrogen, phosphorus, and E. coli, the West River Dairy expansion represents a permanent threat to regional water security. I urge the MPCA to require a comprehensive EIS to study these cumulative impacts.

Rose and Dan Murphy — Letter 1344 FP

We have the following concerns regarding Riverview's proposed expansion

-an Environmental Impact review of industrial measures must be done

-impact of local water supply—future water supply, safety of water available, especially long term (we are aware of the issues created by Riverview in AZ)

-expansion will likely be a boost to the local economy, but consider how many small dairy farms have been/will be forced to sell out having a negative impact on the local economy

Kim Larson — Letter 1345 FP

ATTN: Charles Peterson

My name is Kim Larson and I am a farmer in Kandiyohi County, MN. My full background is not only an agricultural producer but the experience as an agricultural regulator, as well. In the early 2000's I was selected to develop, and carry out the duties as the initial Delegated Feedlot Officer for Kandiyohi County. Over the three years that I devoted to the position, I developed a unique perspective of both sides of the process, and I believe that experience benefits my assessments in this discussion.

In preparation, I committed myself to reviewing the entire Environmental Assessment Worksheet (EAW). Beyond the 72 pages posted online, are the 26 categories of Attachments totaling hundreds of pages.

Associated Agency Reviews Confirm No Significant Concerns

The State Historic Preservation Office found no properties listed on the National or State Registers and no known archaeological resources that would be affected by this project. The DNR Natural Heritage Review found no ecologically significant areas along with no State-listed endangered or threatened species on the project site. The review within the route of the water pipeline returned with *"No Further Review Required"* across all categories. In response to Agency comments from MPCA and the State Archaeologist, Riverview voluntarily removed certain manure application fields from the manure plan, demonstrating responsiveness.

Water Utilization

The EAW is explicit in backgrounding the fact that the well that will supply the West River expansion originally received permitting for 452 million gal/yr. Riverview is reducing that initially granted appropriation to 226 million gal/yr. It would be hard to ignore the extraordinary effort that Riverview put forth in being creative enough through this expansion to significantly reduce the total permitted water appropriation capacity in this aquifer. If a 452 million gal/yr appropriation was initially found to be sustainable in this location, an appropriation of half that amount cannot logically constitute a significant environmental impact, especially considering the on-going regulatory measures incorporated into the DNR's permit.

DNR Comment Letter (March 17, 2026) Inaccuracies

It is puzzling to understand the DNR's statements that the EAW had not considered any impacts on the Pomme de Terre River. EAW Section 12.B.3 (pg 34-37) specifically discusses impacts to the Pomme de Terre, including detailed pumping restrictions based on stream flows (Tables 16 & 17). Included under Section 12.B.g.4 includes multiple points addressing pumping restrictions applied to avoid indirect impacts. The letter further indicates that groundwater is *"limited"* in the project area. However, this would be in conflict with their previously detailed review of the aquifer in this location where the DNR found water usage, twice the currently proposed appropriation, to be fully sustainable.

EAW is Comprehensive and Complete

This EAW is far beyond a typical livestock EAW review. As I pointed out initially, there are literally several hundred pages of technical analysis covering ground water, surface water, air quality, natural resources, and cumulative effects. Under Minnesota law, an EAW is intended to be a *"brief document"* designed to set out *"basic facts"* about a project. I believe that it is self-evident that this EAW published by MPCA, greatly exceeds that standard in advance, as it appears that the MPCA has already produced an EIS level of information with respect to this project.

Furthermore, under Minnesota law (Minn. R. 4410), an EIS is required only when there is potential for *"significant environmental effects".* It does not reference any prerequisite for an EIS determined on the basis of an animal unit (A.U.) threshold. As Minnesota AgriGrowth noted in their comments, the purpose of an EIS is to assess environmental impacts, not create public policy on the appropriate size of dairy farms in Minnesota, as that should obviously remain with the representation of elected legislators.

Finally, under Minnesota Rules, an RGU must consider *"the extent to which the environmental effects are subject to mitigation by the ongoing public regulatory authority."* Within this EAW, multiple layers of ongoing regulatory …. DNR water appropriation permitting, MPCA individual feedlot permitting, and NPDES zero-discharge requirements …. all serve as specific, targeted mitigation measures that Minnesota courts have recognized as sufficient enough to validate the findings for potential environmental effects.

Consideration of an Individual Permit

The development of an individual permit for this project further shows that the Agency has all of the protections and tools in place to ensure this project is fully protective of the environment, and that no potential for significant environmental effects could be found. As a former County Feedlot Officer, I recall the numerous times in our County's permitting process that when a specific item of concern was identified, we did our best to prevent *"regulation overreach"* by targeting those items with *focused mitigating conditions* that would provide the *specific protection* that is sought.

Conclusion

Upon thorough review, I would encourage a decision by the agencies involved to approve the West River Dairy expansion. With the rigorous safeguards for environmental security well documented in this EAW, the request for an EIS would be considered overreach. And finally, it would be regrettably unfortunate if the process of environmental review for livestock proposals morphed into …. *an act of prohibition.*

Respectfully,
Kim Larson

Diane Baum

I am against this for reasons including concern about groundwater contamination, as well as sustainability of the Pomme de Terre aquifer to provide watwer to not only this endeavor, but to continue to have water available for other businesses, residents and farmers in our community. Based on the performance of the Sulphur Valley, AZ operation, I have serious doubts about the trustworthiness of this project here in Morris.

Kevin Meixel

We here at Meixel Farms, and Meixel Truck sales support the west river dairy expansion. They always have practical logistics planning, and clear milestones to help scale production smoothly. We enjoy doing business with them because of their commitment to quality, transparency, and collaboration—the kind of partnership that values open communication and mutual success. Their expansion creates many local jobs, from farming and harvesting to processing, packaging, and distribution, which strengthens the local economy and builds a more resilient community. By investing in local talent and infrastructure, they not only boost employment but also foster entrepreneurial spirit, support small businesses, and contribute to steady, inclusive growth that benefits families and neighborhoods alike.

It's important for those who oppose the dairy expansion to consider the broader implications of their stance. By resisting this growth, they may be overlooking the significant benefits it can bring to the local community and economy. The expansion is not just about increased production; it represents a vision for the future, one that fosters job creation and stimulates local businesses. Without embracing such opportunities, there is a risk of stagnation, both economically and socially. It's essential to look beyond immediate concerns and recognize that progress often requires bold steps forward. Engaging with the expansion can provide a pathway to innovation, sustainability, and a thriving community that benefits everyone in the long run.

Nancy Thorson **Letter 1348 FP**

I think allowing Riverview LLP to expand their operations in Morris would be a big mistake, knowing of their previous manure spills in the state.

Blake Criswell **Letter 1349 FP**

ATTN: Charles Peterson

My name is Blake L. Criswell, CFS, and I am the owner and consultant of GotWhey, LLC, a Minnesota registered LLC, consulting to dairy manufacturing plants across the United State and in Minnesota like Riverview. I am writing in full support of their proposed West River Dairy expansion in Stevens County.

Through my work in the dairy manufacturing industry, responsible, strong, and stable milk production is key to maintaining a high-quality supply of milk in the region.

The proposed expansion represents a meaningful economic benefit to the region. It will generate demand for local vendors, support both construction and long-term employment, and contribute to the vitality of rural communities that rely on agriculture.

From my direct experience, Riverview is a professional and reliable partner that contributes positively to the communities where it operates. Their presence strengthens the local economy and supports a broad network of agricultural and service-related businesses.

Projects like this are essential to maintaining a competitive and sustainable rural economy in Minnesota. Continued investment in agriculture ensures that local businesses can continue to provide jobs, services, and economic stability close to home.

No EIS is needed as the state environmental review process is rigorous and very sufficient. I respectfully encourage your support and approval of this important project.

Sincerely,
Blake L. Criswell, CFS
Shorewood, MN

Lynnette Kayser **Letter 1350 FP**

The environmental impact to the community will be devastating. Air and water quality will be affected in a very bad way!

Mitchell DeBuhr **Letter 1351 FP**

Living close to the dairy, I am concerned about the water input this dairy will require. I am also concerned with water quality. I have a family and livestock living off well water. Loosing that resource would be catastrophic. I have concern regarding local traffic and wildlife impact. Many times trucks running to the dairy disregard traffic laws and don't share road space safely when we are working in ditches. Lastly with the need for land and the ability for them to pay large prices, it affects local families being able to afford land as prices are driven up.

Tracey Eliason **Letter 1352 FP**

I can't believe this is being considered. The increase to this facility will cause well water contamination that down the road could in put local water tables and personal wells at stake. The other side of this debate is manure storage. This may sound good but it all has to be disposed of and that much manure will have to impact the water supply in the future. What will be the options then? I grew up in Hancock 9 miles from Morris and some days the smell was bad, I can only imagine by increasing the dairy to this extremely large size will make living in the surrounding area unbearable.

Brady Koehl **Letter 1353 FP**

Dear Community Members,

First off, I wanted to introduce myself. My name is Brady Koehl, & I have now lived in Stevens County for 32 years & counting (with a brief hiatus to attend college in Marshall, MN). I am a resident of Hancock, MN – I am a father, husband, farmer, accountant, city council member, & community volunteer. This isn’t really my cup of tea to make a public comment, but the more I thought about it, the more I thought there were some things I needed to say on this matter.

I do want to start off by saying, I understand & acknowledge the environmental concerns. As farmers in greater MN, this is something that we are conscious of every day. As everything scales, & the size of the equipment, livestock herds, & everything in between grows larger – this can seem very intimidating & can be perceived in a negative way by many. I am here to tell you we are hyper aware of this. However, I take comfort in knowing that an operation like Riverview has already done more than their share of due diligence on a project of this nature, including the necessary research in the background, permitting, etc. to make sure that this is done in the correct way. This type of operation already operates under strict regulatory oversight, & the systems are in place to meet MPCA requirements.

Further, I wanted to dig a little bit into some of the specific concerns. I have heard comments about the size of the dairy, & the emissions from the animals., etc. Keep in mind – this dairy will be large, but half of the dairy is already in existence! Yes, the dairy that will be operating after the expansion will be the largest in MN. But it is not all new construction – half is already operating smoothly today. On top of this, I would encourage you to explore some of the positive things that Riverview is already doing to offset many of these concerns. From ensuring the operation is energy efficient as possible – this is something that is done in the name of cost – to capturing the methane gas & re-purposing this in an environmentally friendly way, the operation is only helped by reducing these things.

I have also heard concerns with the manure that will be a biproduct of this increased herd. As a farmer that has used this bi-product, the misconceptions of this being a negative for the land & water are often mis-cast. Regardless of the form, farmers need fertilizer as part of their crop plan. The larger percentage that comes from organic matter sources, the more positive of an impact there is the potential for on the land. Also – as a farmer that is in the business of organic production, this manure becomes a necessity & helps drive the growth in that area of our business.

Finally, the water. This is a concern, & I know this is something that has been seen around the nation. However, in a highly rural area like Stevens County, the water issues that are often tied to overuse or strain on local water systems in more densely populated or drought-prone areas have not come to light. As we become more efficient with our water use, more intentional with our practices, & are conscious of the numerous issues with water around the nation, & around the world – this is being considered, measured, studied, & remedied wherever possible. On top of this – Riverview has a plan in place to re-use much of the water that is in the end-product that is a key cog of this expansion plan. I would encourage you to ask their representatives about this, as it is a very cool concept.

Finally, to anyone reading this that is not familiar with Stevens County, I would encourage you to come & pay us a visit. This area is special & is uniquely positioned to pursue this kind of opportunity. We tend to join as one in support of projects of this nature, & we recognize the many benefits that Riverview has brought to our community, our families, & to the many individuals that are involved with the economics of the area. On top of that, on the drive west past the existing west-river dairy, I am reminded of the beauty of the countryside that we are lucky enough to live in. When you drive past, yes, you will note the operation. But I would encourage you to reach out & ask for a tour & explore more before you develop an opinion. If you would like to talk about this – feel free to reach out to me – I am happy to discuss both sides of the arguments for & against this expansion. I am always open to more information.

Sincerely,
Brady Koehl

Steve Olinger **Letter 1354 FP**

This expansion is very troubling. concerns with the amount of manure, amount of water. Very concerning what this expansion will have on the sites dairy farmers who already have been under extreme pressure. Why cn be done with the manure, can it really be used for fertilizer without increasing Athene risk of nitrate pollution?

Douglas Lande **Letter 1355 FP**

Requiring a full environmental impact assessment in this case should be required. A large CFO that degrades soil and water and air should not be allowed in a State that says it stands for a healthy environment.

Francisco Guadarrama Capitaine **Letter 1356 FP**

I support West River Dairy Expansion and Feedlot Permit

No EIS required. Have a great day

Thank you!

Rebeca Ramos **Letter 1357 FP**

I support West river expansión, no EIS required

Diane Baum **Letter 1358 FP**

This is a revised comment from my previous one. I attended the MPCA meeting April 28. After seeing so many in the crowd who are a part of Riverview dairy, I have come to the conclusion that the dairy itself stacked the meeting and dominated the discussion, to the detriment of those who also wanted to participate- space was limited and many were turned away. I still have very valid concerns regarding the proximity of this operation to the Pomme de Terre River, which is already stressed out due to farm fertilizer runoff. I am concerned about the contaminants already in that river that, although they meet EPA guidelines, as was mentioned last night, those guidelines are out of date in regards to the current health concerns this river poses. The potential for an accidental leak at Riverview makes this a very tenous situation. To make a leap from 8,000 to 20,000 animals without regard for potential hazards is foolish at best. Riverview has already experienced a manure leak at its Murdock facility, why is this risk being allowed here in Morris? I urge you all to fully consider the repercussions of this and make a decision that will benefit ALL residents of Stevens County and Morris, not JUST those who will benfit financially. Thank you.

Todd Charnetzki **Letter 1359 FP**

Having worked with Riverview LLC for many years, I would support this project. The are wonderful stewards of the land, cows, and environment they control. They actually help their neighbors do better through example and open communication.

Samantha Kramer **Letter 1360 FP**

I fully support the project and appreciate the work Riverview has done to ensure the safety of the community and stewardship of the animals.

Jerry Seibel **Letter 1361 FP**

I attended the recent public hearing on the West River expansion permit and would like to submit the following public comment. At the outset, I should note that many of the comments at the hearing, although perhaps scripted, seem to accurately reflect the fact that Riverview is very generous and appears to be a good neighbor. While these are laudable attributes, it appears that they may not be very relevant to the environmental review that your permitting process contemplates.

It is my understanding that the proposed expansion would result in an approximate 200% increase in animal units at this one location. I may not be reading it correctly but it appears that there might be an allowable increase of up to 26000 animal units, which would be over a 300% increase. In either case, it would result in the largest feedlot in one location in Minnesota if not the country. It appears as if the proposal, from an environmental standpoint, is going where no man has gone before.

The thrust of my comment is that there needs to be a focus on the cumulative environmental effect of this proposal upon the entire geographic area. Although the proposed expansion is the largest feedlot in the geographic area, it is not the only feedlot in the area. Whether these are dairy, pig or cattle feedlots, they all have a potential environmental effect upon the air, soil and water. Additionally, these feedlots are not the only users of these resources. Area farms not associated with West River also apply either manure or fertilizer to virtually every field that is farmed in the area. Although this is anecdotal and not necessarily accurate, it appears that irrigation of cropland in the area has increased, placing a further strain on water resources. It seems incongruous that the cumulative effect of the largest feedlot expansion in the state, if not the nation, should not be more fully explored through utilization of an EIS or conditions on the permit approval mandating graduated expansion with follow up mandatory environmental assessment of the whole area.

I am fully aware that additional delay could have some economic impact upon Riverview. So would an environmental disaster. From the presentation at the public meeting, I am aware that the proposed application includes certain provisions designed to mitigate negative environmental impacts of the feedlot. I am not knowledgeable as to whether the mitigation efforts are state of the art, but I am assuming they probably are. However, state of the art does not equate to absolute certainty. Mistakes or failures still happen. Once a negative impact happens, you cannot put the toothpaste back in the tube or the poop back in the cows. I can't believe that the policy of the state of Minnesota is going to permit the largest feedlot expansion in a single geographic area without more fully exploring the already existing environmental condition of the area. I am not sufficiently knowledgeable whether it is more environmentally friendly to concentrate large feedlots in a single geographic area or to spread them out through the state, but I assume that MPCA staff has such requisite knowledge.

Thank you for the opportunity to comment and for your thoughtful approach to this issue.

Dick Cheney **Letter 1362 FP**

I fully support the expansion of this facility. I believe in a free market, and it is my belief that this riverview expansion satisfies the requirements of the State pursuant to the clean water act. I believe what river view has done and is doing to advance industry within the State is advantageous to the citizens of the State. I have toured river view facilities in the past. I have never observed anything that would have struck me as deprecative to the resources of the State. I believe in a robust economy, and one of the land uses that fuels that economy in the state of Minnesota is production of commodities like livestock and grains. Minnesota is very protective of its resources via its regulatory environment, any entity that can navigate those regulations is in it for the long haul. I believe river view has and will continue to stand the test of time. I also believe the agents of the state have provided and will continue to provide the most accurate information regarding expansions like river view. The public is stupid and reacts on emotions. I don't believe a company willing to put up funding will jeopardize that by overlooking issues the agents of the state have. I love you.

Lilia Mendoza Acosta **Letter 1363 FP**

I think it is an opportunity for more jobs.

It has given my family and me hope; thanks to the employment it provides, we are able to give our children a better future. Like any job, it is demanding and time-consuming, but it is our duty as parents to build a good future for our children.

Michael Smith **Letter 1364 FP**

The proposed Riverview expansion in Stevens County poses significant environmental and economic harm to the county, it's water supply, it's environment, it's economy and it's citizens. The water sources and related ecosystems are fragile already, and this unprecedented expansion threatens the short and long term sustainability of these systems. In addition, small family farms and county residents face economic threats from mega corporate farm operations, negative impacts on water, land and other environmental and economic resources critical to remaining in business and loss of future viability. At the very least, we urge MPCA to require an extensive Environmental Impact Study prior to any consideration of an expansion request of this magnitude.

Hunter Bohn **Letter 1365 FP**

As a resident of Morris and a person who loves to utilize outdoor public spaces for recreation activities, I am concerned by the amount of waste this change would produce. The nutrient load from manure on the lands surrounding the facility will likely be disproportionate, with closer locations receiving more inputs than locations farther away, as a function of transport cost and equipment abilities. I am concerned that public water bodies will be impacted, affecting fishing, boating, and wildlife observation opportunities in the vicinity. Many of the lakes in the area are already known to be relatively shallow, and green algae (cyanobacteria) blooms are often encountered in the summer months. These blooms are detrimental to fish health and to the health of birds that use these lakes for breeding and migration sites. The health of humans and pets can also be affected by these blooms, if severe enough. Adding more nutrients to the landscape with increased manure supplies under this proposal will negatively affect the surrounding waterways and the wildlife and people that utilize them for survival and leisure.

Federico Cano Nepauseno **Letter 1366 FP**

Thank you for this opportunity to share my opinion, I support completely this project, I think it's a great time to start a new job for different people.

David Hauge **Letter 1367 FP**

The dairy x beef calf has exploded. They will be big enuf to supply blackshirt feed yards with significant numbers of these calves. Commercial market that they are taking advantage of and ultimately hurts the rancher and beef producers.

David Israels-Swenson **Letter 1368 FP**

I would really like to see a full environmental impact assessment on this plan. I appreciate the growth and diversity Riverview has brought to the Morris community but am concerned that an operation of this size may negatively impact our local water quality and believe that caution is merited.

Gary Dukes **Letter 1369 FP**

Subject: Formal Opposition to the West River Dairy Expansion (Riverview LLP) and Petition for a Full Environmental Impact Statement (EIS)

I am writing to formally express my strong opposition to the proposed expansion of the West River Dairy facility near Morris, MN. This project, which seeks to increase capacity from 7,855 cows to 18,855 (totaling over 26,000 animal units), is unprecedented in the state of Minnesota. Given the massive scale and the history of this specific site, I urge the MPCA to deny the permit or, at minimum, require a comprehensive Environmental Impact Statement (EIS) before further consideration.

1. Water Quality and Watershed Impairment

The facility is located within the Pomme de Terre River watershed, a system already listed as impaired for bacteria and nutrients.

• Waste Volume: The expansion would result in approximately 250 million gallons of liquid manure storage. The risk of catastrophic failure or "allowable" seepage from clay-lined basins poses a permanent threat to local groundwater and the Pomme de Terre River, which flows into the Minnesota River.

• Application Risks: In a region prone to heavy spring rains, the saturation of phosphorus and nitrogen in the soil leads to inevitable runoff, worsening toxic algal blooms downstream.

2. Massive Groundwater Depletion

Riverview LLP has requested to pump 226 million gallons of water annually. Concentrated pumping of this magnitude threatens the domestic wells of neighbors and the long-term viability of the aquifer for the broader community.

3. Public Health

The emission of hydrogen sulfide, ammonia, and nitrous oxide (N2O) from a facility of nearly 19,000 cows is a significant public health hazard.

• Respiratory Impact: Neighbors are subjected to particulate matter and noxious gases that are linked to asthma, bronchitis, and other chronic respiratory conditions.

• Climate Change: N2O is a greenhouse gas roughly 300 times more potent than CO2. Permitting a single facility to emit such a concentrated volume contradicts Minnesota's stated climate goals.

4. Social Justice and Economic Disparity

The expansion of "Mega-Dairies" is not a neutral economic development; it is a driver of rural inequity.

• Consolidation vs. Community: By flooding the market with industrial-scale milk production, Riverview systematically pushes small- and mid-sized family farms out of business. This destroys the fabric of rural Stevens County, replacing independent business owners with a transient, low-wage labor model.

• Environmental Justice: Industrial CAFOs are consistently sited in rural areas where residents have fewer resources to fight protracted legal battles. This places the "negative externalities" of corporate profit—pollution, road damage, and smell directly onto the shoulders of local citizens while the profits are exported.

• Lack of Oversight: In 2014, the MPCA Citizens' Board ordered an EIS for a much smaller version of this project. Since that board was abolished, the lack of a mandatory EIS for a project three times larger represents a failure of democratic oversight and a victory for corporate lobbying over public interest.

Conclusion

The MPCA must recognize that the "West River Dairy Expansion" is not a standard agricultural project; it is an industrial experiment at a scale Minnesota has never seen. I urge that a full EIS be conducted to study the cumulative impacts on our water, our climate, and our rural social structure.

Sincerely,
Gary Dukes

• Watershed Impairments: MPCA Pomme de Terre River Watershed Report

• MPCA Environmental Assessment Worksheet (EAW): MPCA Environmental Review Projects
• Minnesota EQB Monitor: EQB Monitor Archives
• MN DNR Permitting and Reporting System (MPARS): DNR Water Appropriation Permit Search
• City of Morris Water Usage: City of Morris Public Works - Water Reports
• Pomme de Terre River Impairments: MPCA Pomme de Terre River TMDL Report
• Regulatory History: EPA FOIA Records (Site Assessments)
• Rivera, J. E., & Chará, J. (2021). CH4 and N2O emissions from cattle excreta: A review of main drivers and mitigation strategies in grazing systems. Frontiers in Sustainable Food Systems, 5. https://doi.org/10.3389/fsufs.2021.657936
• van der Weerden, T. J., Luo, J., Dexter, M., & Rutherford, A. J. (2014). Nitrous oxide, ammonia and methane emissions from dairy cow manure during storage and after application to pasture. New Zealand Journal of Agricultural Research, 57(4), 354-369. https://doi.org/10.1080/00288233.2014.935447
• PMC. (2026). Disparities in exposure to concentrated animal feeding operations (CAFOs) and other environmental justice variables. PubMed Central. https://pmc.ncbi.nlm.nih.gov/articles/PMC12413751/

David Jungst **Letter 1370 FP**

"This permit requires the facility to be designed, operated, and maintained to prevent discharge to waters, EXCEPT IN AN EXTREME STORM EVENT."

I have lived in this part of Minnesota for over 50 years. I know West central Minnesota gets extreme weather.

This facility, the Riverview LLP West River Dairy, will see extreme storm events and it will cause damages to the surrounding area. Just last summer in two days, July 27 and 28, the City of Morris got over seven inches of rainfall. When the storage ponds at this site over top, the storm water and manure will flow downstream to the east where just across the road is a large county tile drain pipe and draw that flows to the Pomme de Terre River less than four miles away.

Conversely, I have seen drought when the Pomme de Terre River completely stopped flowing and was reduced to puddles in its channel just downstream from this facility where the well is to be located to supply it.

An EAW (Environmental Assessment Worksheet) is insufficient for this site. The magnitude of this animal confinement operation, which will be the largest in the state of Minnesota, warrants that an Environmental Impact Statement should be required before a permit for this feedlot expansion can be issued.

Dave Vipond, H2 Land Stewards **Letter 1371 FP**

Dear MPCA Decision Makers,

On behalf of H2 Land Stewards, we respectfully submit this letter in support of the Riverview Farms West River Dairy Expansion.

H2 Land Stewards is a grassroots, nonprofit organization representing several hundred Minnesota residents, primarily landowners and agricultural producers. Our organization was established to educate members about their landowner rights and to protect those rights from erosion through unnecessary, inconsistent, or disproportionate government action. We strongly support regulatory processes that are fair, predictable, and grounded in sound science.

Riverview Farms has demonstrated a longstanding commitment to responsible land stewardship and proactive conservation practices. Environmental safeguards are already built into their existing systems and operational plans. These are established, proven practices that function as intended to protect soil and water resources. Riverview Farms has shown initiative by planning ahead and investing in systems that reduce risk and improve environmental protection, rather than relying on reactive measures.

While the proposed West River Dairy will be larger in scale than some other operations, it is not different in kind. The expansion does not introduce new practices, new risks, or fundamentally different impacts. The same conservation measures, best management practices, and regulatory oversight that apply to comparable dairy operations are already incorporated here. Size alone does not warrant treating this project differently from others that operate under the same established framework.

For these reasons, H2 Land Stewards does not believe a full Environmental Impact Statement (EIS) is justified. Existing environmental safeguards are already embedded in the system, and additional environmental review requirements would not meaningfully increase environmental protection. Instead, requiring an EIS based solely on scale risks creating regulatory inconsistency and setting a precedent that discourages responsible growth by landowners who are already operating within compliance.

Riverview Farms has approached this expansion transparently and in good faith, engaging with the permitting process and demonstrating a cooperative posture toward regulatory oversight. This proactive approach should be recognized and encouraged. Regulatory decisions should remain proportional to demonstrated environmental risk and based on actual operational differences—not assumptions tied to size alone.

H2 Land Stewards urges the MPCA to give the West River Dairy Expansion full and fair consideration and to recognize that responsible agricultural growth, supported by existing conservation systems, does not warrant unnecessary regulatory escalation. Thank you for your time and consideration.

Respectfully,
H2 Land Stewards

Gary Wertish, Minnesota Farmers Union — Letter 1372 FP

Dear Commissioner Kessler:

On behalf of Minnesota Famers Union (MFU) and responding to a vote from our Full Board, I write to request that you require an Economic Impact Statement (EIS) for Riverview LLP's permit to expand their West River Dairy in Stevens County. This scale of expansion is unprecedented in our state and we believe strongly that Minnesotans deserve a fuller examination of its environmental, economic, and social consequences.

MFU is a grassroots organization that has represented Minnesota's family farmers, ranchers and rural communities since 1918. Our membership and our Full Board include family dairies, including many who are struggling to stay in business while they shoulder prices below their cost of production. This challenge is not new with the number of Minnesota dairies declining by nearly half in the last decade, dropping from 3,470 in 2016[1] to just 1,600 farms today.[2] And while farms are declining, cows are

[1] Minnesota Dairy Industry Profile. Minnesota Department of Agriculture, 2016. https://www.mda.state.mn.us/sites/default/files/inline-files/dairyindprofile.pdf.
[2] Dairy Industry Consolidates. Dairy Star, 2026. https://dairystar.com/stories/dairy-industry-consolidates,30685?.

consolidating into fewer operations. This one company is permitted for nearly a third of Minnesota's dairy herd.[3]

This consolidation has consequences not just for those families, but also for rural schools, small businesses, veterinary practices, churches, and other institutions that make life possible in rural Minnesota. According to an analysis from 2020, the average Minnesota dairy generates $1.6 million in economic activity.[4] A more complete analysis of the economic and social consequences of this project is needed.

Beyond that, we believe there are important environmental concerns that an EIS would more fully address. Our members understand that livestock projects draw water year-round and we want to ensure that we are stewarding this shared resource and safeguarding sufficient supply for neighboring farms. We also understand that consolidating livestock increases the potential consequences of a natural disaster, zoonotic disease, or human disease affecting workers.

To close, this project is different than those that are approved through our existing processes. From my memory of that time, when we established our current regulatory framework for feedlots in the late 1990s no-one contemplated a nearly 19,000 cow dairy operation. That is more than 60 times the average size herd in our state.

This project is different and deserves distinct consideration and the full public comment afforded by an EIS. If you have any questions, please contact our Government Relations Director, Stu Lourey, at stu@mfu.org or (320) 232-2047. Thank you for considering the needs and perspectives of Minnesota's farm families.

Sincerely,
Gary Wertish
President, Minnesota Farmers Union

Eric Lindberg, Minnesota Center for Environmental Advocacy — Letter 1373 FP

Minnesota Center for Environmental Advocacy's

Comments on the Draft NPDES Permit for the West River Dairy Expansion

May 7, 2026

INTRODUCTION

Minnesota Center for Environmental Advocacy (MCEA) respectfully submits the following comments on the draft National Pollutant Discharge Elimination System (NPDES) permit for Riverview, LLP's (Riverview) proposed expansion of the West River Dairy in Stevens County. MCEA is a nonprofit with expertise in environmental law and policy. For more than 50 years, MCEA has worked in courts, at the legislature, and with public agencies to enact, strengthen, and enforce smart environmental laws.

Riverview is proposing a feedlot expansion that would accommodate an additional 11,000 cows, together with a new 1,304-foot by 692-foot cross-ventilated freestall barn, a new milking parlor, three new liquid manure storage areas, a temporary manure tank, and a solid manure storage building sized for up to a year of storage. Riverview reports that its proposed expansion would produce more than

[3] Proposed dairy in Morris would become Minnesota's largest feedlot. Star Tribune, March 16, 2026. https://www.startribune.com/proposed-dairy-in-morris-would-become-minnesotas-largest-feedlot/601596774.
[4] The Role of Dairy Farmers In Minnesota's Rural Economy. University of Minnesota Extension, June 9, 2020. https://conservancy.umn.edu/server/api/core/bitstreams/8b58793b-073e-4c43-81fd-96e0ffe1d172/content.

72,000 tons of carbon dioxide equivalent emissions (CO_2e) per year, as estimated in the corresponding Environmental Assessment Worksheet (EAW).[1]

As drafted, the Minnesota Pollution Control Agency (MPCA) cannot issue the permit for this expansion, because the permit does not comply with Minnesota law. Subpart 4 of Minnesota Rule 7020.0505 requires Riverview to submit an Air Emission Plan describing "methods and practices that will be used to minimize air emissions resulting from animal feedlot or manure storage area operations." Methane, nitrous oxide, and carbon dioxide are "air emissions resulting from animal feedlot or manure storage area operations." Yet Riverview's Air Emission Plan contains no greenhouse gas (GHG) emission controls, no monitoring or reporting obligation directed at GHG emissions, and no incorporation of GHG emissions mitigation proposals discussed in the project's EAW. The application and draft permit fail to address GHG emissions at all.

Because the draft permit incorporates Riverview's application materials—including the deficient Air Emission Plan—as enforceable terms, the noticed permit itself fails to comply with the plain language of Minnesota Rule 7020.0505, subpart 4(B)(1). Before issuing a permit, Riverview must submit an Air Emission Plan that satisfies the requirements of the rule by describing methods and practices that will be used to minimize GHG emissions, and MPCA must re-notice the draft permit for public comment.[2]

I. PROPOSED PROJECT AND REGULATORY BACKGROUND

A. Riverview's Project

Riverview, the fifth largest dairy farming company in the world and the second largest in the United States,[3] has operated the West River Dairy in Stevens County since 2004. West River Dairy houses over 7,800 head of dairy cows and is one of the largest feedlot projects in the state of Minnesota.[4] Riverview now seeks an 11,000-head expansion. The Expansion Project would house thousands of additional cows in a crossventilated, total-confinement, free-stall barn. Clay-lined basins with impermeable covers would be used to collect and store manure and wastewater. The resulting 18,855-head feedlot would be the largest in state history.[5]

The expansion would significantly increase West River Dairy's GHG emissions. New GHG emission sources include direct emissions from livestock digestion and manure management, alongside indirect emissions from feed production, energy use, and other life-cycle emissions associated with animal agriculture. The EAW reports that Riverview's Expansion Project would add at least 72,000 tons of CO_2e

[1] MPCA, RIVERVIEW'S ENVIRONMENTAL ASSESSMENT WORKSHEET FOR WEST RIVER DAIRY EXPANSION 65 (2026) https://webapp.pca.state.mn.us/eqb-search/project-detail/88731?siId=88731-PROJ0000000004 [hereinafter "*Riverview's EAW for West River Dairy*"].

[2] *See* Minn. R. 7001.0140, subp. 1 (providing that MPCA "shall issue" a permit only if it determines that the proposed permittee will comply with all applicable pollution control rules); Minn. R. 7001.0150, subp. 2(B) (requiring that the permit include conditions ensuring compliance with applicable Minnesota statutes and rules).

[3] MILICA KOCIC & TORSTEN HEMME, IFCN DAIRY RSCH. NETWORK, IFCN TOP-10 LIST: DAIRY FARMING COMPANIES WORLDWIDE 2020 (2020), https://ifcndairy.org/wp-content/uploads/2020/02/IFCN-Top-10- List-Dairy-Farming-Companies-Worldwide-2020.pdf [Exhibit 1] (listing Riverview as the fifth largest dairy company worldwide by number of cows and fourth largest by production of raw milk); *see also* Ana Sofia Santos, *Global Dairy Production: Top 10 Largest Dairy Farms in the World*, CEVA SANTÉ ANIMAL (Jan. 21, 2026), https://ruminants.ceva.pro/global-dairy-production [Exhibit 2] (ranking Riverview as the fifth largest dairy farming company worldwide by raw milk production and the largest in the United States).

[4] Riverview's EAW for West River Dairy, supra note 1, at 2; see also Greg Stanley, Proposed Dairy in Morris Would Become Minnesota's Largest Feedlot, STAR TRIB. (Mar. 16, 2026), https://www.startribune.com/proposeddairy-in-morris-would-become-minnesotas-largest-feedlot/601596774.

[5] *Riverview's EAW for West River Dairy*, *supra* note 1, at 2; Minn. Pollution Control Agency (MPCA) & Minn. Geospatial Commons, *Feedlots in Minnesota*, https://gisdata.mn.gov/dataset/env-feedlots (last visited May 5, 2026).

per year to the existing West River Dairy facility.[6] That estimate excludes GHG emissions associated with upstream feed production, downstream processing, and other life-cycle sources.[7] Even at this lower bound, 72,000 tons of CO_2e represents one-sixth of the entire statewide emission reductions achieved by Minnesota's Priority Climate Action Plan cost-share and grants program.[8] Offsetting the reported lifetime GHG emissions from Riverview's Expansion Project would require a decade's worth of carbon sequestration by 32 million trees.[9] [10]

B. Regulatory Background

Minnesota's largest feedlots are subject to state and federal laws that require feedlot owners to obtain permits designed to protect human health and the environment from feedlots' adverse effects. NPDES permits are required for any concentrated animal feeding operation that discharges to waters of the United States.[11] Alongside federal NPDES permits, MPCA issues State Disposal System (SDS) permits that "address program issues which the federal regulations do not cover under an NPDES permit program."[12] If a project would house 1,000 or more animal units, a feedlot applicant may apply for an independent SDS permit, or it may apply for a federal NPDES permit that incorporates Minnesota's SDS permit requirements.

Riverview's Expansion Project would add 15,400 animal units to the existing West River Dairy, far exceeding the state SDS permit threshold, and the company has elected to apply for a federal NPDES permit that includes Minnesota's SDS permit restrictions.[13]

C. Air Emission Plans

Many conditions and restrictions in Riverview's draft NPDES permit are required by Chapter 7020 of the Minnesota Rules (the "Feedlot Rules"). MPCA established the Feedlot Rules in 1971 under the agency's authority to "adopt, amend, and rescind rules and standards having the force of law . . . [for] the prevention, abatement, or control of water, air, and land pollution."[14] The Feedlot Rules address a wide range of environmental impacts. When MPCA proposed changes to the Feedlot Rules in 1999, the agency noted in its Statement of Need and Reasonableness (SONAR) for the rule changes that it "intends to use the SDS permit as it has under the current program to address program issues which the federal

[6] Riverview's EAW for West River Dairy, supra note 1, at 62.
[7] *Id.* at 62–63.
[8] MPCA, Priority Climate Action Plan: Climate Pollution Reduction Grants 75–76 (Feb. 2024), https://www.pca.state.mn.us/sites/default/files/aq1-70.pdf (estimating that state cost-share and grants produced annual reductions of more than 450,000 tons CO2e).
[9] Compare Riverview's EAW for West River Dairy, supra note 1, at 62 with U.S. Env't Prot. Agency, GreenhouseGas Equivalencies Calculator, https://www.epa.gov/energy/greenhouse-gas-equivalencies-calculator (last visited May 7, 2026).
[10] For a fuller assessment of the GHG emissions from Riverview's proposed expansion, see the attached Comments of MCEA et al. on the Environmental Assessment Worksheet for the West River Dairy Expansion (May 7, 2026) [hereinafter Comments of MCEA et al.], with corresponding exhibits offered as part of this permit comment and the administrative record for MPCA's consideration of the draft NPDES permit for Riverview's Proposed Expansion.
[11] See 40 C.F.R. § 122.23(a), (d)(1), (f).
[12] MPCA, Statement of Need and Reasonableness, In the Matter of Proposed Amendments to Minnesota Rules Relating to Animal Feedlots, Storage, Transportation, and Utilization of Animal Manure, Minn. R. pt. 7001.0020, Minn. R. pts. 7002.0210–.0280, Minn. R. ch. 7020, at 94 (Dec. 8, 1999), https://www.leg.mn.gov/archive/sonar/SONAR-03001.pdf [hereinafter 1999 SONAR].
[13] MPCA, Draft NPDES/SDS Permit No. MN0072273 for Riverview LLP—West River Dairy § 6.2 (2026) [hereinafter Draft NPDES Permit].
[14] Minn. Stat. § 116.07, subds. 2(a), 4.

regulations do not cover under an NPDES permit."[15] MPCA went on to specify that such issues include feedlot emissions: "The Agency has included provisions for addressing air quality issues in SDS and interim permits under the current program. In addition, the proposed rule requires owners having 1,000 animal units or more to develop and implement an Air Emission Plan (part 7020.0505, subp. 4, item B, subitem 1.)"[16]

The Feedlot Rules contain specific provisions dealing with odor complaints and reference a specific standard for the toxic pollutant hydrogen sulfide. In addition, Minnesota Rule 7020.0505, subpart 4, requires a more general plan to address "air emissions." It states, in relevant part:

> B. In addition to the requirements of item A, a permit application for an animal feedlot capable of holding 1,000 animal units or more or a manure storage area capable of holding the manure produced by 1,000 animal units or more must contain:
>
> (1) an air emission plan that includes:
>
> (a) methods and practices that will be used to minimize air emissions resulting from animal feedlot or manure storage area operations including manure storage area start-up practices, loading, and manure removal; . . .

In its 1999 SONAR, MPCA explained this new planning requirement by noting that "the need clearly exists to establish standards for the design, construction, and operations of animal feedlots and manure storage areas such that the negative impacts of gases generated at these facilities are minimized, particularly past the property line of a facility."[17] The agency supported that conclusion by highlighting "a very comprehensive and recent review of the effects of animal agriculture on air quality" from the University of Minnesota, together with a 1999 report from the Office of the Legislative Auditor.[18]

Both reports described feedlots' contribution to global warming. The Generic EIS explained that:

> [E]missions from animal production systems include an extensive list (168) of gaseous compounds. The three most researched gases are hydrogen sulfide, ammonia, and methane. Hydrogen sulfide poses the largest safety risk in confined spaces (indoor) and is of concern in the ambient air (outdoor) mainly because of the Minnesota state ambient air standard for this gas. It seems that swine facilities and manure storage units produce the largest concentrations and emissions of hydrogen sulfide. Ammonia is also produced by animal production systems, especially poultry facilities. Indoor concentrations of ammonia pose some health concerns inside buildings but emissions may contribute to ecological damage to the environment. **Finally, methane emissions, which are more of a problem with cattle than other animal species, contribute to global warming concerns**.[19]

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[15] 1999 SONAR, supra note 12, at 94; see also MPCA, Proposed Permanent Rules Relating to Animal Feedlots and Storage, Transportation, and Utilization of Animal Manure, 24 Minn. State Reg. 848, 863 (Dec. 20, 1999), https://www.revisor.mn.gov/state_register/24/25/.

[16] *1999 SONAR*, *supra* note 12, at 94.

[17] Id. at 19.

[18] Id.; see MINN. ENVTL. QUALITY BD., Generic Environmental Impact Statement on Animal Agriculture: A Summary of the Literature Related to Air Quality and Odor (H) (Sept. 1999), https://www.lrl.mn.gov/docs/pre2003/other/990616/vol2.pdf [Exhibit 133] [hereinafter Generic EIS Volume 2]; OFFICE OF THE LEGIS. AUDITOR, Animal Feedlot Regulation: A Program Evaluation Report (Jan. 1999), https://www.auditor.leg.state.mn.us/ped/1999/fedlt99.htm [Exhibit 134] [hereinafter *Office of the Legis.Auditor*].

[19] *Generic EIS Volume 2, supra* note 18, at H-41 (emphasis added).

Regarding GHGs in particular, the Generic EIS highlighted it "is well known that methane emissions from animal agriculture, or any other source, contribute to global warming."[20] The report discussed scholarship identifying "global emission rates of methane at 540 x 109 kilograms per year with 5% of the emissions resulting from the anaerobic decomposition of animal manure and another 15% coming from the gut of ruminant animals."[21] Based on its survey of the literature, the Generic EIS stressed that "methane and other greenhouse gas emissions from animal agriculture have an impact far beyond the immediate location of their source."[22]

The Office of the Legislative Auditor released its own 1999 report that, among other concerns, flagged environmental risks posed by GHG emissions:

> The main purpose of feedlot regulation is to protect Minnesota citizens from pollution caused by animal manure. Manure is a valuable resource that can provide beneficial nutrients to the soil and thus help in the production of crops. However—if improperly stored, transported, or disposed—manure may pollute lakes and streams or drinking water sources. Manure can also produce unpleasant and annoying odors and emissions, possibly affecting the health of nearby residents. In addition, **emissions from manure may contribute to acid rain and greenhouse gas effects** . . .
>
> In addition to concerns about water pollution, feedlots with high concentrations of manure may produce unpleasant odors and emit gases such as hydrogen sulfide, ammonia, and various volatile organic compounds that may affect air quality. With the trend to larger feedlots and bigger manure storage facilities, complaints about feedlot odors and concerns about air quality have increased in recent years. Other environmental concerns raised include the health and nuisance impacts of flies, the effects of endotoxins in the air at certain facilities, **and the contribution of manure emissions to greenhouse gas effects and acid rain.**[23]

II. RIVERVIEW'S AIR EMISSION PLAN OMITS GHG EMISSIONS

Riverview's NPDES permit application included an Air Emission Plan describing steps Riverview could take to mitigate odors from the Expansion Project.[24] The Plan lists two sources at the industrial dairy that are "likely to generate significant odors": animal holding areas and manure storage areas. Riverview identifies several steps for mitigating odors from these sources. For animal holding areas, the Air Emission Plan includes proposals to "disperse/mix air with tree plantings," "promptly clean up any spilled feed," and eight other odor mitigation proposals. For manure storage areas, the Plan includes an additional fourteen odor mitigation measures, including proposals to "cover the solid manure stockpile" and to "notify neighbors of manure application and avoid holidays."[25] After listing twenty-four odor mitigation proposals, the plan states that if "continued odor complaints are validated, at least one of the practices identified . . . will be implemented pursuant to MPCA request/approval."[26] The Air Emission Plan does not commit the company to employing any of the identified odor mitigation measures.

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[20] *Id.* at H-47.
[21] *Id.* at H-40.
[22] *Id.* at H-47.
[23] *Office of the Legis. Auditor*, *supra* note 18, at xi, 13 (emphases added).
[24] *Riverview's EAW for West River Dairy*, *supra* note 1, at 446, 455–56 (Attachment 22, Minnesota NPDES Individual Feedlot Permit Application at 1, 9).
[25] *Id.* at 455–56.
[26] *Id.* at 456.

In addition to strategies for odor control, the Air Emission Plan contains measures targeting hydrogen sulfide. The plan notes that MPCA may "request a report" from Riverview in the event that ambient air quality monitoring "indicates an exceedance of the Hydrogen Sulfide Standard."[27] In this report, Riverview would demonstrate that it is deploying at least one of ten hydrogen sulfide emissions controls, including, for example, "chemical additions," "straw cover," or "composting," to manage hydrogen sulfide emissions.[28]

Despite the Feedlot Rules' broadly-worded directive to describe "methods and practices that will be used to minimize air emissions," Riverview's Air Emission Plan fails to identify any other pollutants that will be emitted from its operation or methods to minimize them. In particular, Riverview's Air Emission Plan contains no analysis of GHG emissions. The plan offers no quantitative or qualitative limit on GHG emissions, no measures specifically targeting GHG mitigation, and no monitoring, recordkeeping, or reporting obligation directed at GHG emissions. The Air Emission Plan does not incorporate, attach, or reference the GHG mitigation measures identified in this project's EAW. As a result, neither Riverview's permit application, nor the resulting draft permit, contains any discussion of "methods and practices that will be used to minimize air emissions" associated with the facility's projected 72,210 tons of annual CO2e emissions.[29]

III. THE PERMIT CANNOT BE ISSUED BECAUSE IT FAILS TO ADDRESS GHG EMISSIONS AS REQUIRED BY MINNESOTA LAW

Subpart 4 of Minnesota Rule 7020.0505 requires Riverview to submit an Air Emission Plan setting out "methods and practices that *will be used* to minimize air emissions" from its operations as part of its permit application. (Emphasis added.) The plain meaning of "air emissions" includes GHGs. Riverview's Air Emission Plan nevertheless omits GHG emissions entirely. Without a plan addressing methods and practices Riverview will use to minimize its GHG emissions, MPCA cannot issue Riverview's NPDES permit.

A. The Feedlot Rules Plainly Require Feedlot Applicants To Describe Methods And Practices For Minimizing GHG Emissions

An applicant for a feedlot or manure storage area capable of holding 1,000 animal units or more must submit an Air Emission Plan. That Plan must include "methods and practices that will be used to minimize air emissions resulting from animal feedlot or manure storage area operations including manure storage area start-up practices, loading, and manure removal."[30]

GHGs are air emissions that must be discussed in Riverview's Air Emission Plan. State law defines GHGs as "emissions."[31] Methane, nitrous oxide, and other GHG emissions are emissions "resulting from animal feedlot or manure storage area operations."[32] Regulatory language is construed according to words' "common and approved usage," and when "clear and free from all ambiguity, the letter of the law shall not be disregarded under the pretext of pursuing the spirit."[33] The rule's plain meaning includes GHG

[27] *Id*.
[28] *Id.*
[29] *Id.*
[30] Minn. R. 7020.0505, subp. 4(B)(1)(a).
[31] *See* Minn. Stat. § 116.06, subds. 9, 2.
[32] Minn. R. 7020.0505, subp. 4(B)(1)(a).
[33] Minn. Stat. §§ 645.08(1), 645.16; *see* Minn. Stat. § 645.001 (Chapter 645's canons of construction apply to administrative rules).

emissions produced by Riverview's feedlot project. Despite this broad and unqualified language, Riverview's Air Emission Plan fails to address GHG emissions at all.[34]

B. Several GHG Mitigation Measures Are Available For MPCA To Require In Riverview's Air Emission Plan

Riverview itself, along with commenters weighing in on the NPDES permit or the EAW, have identified several GHG mitigation measures that MPCA can make enforceable through Riverview's Air Emission Plan as required by the applicable rule. For instance, the EAW reports that Riverview will "utilize crossbred dairy cows selected for improved production efficiency relative to conventional dairy breeds," producing lower GHG emissions on a per-animal basis.[35] The EAW asserts that Riverview will minimize greenhouse gas emissions by adopting "efficient feed practices, including sourcing the majority of ingredients locally, adjusting rations to maximize production and minimize spoilage, and reducing emissions through implementation of feed additives like Rumensin," and states that manure "will be incorporated into the soil during land application by [Commercial Animal Waste Technicians], thereby reducing emissions."[36] In total, Riverview lists more than a dozen strategies in the EAW for minimizing this project's greenhouse gas emissions. These measures can easily be translated into terms in Riverview's Air Emission Plan and incorporated into the permit.

Alongside mitigation measures listed in Riverview's Draft EAW, public commenters have advocated that several important measures be added to the Final EAW. The Comments of MCEA et al. on the EAW describe additional ways for Riverview to "minimize air emissions" from its proposal, including practices related to manure management, livestock management, and even energy use and procurement. For details on these measures, please see the attached Comments of MCEA et al. at pages 18–27 and supporting exhibits. Ample GHG management strategies exist to include in a revised permit application and revised public notice.

To ensure Riverview's EAW mitigation measures translate to real-world reductions, MPCA must adhere to the Feedlot Rules by including an Air Emission Plan in the *permit* that specifies enforceable measures Riverview will take to minimize its air emissions, including GHG emissions. Because the draft permit incorporates Riverview's application materials as enforceable permit terms,[37] the omission of any GHG mitigations from the Air Emission Plan means the draft permit itself fails to comply with the plain language of Minnesota Rule 7020.0505, subp. 4(B)(1). As noticed, the permit cannot be issued.[38]

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[34] MPCA has undisputed authority to regulate greenhouse gas emissions from facilities within the state of Minnesota. *See* Minn. Stat. § 116.07, subd. 2(a)–(b) (authorizing rulemaking for "the prevention, abatement, or control of air pollution"); *Minn. Auto. Dealers Ass'n v. Minn. Pollution Control Agency*, No. A22-0796 (Minn. Ct. App. Jan. 30, 2023) (upholding MPCA's Clean Cars Minnesota rule and confirming that the agency's air-pollution authority encompasses greenhouse gases); *In re Denial of Contested Case Hearing Request & Modification of a Notice of Coverage Under Individual NPDES Feedlot Permit No. MN0067652*, No. A19-0207, 2019 WL 5106666 (Minn. Ct. App. Oct. 14, 2019) (holding that MPCA's refusal to analyze greenhouse gas emissions in a feedlot EAW was arbitrary and capricious); *In re Proposed Rules of the Minn. Pollution Control Agency Governing Permits for Greenhouse Gas Emissions*, OAH Docket No. 8-2200-22910-1, 2012 WL 6645129 (Minn. Off. Admin. Hearings Nov. 9, 2012) (concluding that MPCA possesses statutory authority under Minn. Stat. § 116.07 to regulate greenhouse gases as air contaminants).

[35] *Riverview's EAW for West River Dairy, supra* note 1, at 64–65.

[36] *Id.*

[37] Draft NPDES Permit, *supra* note 13, § 6.4 ("[T]he Permittee is authorized to construct and operate the facility according to the submitted and MPCA-approved permit application materials . . . The application materials are an enforceable part of this Permit.") (citing Minn. R. 7001.0150).

[38] In addition to being required by the feedlot rule, an Air Emission Plan that sets out mandatory GHG mitigation measures helps to satisfy the requirements of the Minnesota Environmental Policy Act. *See Comments of MCEA et al., supra note 10*; *Citizens Advocating Responsible Dev. v. Kandiyohi Cnty. Bd. of Comm'rs*, 713 N.W.2d 817, 835 (Minn. 2006) (explaining that

C. Exempting Riverview From Addressing GHG Emissions Based On MPCA's Air Emission Plan Template Would Reflect Unlawful And Unpromulgated Rulemaking

Riverview's Air Emission Plan appears to be generated from an online form made available to applicants through MPCA's website. If MPCA allows feedlot applicants to comply with Minnesota Rule 7020.0505, subp. 4(B)(1) by simply checking the "affirmed" box on the template form, the agency would be enforcing an invalid and unpromulgated rule.

Administrative rules include any "agency statement of general applicability and future effect" adopted to implement or make specific the law the agency administers.[39] If a state agency wishes to create an administrative rule, it must engage in a rulemaking process that includes notice published in the State Register, a statement of need and reasonableness, opportunity for written and oral public comment, and frequently independent review by an administrative law judge.[40] State agencies are prohibited from enforcing a "policy, guideline, bulletin, criterion, manual, standard, or similar pronouncement" as though it were a duly adopted rule.[41] To separate lawful guidance documents from unpromulgated rules, Minnesota courts examine whether agency documents offer an "interpretation of a rule [that] corresponds with its plain meaning."[42]

If MPCA's template form is used to demonstrate compliance with Minnesota Rule 7020.0505, subp. 4(B)(1), the agency would be enforcing an unpromulgated rule. First, the form contradicts the Feedlot Rules' plain meaning by wrongly restricting the Rules' scope. Subpart 4 of Minnesota Rule 7020.0505 requires an Air Emission Plan that addresses "emissions resulting from animal feedlot or manure storage area operations." Those emissions include GHGs. By interpreting the rule to omit GHG emissions, contrary to the rule's plain text, MPCA's form falls outside the bounds of lawful interpretation.

Second, MPCA's form fails to describe "methods and practices that *will be used* to minimize air emissions." (emphasis added). Despite the rule's mandatory language, MPCA's form rests on hypotheticals. *If* continued odor complaints are validated, then the template states "at least one of the practices identified above will be implemented," and *if* ambient air quality monitoring "indicates an exceedance of the Hydrogen Sulfide Standard," the owner may be required to submit a second, separate air emissions report offering "documentation that one of the following [strategies] will control the emissions."[43] Absent complaints or exceedances, the template form does not require feedlot applicants to commit to *any* air emission reduction strategies. This approach is inconsistent with the Feedlot Rules' directive to describe emission reduction measures that "will be used."

D. Including GHG Emissions In Feedlot Air Emission Plans Is Consistent With Minnesota's Climate Commitments And The Minnesota Environmental Rights Act

Failing to address GHG emissions in a feedlot permit proposed by one of the largest industrial dairy producers in the world, for what would become the largest dairy operation in the State, is inconsistent with Minnesota's ambitious climate commitments. The Minnesota Legislature has set climate targets to reduce GHG emissions across every sector of the economy. Beginning with the Next Generation Energy Act in 2007, and continuing through the Next Generation Climate Act of 2023, the Legislature has targeted a fifty-percent reduction relative to 2005 by 2030 and net zero by 2050, and it has directed

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mitigation measures must be "specific, targeted, and . . . certain"). Unless made enforceable requirements of the permit, the measures identified in Riverview's EAW are merely vague promises of good intent. *See id.*

[39] Minn. Stat. § 14.02, subd. 4.

[40] *See* Minn. Stat. §§ 14.05, 14.131, 14.14, 14.22, 14.50.

[41] Minn. Stat. § 14.381, subd. 1.

[42] *Cable Commc'ns Bd. v. Nor-W. Cable Commc'ns P'ship*, 356 N.W.2d 658, 667 (Minn. 1984).

[43] *Riverview's EAW for West River Dairy, supra* note 1, at 455–56.

every state agency, including MPCA, to contribute to achieving these targets.[44] The Legislature confirmed that the goal is "to reduce statewide greenhouse gas emissions across *all sectors* producing greenhouse gas emissions."[45] Animal agriculture is not exempt.

Despite these requirements, methane emissions from the agricultural sector have *increased* approximately fifteen percent since 2005, emissions from livestock digestion have *increased* approximately three percent over the same period, and total GHG emissions from the agricultural sector are rising even as statewide GHG emissions have fallen.[46] Agriculture now accounts for roughly a quarter of Minnesota's net GHG emissions, and animal agriculture is the single largest source of methane in Minnesota.[47] To align with Minnesota's climate targets, MPCA must enforce the Feedlot Rules by requiring feedlot owners to plan for GHG emission reductions from their agribusiness projects, including Riverview's unprecedentedly large expansion proposal.

Enforcing the Air Emission Plan requirement would also align with the Minnesota Environmental Rights Act (MERA). MERA, one of Minnesota's bedrock environmental laws, was passed in 1971 "to create and maintain within the state conditions under which human beings and nature can exist in productive harmony in order that present and future generations may enjoy clean air and water, productive land, and other natural resources with which this state has been endowed."[48] MERA allows Minnesota residents to bring civil actions "against any person, for the protection of the air, water, land, or other natural resources located within the state, whether publicly or privately owned, from pollution, impairment, or destruction."[49] Minnesota residents may also challenge "any environmental quality standard, limitation, rule, order, license, stipulation agreement, or permit [as] inadequate to protect the air, water, land, or other natural resources located within the state from pollution, impairment, or destruction."[50]

Given the scale of the climate crisis, and the need to reduce GHG emissions from the agricultural sector, requiring emission reduction efforts from one of the country's largest dairy operators is fully consistent with MERA's protective purpose. Unmitigated GHG emissions from the state's largest industrial feedlot would adversely affect the environment.[51] The Feedlot Rules contain no other GHG regulatory mechanism beyond Minnesota Rule 7020.0505's planning requirement. Allowing Riverview to submit an Air Emission Plan that omits GHGs, a crucial source of "air emissions resulting from animal feedlot or manure storage area operation," would risk the pollution, impairment, or destruction of Minnesota's natural resources.

CONCLUSION

For the above reasons, MPCA cannot issue the draft NPDES permit as noticed. MPCA should require Riverview to submit a revised Air Emission Plan that identifies enforceable methods and practices to minimize greenhouse gas emissions resulting from the West River Dairy Expansion Project, incorporate those measures into a revised draft permit, and re-notice the revised permit for public comment.

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[44] Minn. Stat. § 216H.02, subds. 1(a), 2.
[45] *Id.* (emphasis added).
[46] Minnesota Greenhouse Gas Inventory, *Sector-Level Details, Agriculture Sector*, *Full Results Table*, MPCA, https://data.pca.state.mn.us/views/Greenhousegasemissionsdata/Sectordetails (last visited May 7, 2026).
[47] Anne Claflin et al., MPCA, *Greenhouse Gas Emissions in Minnesota 2005–2022* at 3, 9 (2025), https://www.pca.state.mn.us/sites/default/files/lraq-3sy25.pdf [hereinafter *MPCA Greenhouse Gas Emissions in Minnesota*].
[48] Minn. Stat. § 116B.01.
[49] Minn. Stat. § 116B.03.
[50] Minn. Stat. § 116B.10.
[51] *MPCA Greenhouse Gas Emissions in Minnesota, supra* note 47, at 3, 9.

Travis Moser **Letter 1374 FP**

Dear Commissioner Kessler and Commissioner Petersen:

We are residents of western Minnesota, eastern North Dakota, and eastern South Dakota, representing generations of farmers, business owners, and communities writing to share our strong support for Riverview's proposed West River Dairy expansion and to offer our perspective as you consider the project's path forward.

Many of us have spent our lives working this land, growing crops, raising livestock and building our livelihood here. We understand firsthand the importance of protecting our natural resources while also sustaining the farms, families, and local economies that depend on them. That balance matters deeply to us, and it is why we support this project.

Riverview is not new to our communities. They have a long track record of operating with care for the land, respect for animals, and a genuine commitment to the people and rural communities where they live and work. We have seen their approach up close: investing in environmental stewardship, partnering with local farmers, and contributing to the long-term vitality of the region.

The proposed West River Dairy expansion has undergone extensive and rigorous review. The Environmental Assessment Worksheet (EAW) and feedlot permit application together include nearly 900 pages of detailed technical analysis, developed over more than three years in coordination with state agencies. The project is subject to oversight from multiple agencies, including the MPCA, DNR, and MDH, ensuring a comprehensive evaluation of groundwater, surface water, air quality, and natural resources.

In addition, the farm will operate under an individual NPDES feedlot permit – one of the most stringent and site-specific permits in Minnesota – and includes enhanced environmental protections that go beyond baseline requirements. Riverview has also taken proactive steps to reduce impacts, including voluntarily cutting permitted groundwater use in half and incorporating stormwater capture and reuse into the project design.

Based on what we know and what has been studied, we believe the current environmental review process is thorough, science-based, and appropriate for this project. An Environmental Impact Statement (EIS) should be reserved for situations where the evidence clearly demonstrates it is necessary. In this case, we are confident the existing process provides a full and careful evaluation.

For our communities, this project is also about the future, supporting family farms, creating economic opportunities, and strengthening our rural areas for generations to come. Riverview's model of working with neighboring farmers and investing locally reflects the kind of agriculture we want to see continue and grow.

We appreciate the seriousness of your roles and the responsibility you carry in reviewing projects like this. We respectfully encourage you to rely on the extensive environmental review already underway and the strong record of stewardship demonstrated by Riverview.

Thank you for your time and consideration.

Sincerely,

Travis & Rita Moser, Spring Valley Farms
Mike Yost, Yost Farm Inc
Michael Yost, Yost Farm Inc
Jim Radermacher, Yost Farm Inc

Kevin Lundberg, L&A Partnership
Cory Ahrends, Swift Pumping
Anthony Anker, Swift Pumping
Dustin Walsh, Walsh Farms
Jackson Walsh, Walsh Farms
Marc Stevens
Megan Horsager
Marcus Goldenstein
Scott Ruiter, Ruiter Farms
Nate Hultgren, Hultgren Farms
Randy Pothen, Pothen Farms
Matt Claussen, Claussen Farms
Stan Claussen, Claussen Farms
Thomas Claussen, Claussen Farms
Richard Walsh
Jim Kanten, Kanten Farms
Brett Petersen, Petersen Farms Inc
Nathan Collins, Collins Family Farms
Kent Bosch, CK Bosch Farms
Eric Boike, Boike Farms
Douglas Finstrom, Finstrom Farms
Erik Finstrom, Finstrom Farms
Cameron Adams, Skaurud Grain Farms
Gregory Anderson, Skaurud Grain Farms
Oloff Bergh, Skaurud Grain Farms
Rickie Brunner, Skaurud Grain Farms
Phillip Earle, Skaurud Grain Farms
Jacobus Esterhuizen, Skaurud Grain Farms
Adriaan Faber, Skaurud Grain Farms
John Gall, Skaurud Grain Farms
Jacob Geldenhuys, Skaurud Grain Farms
Marco Griebenauw, Skaurud Grain Farms
Edward Kriel, Skaurud Grain Farms
John McArthur, Skaurud Grain Farms
Joseph McArthur, Skaurud Grain Farms
James Menge, Skaurud Grain Farms
Matthew Miller, Skaurud Grain Farms
Richard Mizzell, Skaurud Grain Farms
Marissa Munsterman, Skaurud Grain Farms
Jim Murn, Skaurud Grain Farms
Dustin Nelson, Skaurud Grain Farms
Kelby Opsahl, Skaurud Grain Farms
Ross Opsahl, Skaurud Grain Farms
John Palm, Skaurud Grain Farms
Nicholas Pederson, Skaurud Grain Farms
Gerhardus Prinsloo, Skaurud Grain Farms
Stephanus Prinsloo, Skaurud Grain Farms
John Rothschadl, Skaurud Grain Farms
Louis Daniel Scheepers, Skaurud Grain Farms
Cory Skaurud, Skaurud Grain Farms
Evan Skaurud, Skaurud Grain Farms
Kathleen Skaurud, Skaurud Grain Farms
Kelly Skaurud, Skaurud Grain Farms
Perry Skaurud, Skaurud Grain Farms
Vicki Skaurud, Skaurud Grain Farms
Shaun Syverson, Skaurud Grain Farms
Grant Visser, Skaurud Grain Farms
Kenneth Winter, Skaurud Grain Farms
Steve Lacey, Lacey Ridge Farms
Jaylene Lacey, Lacey Ridge Farms
Brian Lacey, Lacey Ridge Farms
Deb Lacey, Lacey Ridge Farms
Natasha Lacey, Lacey Ridge Farms
Blake Steenblock, Spring Valley Farms
Paul Adams, Paul Adams Farms
Travis Miller, Mill Farms
Jessica Miller, Mill Farms
Greg Halubok, Summit Farms
Alicia Halubok, Summit Farms
Madison Yaggie-Schuler, Children's Discovery Center
Tanner Davison, Champion Farms
Frank Davison, Champion Farms
Kelsey VanOverbeke, Associate Agronomist
Nate Summerville, Summerville Electric
Dylan Summerville, Summerville Electric
Anthony Anker, Swift Pumping
John Habedank
Bradan Krump, Krump Brothers Farms
Randy Rittenour, JLR Farms
Janelle Rittenour, JLR Farms
Jerry Loxtercamp, Jerry's Pumping
Todd Klein, TAKCO Inc
Boone Carlson, Carlson Ag
Allen Yaggie, Allen Yaggie Farms Inc
Jesse Morgan, Christine Morgan Farms
Scott Hagy
David Heil
Scott Hennen
Brent Koehl
Keith Koehl
Lucas Koehl, Doubletree Farm
Levi Koehl, Doubletree Farm
Kurtis Koehl, Doubletree Farm

Kyle Koehl, Doubletree Farm
Derek Koehl, Doubletree Farm
Adam Koehl, Doubletree Farm
Randall Gorder
Trent Prestegord, Prestegord Farms
Tom & Stephanie Borgen, Borgen Farms
Michael Porter, MJP Trucking
Joel Rinke, Rinke Farms & Triple J Seed
Jake Rinke, Rinke Farms & Triple J Seed
James Rinke, Rinke Farms & Triple J Seed
Brian Rinke, Rinke AG
Steve Fridgen, Steve Fridgen Farms
Richard Jonhson, Johnson Farms
Adam Lichtsinn, Adam Lichtsinn Farms
Craig Lichtsinn, Adam Lichtsinn Farms
Steve Rinke, SR Farms
Mitch Frisch, Wheaton Resident
Paul Frisch, Frisch Farms
Tom Frisch, Frisch Farms
Travor Timm, T&T Cattle
Trent Timm, T&T Cattle
Kyle Bessler, Bessler Farms
Lee Sebek, Sebek Farms
Ron Kohl, Kohl Farms
Dillon Lien, Lien Farms
Shane Rein, Rein Construction
Derek Hansen, DC Trucking & Tree Services
Mitch Bodin, Bodin Construction
Brian Vig, Vig Livestock & Grain
Linn Vig, LVFI Farms
Gus Buss, Proper Welding & Fabrication
Brandon Gieser, Gieser Farms
Steven Steiner, Steiner Livestock
Renny Tank, Tank Farms
Jake Doyle, Puck Application
Justin Gaukler, Gaukler Farms
Jason Medhaug, Medhaug Farms
Jerry Nelson
Denver Nickeson, Nickeson Harvesting
Lonnie Jones, JNL Harvesting
Paul Mund, MG Harvesting
Nathan Koehl, CRK Partners
Tyler Scott, CRK Partners
Andrew Steiner, CRK Partners
Benjamin Koehl, CRK Partners
Byron Koehl, CRK Partners
Kaleb Koehl, CRK Partners
Taylor Gramm, CRK Partners
Arvin VanEps, CRK Partners
Brady Koehl, CRK Partners
Andrew Yost, CRK Partners
Mitch Koehl, CRK Partners
Clark Koehl, CRK Partners
Coby Backman, CRK Partners
Kevin Koehl, CRK Partners
Marciano Gonzales Garcia, CRK Partners
Megan Wulf, Spring Valley Farms
Lane Wulf, Spring Valley Farms
Jerry & Kedron Nohl, Spring Valley Farms
Fabian Hernandez, Spring Valley Farms
Greg Reuter, Spring Valley Farms
Hein Enslin, Spring Valley Farms
Jon Moser
Kurt & Savannah Wulf, Spring Valley Farms
Lowell & Karen Moser, Spring Valley Farms
Eric Meischner, Spring Valley Farms
Brent Evink, Spring Valley Farms
Eric Zeltwanger, Spring Valley Farms
Emmit Wulf, Spring Valley Farms
Reed Wulf, Spring Valley Farms
Carlos Hernandez, Spring Valley Farms
Craigan Wulf, Spring Valley Farms
Ed Wilkinson, Wilkinson Farms
Chad Malone
Kirk Aughenbaugh, Aughenbaugh Farms
Alan Aughenbaugh, Aughenbaugh Farms
Matt Aughenbaugh, Aughenbaugh Farms

Ronald Visser **Letter 1375 FP**

Ronald Visser

Go on a tour! Riverview does them on every dairy. This is the best way to fully understand the dairy operation.

What you will see is:

A great cow environment-the barns are designed with cow comfort as top priority. The cows are calm when milking. They have access to feed, water, and a bed all day.

A great employee culture-the team is professional, hardworking and loves the cows.

A clean site-the farm is well organized, kept clean and well maintained.

A great manure plan-the manure lagoons are covered to control odor and to keep precipitation and manure separate; the lagoons have plenty of storage capacity-14 months. You might see manure injected into the soil after harvesting in the fall.

No rodents-the clean facility along with a pest control program keeps rodents in check.

Very few flies-the clean facility, constant air flow in the barn and a fly control program limit the flies.

My parents built a new 60 cow tie-stall barn in 1973 when I was 3 years old. I've been told that our county had 175 dairy farms at the time. 7 milk processors competed for our milk. Today, none of those farms have dairy cows. The entire dairy infrastructure (processing, veterinarians, nutritionists, consultants, ag lenders-dairy, equipment dealers/repairs, etc.) is gone. I have watched a similar transition in the far north of Minnesota, all of North Dakota and Black Hill area in South Dakota. Very few dairy farms remain in these areas, and the infrastructure is far away or gone. Milk processing left drove most of this.

I have spent my entire life in the dairy industry. I have witnessed the transition from tie-stall barns to larger free-stall barns in the Midwest. Most of the traditional cow regions in the Midwest and Northeast are now a blend of both. This trend will continue as small tie-stall barns get replaced with larger free-stall barns. The dairy infrastructure here is good.

The dairy industry has had regions in Idaho, Texas, Indiana, South Dakota and Kansas where the dairy infrastructure took off or is taking off. The harsh reality is that these new pockets of dairy rarely include the addition of small dairy farms. What we have currently in the United States dairy industry (and Global) are traditional cow regions, areas that are losing and areas that are gaining.

Riverview plays a huge role in maintaining a healthy dairy infrastructure in Minnesota. The dairy industry in Minnesota is stronger because of Riverview. Making it more difficult, or impossible, for Riverview, or any other dairy operation, to obtain permits to operate in Minnesota will result in the movement of dairy infrastructure and the dairy industry somewhere else. Making it less difficult for Riverview, or any other dairy operation, to obtain permits to operate in Minnesota will result in the movement of dairy infrastructure and the dairy industry into Minnesota.

The dairy industry is no different than any other industry as it relates to the environment. We have become better stewards of the land through knowledge and regulations. You can still find people or businesses that have complete disregard for the environment. The next level for me is those that are willing to follow the rules. Most farmers that I know are above these levels as they do their best to be efficient and follow practices that are positive for the environment. The next level for me is doing things to improve the environment that add cost to their business. The ultimate level is where you can find Riverview. The environmental impact is considered in every decision that they make, often resulting in additional costs and reduced efficiency.

I would like to see the dairy industry grow in my home state of Minnesota. I live a mile from a Riverview site. I breathe the air and drink the water from my well. Yes, I appreciate the protections in place for our environment. The rules need to be in place and verified for the first two levels mentioned in the previous paragraph. We don't need additional regulations for those like Riverview at the ultimate level. We do need to explore ways to make it easier (or an option) to grow for those "good farmers" at level 3

or 4 above. I don't see that right now in Minnesota. I do see our neighboring states provide this opportunity.

Riverview plays a huge role in supporting other agriculture infrastructure and other agricultural industries in Minnesota as well. The farmers next to the dairy benefit in many ways: manure as fertilizer for improved soil health, additional cropping options with corn silage and alfalfa haylage, and use of machinery and labor during forage harvest and manure application. This reaches further with the use of by-products from corn and soybean processing as food sources for dairy cows.

The additional cows proposed as part of this expansion are not introducing anything new or untested. Riverview has extensive experience managing operations of this size safely and responsibly. The current Environmental Assessment Worksheet (EAW) process is doing exactly what it is intended to do—evaluating potential impacts and ensuring environmental protections are in place. Based on the proven track record of Riverview and the safeguards provided through the EAW process; this expansion does not warrant a full Environmental Impact Statement (EIS). The existing environmental review process already provides adequate protection for Minnesota's natural resources while allowing responsible agricultural operations to move forward. Riverview Farms has shown that agricultural growth and strong environmental stewardship can go hand in hand. I respectfully encourage the MPCA to consider their outstanding environmental record and support the proposed West River Dairy expansion. Thank you for your time and consideration, and for the important work you do to protect Minnesota's environment.

Josh VanDerPol **Letter 1376 FP**

I would request that you require an EIS. These Riverview sites are not farm scale, but industrial scale. They need to regulated at the highest possible level to protect our shared environment and water resources. The amount of water pulled from the ground is very concerning for anyone on the same aquifer. The size that they are if something goes wrong with manure application or storage it would be disastrous.

Appendix B-3

Minnesota Pollution Control Agency

West River Dairy Expansion
Environmental Assessment Worksheet (EAW)

Comment Letters Received and Attachments

Attachments to Letter 0090 Diane Michelfelder

Impacts of Waste from Concentrated Animal Feeding Operations on Water Quality

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Waste from agricultural livestock operations has been a long-standing concern with respect to contamination of water resources, particularly in terms of nutrient pollution. However, the recent growth of concentrated animal feeding operations (CAFOs) presents a greater risk to water quality because of both the increased volume of waste and to contaminants that may be present (e.g., antibiotics and other veterinary drugs) that may have both environmental and public health importance. Based on available data, generally accepted livestock waste management practices do not adequately or effectively protect water resources from contamination with excessive nutrients, microbial pathogens, and pharmaceuticals present in the waste. Impacts on surface water sources and wildlife have been documented in many agricultural areas in the United States. Potential impacts on human and environmental health from long-term inadvertent exposure to water contaminated with pharmaceuticals and other compounds are a growing public concern. This workgroup, which is part of the Conference on Environmental Health Impacts of Concentrated Animal Feeding Operations: Anticipating Hazards—Searching for Solutions, identified needs for rigorous ecosystem monitoring in the vicinity of CAFOs and for improved characterization of major toxicants affecting the environment and human health. Last, there is a need to promote and enforce best practices to minimize inputs of nutrients and toxicants from CAFOs into freshwater and marine ecosystems. *Key words:* **ecology, human health, poultry, swine, water contaminants, wildlife.** *Environ Health Perspect* **115:308–312 (2007). doi:10.1289/ehp.8839 available via** *http://dx.doi.org/* **[Online 14 November 2006]**

Background and Recent Developments

Concentrated animal feed operations and water quality. Animal cultivation in the United States produces 133 million tons of manure per year (on a dry weight basis) representing 13-fold more solid waste than human sanitary waste production [U.S. Environmental Protection Agency (U.S. EPA) 1998]. Since the 1950s (poultry) and the 1970s–1980s (cattle, swine), most animals are now produced for human consumption in concentrated animal feeding operations (CAFOs). In these industrialized operations, the animals are held throughout their lives at high densities in indoor stalls until they are transported to processing plants for slaughter. There is substantial documentation of major, ongoing impacts on aquatic resources from CAFOs, but many gaps in understanding remain.

Contaminants detected in waste and risk of water contamination. Contaminants from animal wastes can enter the environment through pathways such as through leakage from poorly constructed manure lagoons, or during major precipitation events resulting in either overflow of lagoons and runoff from recent applications of waste to farm fields, or atmospheric deposition followed by dry or wet fallout (Aneja 2003). The magnitude and direction of transport depend on factors such as soil properties, contaminant properties, hydraulic loading characteristics, and crop management practices (Huddleston 1996). Many contaminants are present in livestock wastes, including nutrients (Jongbloed and Lenis 1998), pathogens (Gerba and Smith 2005; Schets et al. 2005), veterinary pharmaceuticals (Boxall et al. 2003; Campagnolo et al. 2002; Meyer 2004), heavy metals [especially zinc and copper; e.g., Barker and Zublena (1995); University of Iowa and Iowa State Study Group (2002)], and naturally excreted hormones (Hanselman et al. 2003; Raman et al. 2004). Antibiotics are used extensively not only to treat or prevent microbial infection in animals (Kummerer 2004), but are also commonly used to promote more rapid growth in livestock (Cromwell 2002; Gaskins et al. 2002; Liu et al. 2005). In addition, pesticides such as dithiocarbamates are applied to sprayfields (Extension Toxicology Network 2003). Although anaerobic digestion of wastes in surface storage lagoons can effectively reduce or destroy many pathogens, substantial remaining densities of microbial pathogens in waste spills and seepage can contaminate receiving surface- and groundwaters (e.g., Burkholder et al. 1997; Mallin 2000). Pharmaceuticals can remain present as parent compounds or degradates in manure and leachates even during prolonged storage. Improper disposal of animal carcasses and abandoned livestock facilities can also contribute to water quality problems. Siting of livestock operations in areas prone to flooding or where there is a shallow water table increases the potential for environmental contamination.

The nutrient content of the wastes can be a desirable factor for land application as fertilizer for row crops, but overapplication of livestock wastes can overload soils with both macronutrients such as nitrogen (N) and phosphorous (P), and heavy metals added to feed as micronutrients (e.g., Barker and Zublena 1995). Overapplication of animal wastes or application of animal wastes to saturated soils can also cause contaminants to move into receiving waters through runoff and to leach through permeable soils to vulnerable aquifers. Importantly, this may happen even at recommended application rates. As examples, Westerman et al. (1995) found 3–6 mg nitrate (NO_3)/L in surface runoff from sprayfields that received swine effluent at recommended rates; Stone et al. (1995) measured 6–8 mg total inorganic N/L and 0.7–1.3 mg P/L in a stream adjacent to swine effluent sprayfields. Evans et al. (1984) reported 7–30 mg NO_3/L in subsurface flow draining a sprayfield for swine wastes, applied at recommended rates. Ham and DeSutter (2000) described export rates of up to 0.52 kg ammonium m^{-2} $year^{-1}$ from lagoon seepage; Huffman and Westerman (1995) reported that groundwater near swine waste lagoons averaged 143 mg inorganic N/L, and estimated export rates at 4.5 kg inorganic N/day. Thus, nutrient losses into receiving waters can be excessive relative to levels (~ 100–200 μg inorganic N or P/L)

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known to support noxious algal blooms (Mallin 2000). In addition to contaminant chemical properties, soil properties and climatic conditions can affect transport of contaminants. For example, sandy, well-drained soils are most vulnerable to transport of nutrients to underlying groundwater (Mueller et al. 1995). Nutrients can also readily move through soils under wet conditions (McGechan et al. 2005).

Presence of contaminants in water sources. The presence of many contaminants from livestock waste has been documented in both surface water and groundwater supplies in agricultural areas within the United States (e.g., Campagnolo et al. 2002; Kolpin et al. 2002; Meyer 2004). Urban wastewater streams also contain these contaminants, and efforts to accurately determine sources of contamination are under way (Barnes et al. 2004; Cordy et al. 2004; Kolpin DW, unpublished data). The U.S. Geological Survey (USGS) began pilot surveillance programs for organic wastewater contaminants in 1999 and expanded that effort to a national scale over the past 5 years (Kolpin et al. 2002). Recent USGS efforts have focused specifically on water quality in agricultural locations (Kolpin DW, unpublished data). Nutrient levels have been detected in high parts per million (milligrams per liter) levels; pharmaceuticals and other compounds are generally measured in low levels (ppb [micrograms per liter]). In Europe, surveillance efforts conducted in Germany documented the presence of veterinary pharmaceuticals in water resources (Hirsch et al. 1999).

Animal wastes are also rich in organics and high in biochemical oxygen-demanding materials (BOD); for example, treated human sewage contains 20–60 mg BOD/L, raw sewage contains 300–400 mg BOD/L, and swine waste slurry contains 20,000–30,000 mg BOD/L (Webb and Archer 1994). Animal wastes also carry parasites, viruses, and bacteria as high as 1 billion/g (U.S. EPA 1998). Swine wastes contain > 100 microbial pathogens that can cause human illness and disease [see review in Burkholder et al. (1997)]. About one-third of the antibiotics used in the United States each year is routinely added to animal feed to increase growth (Mellon et al. 2001). This practice is promoting increased antibiotic resistance among the microbial populations present and, potentially, increased resistance of naturally occurring pathogens in surface waters that receive a portion of the wastes.

Contaminant impacts. Some contaminants pose risks for adverse health impacts in wildlife or humans. The effects of numerous waterborne pathogens on humans are well known, although little is known about potential impacts of such microorganisms on aquatic life. With respect to nutrients, excessive phosphorus levels can contribute to algal blooms and cyanobacterial growth in surface waters used for recreation and as sources of drinking water. Research is beginning to investigate the environmental effects, including endocrine disruption and antibiotic resistance issues (Burnison et al. 2003; Delepee et al. 2004; Fernandez et al. 2004; Halling-Sorensen et al. 2003; Sengelov et al. 2003; Soto et al. 2004; Wollenberger et al. 2000). However, knowledge is limited in several crucial areas. These areas include information on metabolites or environmental degradates of some parent compounds; the environmental persistence, fate, and transport and toxicity of metabolites or degradates (Boxall et al. 2004); the potential synergistic effects of various mixtures of contaminants on target organisms (Sumpter and Johnson 2005); and the potential transport and effects from natural and synthetic hormones (Hanselman et al. 2003; Soto et al. 2004). Further, limited monitoring has been conducted of ecosystem health in proximity to CAFOs, including monitoring the effects on habitats from lagoon spills during catastrophic flooding (Burkholder et al. 1997; Mallin et al. 1997; Mallin et al. 2000).

Ecologic and wildlife impacts. Anoxic conditions and extremely high concentrations of ammonium, total phosphorus, suspended solids, and fecal coliform bacteria throughout the water column for approximately 30 km downstream from the point of entry have been documented as impacts of waste effluent spills from CAFOs (Burkholder et al. 1997; Mallin et al. 2000). Pathogenic microorganisms such as *Clostridium perfringens* have been documented at high densities in receiving surface waters following CAFO waste spills (Burkholder et al. 1997). These degraded conditions, especially the associated hypoxia/anoxia and high ammonia, have caused major kills of freshwater fish of all species in the affected areas, from minnows and gar to largemouth bass, and estuarine fish, including striped bass and flounder (Burkholder et al. 1997). Waste effluent spills also stimulated blooms of toxic and noxious algae. In freshwaters, these blooms include toxic and noxious cyanobacteria while in estuaries, harmful haptophytes and toxic dinoflagellates arise. Most states monitor only water-column fecal coliform densities to assess whether waterways are safe for human contact. World Health Organization (WHO) guidelines for cyanobacteria in recreational water are 20,000 cyanobacterial cells/mL, which indicates low probability of adverse health effects, and 100,000 cyanobacterial cells/mL, which indicates moderate probability of adverse health effects (WHO 2003). Yet fecal bacteria and other pathogenic microorganisms typically settle out to the sediments where they can thrive at high densities for weeks to months following CAFO waste effluent spills (Burkholder et al. 1997).

The impacts from CAFO pollutant loadings to direct runoff are more substantial after such major effluent spills or when CAFOs are flooded and in direct contact with surface waters (Wing et al. 2002). Although the acute impacts are often clearly visible—dead fish floating on the water surface, or algal overgrowth and rotting biomass—the chronic, insidious, long-term impacts of commonly accepted practices of CAFO waste management on receiving aquatic ecosystems are also significant (U.S. EPA 1998). One purpose of manure storage basins is to reduce the N content of the manure through volatilization of ammonia and other N-containing molecules. Many studies have shown, for example, that high nutrient concentrations (e.g., ammonia from swine CAFOs, or ammonia oxidized to NO_3, or phosphorus from poultry CAFOs) commonly move off-site to contaminate the overlying air and/or adjacent surface and subsurface waters (Aneja et al. 2003; Evans et al. 1984; Sharpe and Harper 1997; Sharpley and Moyer 2000; Stone et al. 1995; U.S. EPA 1998; Webb and Archer 1994; Westerman et al. 1995; Zahn et al. 1997). Inorganic N forms are added to the atmosphere during spray practices, and both ammonia and phosphate can also adsorb to fine particles (dust) that can be airborne. The atmospheric depositions are noteworthy, considering that a significant proportion of the total ammonium from uncovered swine effluent lagoons and effluent spraying (an accepted practice in some states) reenters surface waters as local precipitation or through dry fallout (Aneja et al. 2003; U.S. EPA 1998, 2000). The contributed nutrient concentrations from the effluent greatly exceed the minimal levels that have been shown to promote noxious algal blooms (Mallin 2000) and depress the growth of desirable aquatic habitat species (Burkholder et al. 1992). The resulting chronically degraded conditions of nutrient overenrichment, while not as extreme as during a major waste spill, stimulate algal blooms and long-term shifts in phytoplankton community structure from desirable species (e.g., diatoms) to noxious species.

A summary of the findings from a national workshop on environmental impacts of CAFOs a decade ago stated that there was "a surprising lack of information about environmental impacts of CAFOs to adjacent lands and receiving waters" (Thu K, Donham K, unpublished data). Although the knowledge base has expanded since that time, especially regarding adverse effects of inorganic N and P overenrichment and anoxia, impacts of many CAFO pollutants on receiving aquatic ecosystems remain poorly understood. As examples, there is poor understanding of the impacts of fecal bacteria and other microbial pathogens from CAFO waste effluent contamination on

aquatic communities; impacts of antibiotic-resistant bacteria created from CAFO wastes on aquatic life; impacts of organic nutrient forms preferred by certain noxious plankton; impacts from the contributed pesticides and heavy metals; and impacts from these pollutants acting in concert, additively or synergistically. This lack of information represents a critical gap in our present ability to assess the full extent of CAFO impacts on aquatic natural resources.

Despite their widespread use, antibiotics have only recently received attention as environmental contaminants. Most antibiotics are designed to be quickly excreted from the treated organism. Thus, it is not surprising that antibiotics are commonly found in human and animal waste (Christian et al. 2003; Dietze et al. 2005; Glassmeyer et al. 2005; Meyer 2004) and in water resources affected by sources of waste (Glassmeyer et al. 2005; Kolpin et al. 2002). Although some research has been conducted on the environmental effects from antibiotics (e.g., Brain et al. 2005; Jensen et al. 2003), much is yet to be understood pertaining to long-term exposures to low levels of antibiotics (both individually and as part of complex mixtures of organic contaminants in the environment). The greatest risks appear to be related to antibiotic resistance (Khachatourians 1998; Kummerer 2004) and natural ecosystem functions such as soil microbial activity and bacterial denitrification (Costanzo et al. 2005; Thiele-Bruhn and Beck 2005).

Human health impacts. Exposure to waterborne contaminants can result from both recreational use of affected surface water and from ingestion of drinking water derived from either contaminated surface water or groundwater. High-risk populations are generally the very young, the elderly, pregnant women, and immunocompromised individuals. Recreational exposures and illnesses include accidental ingestion of contaminated water that may result in diarrhea or other gastrointestinal tract distress from waterborne pathogens, and dermal contact during swimming that may cause skin, eye, or ear infections. Drinking water exposures to pathogens could occur in vulnerable private wells; under normal circumstances community water utilities disinfect water sufficiently before distribution to customers. Cyanobacteria (blue–green algae) in surface water can produce toxins (e.g., microcystins) that are known neurotoxins and hepatotoxins. Acute and chronic health impacts from these toxins can occur from exposures to both raw water and treated water (Carmichael et al. 2001; Rao et al. 2002). Removal of cyanotoxins during drinking water treatment is a high priority for the drinking water industry (Hitzfield et al. 2000; Rapala et al. 2002). The WHO has set a provisional drinking water guideline of 1 μg microcystin-LR/L (Chorus and Bartram 1999). While there are no drinking water standards in the United States for cyanobacteria, they are on the U.S. EPA Unregulated Contaminant Monitoring Rule List 3 (U.S. EPA 2006).

Exposure to chemical contaminants can occur in both private wells and community water supplies, and may present health risks. High nitrate levels in water used in mixing infant formula have been associated with risk for methemoglobinemia (blue-baby syndrome) in infants under 6 months of age, although other health factors such as diarrhea and respiratory disease have also been implicated (Ward et al. 2005). The U.S. EPA drinking water standard of 10 mg/L NO_3–N and the WHO guideline of 11 mg/L NO_3–N were set because of concerns about methemoglobinemia. (Note: "nitrate" refers to nitrate–nitrogen). Epidemiologic studies of noncancer health outcomes and high nitrate levels in drinking water have reported an increased risk of hyperthyroidism (Seffner 1995) from long-term exposure to levels between 11–61 mg/L (Tajtakova et al. 2006). Drinking water nitrate at levels < 10 mg/L has been associated with insulin-dependent diabetes (IDDM; Kostraba et al. 1992), whereas other studies have shown an association with IDDM at nitrate levels > 15 mg/L (Parslow et al. 1997) and > 25 mg/L (van Maanen et al. 2000). Increased risks for adverse reproductive outcomes, including central nervous system malformations (Arbuckle et al. 1988) and neural tube defects (Brender et al. 2004; Croen et al. 2001), have been reported for drinking water nitrate levels < 10 mg/L.

Anecdotal reports of reproductive effects of nitrate in drinking water include a case study of spontaneous abortions in women consuming high nitrate water (19–26 mg/L) from private wells (Morbidity and Mortality Weekly Report 1996).

While amassing experimental data suggest a role for nitrate in the formation of carcinogenic *N*-nitroso compounds, clear epidemiologic findings are lacking on the possible association of nitrate in drinking water with cancer risk. Ecologic studies have reported mixed results for cancers of the stomach, bladder, and esophagus (Barrett et al. 1998; Cantor 1997; Eicholzer and Gutzwiller 1990; Morales-Suarez-Varela et al. 1993, 1995) and non-Hodgkin lymphoma (Jensen 1982; Weisenburger 1993), positive findings for cancers of the nasopharynx (Cantor 1997), prostate (Cantor 1997), uterus (Jensen 1982; Thouez et al. 1981), and brain (Barrett et al. 1998), and negative findings for ovarian cancer (Jensen 1982; Thouez et al. 1981). Positive findings have generally been for long-term exposures at > 10 mg/L nitrate. Case–control studies have reported mixed results for stomach cancer (Cuello et al. 1976; Rademacher et al. 1992; Yang et al. 1998); positive results for non-Hodgkin lymphoma at > 4 mg/L nitrate (Ward et al. 1996) and colon cancer at > 5 mg/L (De Roos et al. 2003); and negative results for cancers of the brain (Mueller et al. 2001; Steindorf et al. 1994), bladder (Ward et al. 2003), and rectum (De Roos et al. 2003), all at < 10 mg/L. Cohort studies have reported no association between nitrate in drinking water and stomach cancer (Van Loon et al. 1998); positive associations with cancers of the bladder and ovary at long-term exposures > 2.5 mg/L (Weyer et al. 2001); and inverse associations with cancers of the rectum and uterus, again at > 2.5 mg/L (Weyer et al. 2001).

Exposure to low levels of antibiotics and other pharmaceuticals in drinking water (generally at micrograms per liter or nanograms per liter) represent unintentional doses of substances generally used for medical purposes to treat active disease or prevent disease. The concern is more related to possible cumulative effects of long-term low-dose exposures than on acute health effects (Daughton and Ternes 1999). A recent study conducted in Germany found that the margin between indirect daily exposure via drinking water and daily therapeutic dose was at least three orders of magnitude, concluding that exposure to pharmaceuticals via drinking water is not a major health concern (Webb et al. 2003). It should be noted that when prescribing medications, providers ensure patients are not taking incompatible drugs, but exposure via drinking water is beyond their control.

Endocrine-disrupting compounds are chemicals that exhibit biological hormonal activity, either by mimicking natural estrogens, by canceling or blocking hormonal actions, or by altering how natural hormones and their protein receptors are made (McLachlan and Korach 1995). Although very low levels of estrogenic compounds can stimulate cell activity, the potential for human health effects, such as breast and prostate cancers, and reproductive effects from exposure to endocrine disruptors, is in debate (Weyer and Riley 2001).

Workshop Recommendations

Priority research needs.

- Ecosystems monitoring: Systematic sustained studies of ecosystem health in proximity to large CAFOs are needed, including effects of input spikes during spills or flooding events.
- Toxicologic assessment of contaminants: Identification and prioritization of contaminants are needed to identify those that are most significant to environmental and public health. Toxicity studies need to be conducted to identify and quantify contaminants

(including metabolites), and to investigate interactions (synergistic, additive, and antagonistic effects).

- Fate and transport: Studies of parent compounds and metabolites in soil and water must be conducted, and the role of sediment as a carrier and reservoir of contaminants must be evaluated.
- Surveillance programs: Programs should be instituted to assess private well water quality in high-risk areas. Biomonitoring programs should be designed and implemented to assess actual dose from environmental exposures.

Translation of science to policy.

- Wastewater and drinking water treatment: Processes for water treatment must be monitored to ensure adequate removal or inactivation of emerging contaminants.
- Pollution prevention: Best management practices should be implemented to prevent or minimize release of contaminants into the environment.
- Education: Educational materials should be continued to be developed and distributed to agricultural producers.

References

Aneja VP, Nelson DR, Roelle PA, Walker JT. 2003. Agricultural ammonia emissions and ammonium concentrations associated with aerosols and precipitation in the southeast United States. J Geophys Res 108(D4):ACH12-1–12-11.

Arbuckle TE, Sherman GJ, Corey PN, Walters D, Lo B. 1988. Water nitrates and CNS birth defects: a population-based case-control study. Arch Environ Health 43:162–167.

Barker JC, Zublena JP. 1995. Livestock Manure Nutrient Assessment in North Carolina. Final Report. Raleigh, NC: North Carolina Agricultural Extension Service, North Carolina State University.

Barnes KK, Christenson SC, Kolpin DW, Focazio MJ, Furlong ET, Zaugg SD, et al. 2004. Pharmaceuticals and other organic wastewater contaminants within a leachate plume downgradient of a municipal landfill. Ground Water Monitoring Rev 24:119–126.

Barrett JH, Parslow RC, McKinney PA, Law GR, Forman D. 1998. Nitrate in drinking water and the incidence of gastric, esophageal, and brain cancer in Yorkshire, England. Cancer Causes Control 9:153–159.

Boxall ABA, Kolpin DW, Halling-Sorenson B, Tolls J. 2003. Are veterinary medicines causing environmental risks? Environ Sci Technol 37:286A–294A.

Boxall ABA, Sinclair CJ, Fenner K, Kolpin DW, Maund SJ. 2004. When synthetic chemicals degrade in the environment. Environ Sci Technol 38:369A–375A.

Brain RA, Wilson CJ, Johnson DJ, Sanderson H, Bestari K, Hanson ML, et al. 2005. Effects of a mixture of tetracyclines to *Lemna gibba* and *Miriophyllum sibiricum* evaluated in aquatic microcosms. Environ Pollution 138:425–442.

Brender JD, Olive JM, Felkner M, Suarez L, Marckwardt W, Hendricks KA. 2004. Dietary nitrites and nitrates, nitrosable drugs, and neural tube defects. Epidemiology 15:330–336.

Burkholder JM, Mallin MA, Glasgow HB, Larsen LM, McIver MR, Shank GC, et al. 1997. Impacts to a coastal river and estuary from rupture of a large swine waste holding lagoon. J Environ Qual 26:1451–1466.

Burkholder JM, Mason KM, Glasgow HB. 1992. Water-column nitrate enrichment promotes decline of eelgrass (*Zostera marina* L.): evidence from seasonal mesocosm experiments. Mar Ecol Prog Ser 81:163–178.

Burnison BK, Hartmann A, Lister A, Servos MR, Ternes T, Van der Kraak G. 2003. A toxicity identification evaluation approach to studying estrogenic substances in hog manure and agricultural runoff. Environ Toxicol Chem 22:2243–2250.

Campagnolo ER, Johnson KR, Karpati A, Rubin CS, Kolpin DW, Meyer MT, et al. 2002. Antimicrobial residues in animal waste and water resources proximal to large-scale swine and poultry feeding operations. Sci Total Environ 299:89–95.

Cantor KP. 1997. Drinking water and cancer. Cancer Causes Control 8:292–308.

Carmichael WW, Azevedo SMFO, An JS, Molica RJR, Jochimsen EM, Lau S, et al. 2001. Human fatalities from cyanobacteria: chemical and biological evidence for cyanotoxins. Environ Health Perspect 109:663–668.

Chorus I, Bartram J, eds. 1999. Toxic Cyanobacteria in Water—A Guide to their Public Health Consequences, Monitoring and Management. Geneva:World Health Organization. Available: http://www.who.int/water_sanitation_health/resourcesquality/toxicyanbact/en/ [accessed 5 January 2007].

Christian T, Schneider RJ, Barber HA, Skutlarek D, Meyer GT, Goldrach HE. 2003. Determination of antibiotic residues in manure, soil, and surface waters. Acta Hydrochim Hydrobiol 31:36–44.

Cordy G, Duran N, Bower H, Rice R, Kolpin DW, Furlong ET, et al. 2004. Do pharmaceuticals, pathogens, and other organic wastewater compounds persist when wastewater is used for recharge? Ground Water Monitoring Rev 24:58–69.

Costanzo SD, Murby J, Bates J. 2005. Ecosystem response to antibiotics entering the aquatic environment. Marine Pollut Bull 51:218–223.

Croen LA, Todoroff K, Shaw GM. 2001. Maternal exposure to nitrate from drinking water and diet and risk for neural tube defects. Am J Epidemiol 153:325–331.

Cromwell GL. 2002. Why and how antibiotics are used in swine production. Anim Biotechnol 13:7–27.

Cuello C, Correa P, Haenszel W, Gordillo G, Brown C, Archer M, et al. 1976. Gastric cancer in Columbia. 1. Cancer risk and suspect environmental agents. J Natl Cancer Inst 57:1015–1020.

Daughton CG, Ternes TA. 1999. Pharmaceuticals and personal care products in the environment: agents of subtle change? Environ Health Perspect 107:907–938.

Delepee R, Pouliquen H, Le Bris H. 2004. The bryophyte *Fontinalis antipyretica* Hedw. bioaccumulates oxytetracycline, flumequine and oxolinic acid in the freshwater environment. Sci Total Environ 322:243–253.

De Roos AJ, Ward MH, Lynch CF, Cantor KP. 2003. Nitrate in public water supplies and the risk of colon and rectum cancers. Epidemiology 14:640–649.

Dietze JE, Scribner EA, Meyer MT, Kolpin DW. 2005. Occurrence of antibiotics in water from 13 fish hatcheries, 2001–03. Intern J Environ Anal Chem 85:1141–1152.

Eicholzer M and Gutzwiller F. 1990. Dietary nitrates, nitrites and *N*-nitroso compounds and cancer risk: a review of the epidemiologic evidence. Nutr Rev 56:95–105.

Evans, RO, Westerman PW, Overcash MR. 1984. Subsurface drainage water quality from land application of swine lagoon effluent. Trans Am Soc Agric Eng 27:473–480.

Extension Toxicology Network. 2003. Exotoxnet—A Pesticide Information Project of the Cooperative Extension Offices of Cornell University, Michigan State University, Oregon State University, and the University of California at Davis. U.S. Department of Agriculture, Extension Service, and the National Agricultural Pesticide Impact Assessment Program. Available: http://ace.orst.edu/info/extoxnet/ [accessed 26 September 2005].

Fernandez C, Alonso C, Babin MM, Pro J, Carbonell G, Tarazona JV. 2004. Ecotoxicological assessment of doxycycline in aged pig manure using multispecies soil systems. Sci Total Environ 323:63–69.

Gaskins HR, Collier CT, Anderson DB. 2002. Antibiotics as growth promoters: mode of action. Anim Biotechnol 13:29–42.

Gerba CP, Smith JE Jr. 2005. Sources of pathogenic microorganisms and their fate during land application of wastes. J Environ Qual 34:42–48.

Glassmeyer ST, Furlong ET, Kolpin DW, Cahill JD, Werner SL, Meyer MT, et al. 2005. Transport of chemical and microbial contaminants from known wastewater discharges: Potential for use as indicators of human fecal contamination. Environ Sci Technol 39:5157–5169.

Halling-Sorensen B, Sengelov G, Ingerslev F, Jensen LB. 2003. Reduced antimicrobial potencies of oxytetracycline, tylosin, sulfadiazine, streptomycin, ciprofloxacin, and olaquindox due to environmental processes. Arch Environ Contam Toxicol 44:7–16.

Ham JM, DeSutter TM. 2000. Toward site-specific design standards for animal-waste lagoons: protecting ground water quality. J Environ Qual 29:1721–1732.

Hanselman TA, Graetz DA, WIlkie AC. 2003. Manure-borne estrogens as potential environmental contaminants: a review. Environ Sci Technol 37:5471–5478.

Hirsch R, Ternes T, Haberer K, Kratz KL. 1999. Occurrence of antibiotics in the aquatic environment. Sci Total Environ 225:109–118.

Hitzfield BC, Hoger SJ, Dietrich DR. 2000. Cyanobacterial toxins: Removal during drinking water treatment, and human risk assessment. Environ Health Perspect 108:113–122.

Huddleston JH. 1996. How Soil Properties Affect Groundwater Vulnerability to Pesticides Contamination. Oregon State Extension Service. Available: http://wwwagcomm.ads.orst.edu/AgComWebFile/EdMat/EM8559.pdf [accessed 26 September 2005].

Huffman RL, Westerman PW. 1995. Estimated seepage losses from established swine waste lagoons in the lower coastal plain of North Carolina. Transact Am Soc Agric Eng 38:449–453.

Jensen K, Krogh PH, Sverdup LE. 2003. Effects of the antibacterial agents tiamulin, olanquindox and metronidazole and the antihelminthic ivermectin on the soil invertebrate species *Folsomia fimeteria* (Collembola) and *Enchytraeus crypticus* (Enchytraeidae). Chemosphere 50:437–443.

Jensen OM. 1982. Nitrate in drinking water and cancer in northern Jutland, Denmark, with special reference to stomach cancer. Ecotoxicol Environ Saf 9:258–267.

Jongbloed AW, Lenis NP. 1998. Environmental concerns about animal manure. J Anim Sci 76:2641–2648.

Khachatourians GG. 1998. Agricultural use of antibiotics and the evolution and transfer of antibiotic-resistant bacteria. Can Med Assoc J 159:1129–1136.

Kolpin DW, Furlong ET, Meyer MT, Thurman EM, Zaugg SD, Barber LB, et al. 2002. Pharmaceuticals, hormones and other organic wastewater contaminants in U.S. streams, 1999–2000: a national reconnaissance. Environ Sci Technol 36:1202–1211.

Kostraba JN, Gay EC, Rewers M, Hamman RF. 1992. Nitrate levels in community drinking waters and risk of IDDM: an ecological analysis. Diabetes Care 15:1505–1508.

Kummerer K. 2004. Resistance in the environment. J Antimicrob Chemother 54:311–320.

Liu X, Miller GY, McNamara PE. 2005. Do antibiotics reduce production risk for U.S. pork producers? J Agric Appl Econ 37:565–575.

Mallin MA. 2000. Impacts of industrial-scale swine and poultry production on rivers and estuaries. Am Sci 88:26–37.

Mallin, MA, Burkholder JM, Shank GC, McIver MR, Glasgow HB, Springer J, et al. 1997. Comparative impacts of effluent from poultry and swine waste holding lagoon spills on receiving rivers and tidal creeks. J Environ Qual 26:1622–1631.

McGechan MB, Lewis DR, Hooda PS. 2005. Modelling through-soil transport of phosphorous to surface waters from livestock agriculture at the field and catchment scale. Sci Total Environ 344:185–199.

McLachlan JA, Korach KS. 1995. Symposium on Estrogens in the Environment, III. Environ Health Perspect 103:3–4.

Mellon MC, Benbrook C, Benbrook KL. 2001. Estimates of antimicrobial abuse in livestock. Cambridge, MA:Union of Concerned Scientists.

Meyer MT. 2004. Use and Environmental Occurrence of Veterinary Pharmaceuticals in the United States. In: Pharmaceuticals in the Environment: Sources, Fate, Effects, and Risks (Kummerer K, ed). New York:Springer-Verlag,155–163.

Morales-Suarez-Varela M, Llopis-Gonzales A, Tejerizo-Perez ML, Ferrandiz Ferragud J. 1993. Concentration of nitrates in drinking water and its relationship with bladder cancer. J Environ Pathol Toxicol Oncol 12:229–236.

Morales-Suarez-Varela MM, Llopis-Gonzalez A, Tejerizo-Perez ML. 1995. Impact of nitrates in drinking water on cancer mortality in Valencia, Spain. Eur J Epidemiol 11:15–21.

Morbidity and Mortality Weekly Report (MMWR). 1996. Spontaneous abortions possibly related to ingestion of nitrate-contaminated well water—LaGrange County, Indiana, 1991–1994. MMWR 45:569–572.

Mueller BA, Newton, K, Holly EA, Preston-Martin S. 2001. Residential water source and the risk of childhood brain tumors. Environ Health Perspect 109:551–556.

Mueller DK, Hamilton PA, Helsel DR, Hitt KJ, Ruddy BC. 1995.

Nutrients in groundwater and surface water of the United States—an analysis of data through 1992. US Geological Survey Water Resour Invest Rep 95–4031.

Parslow RC, McKinney PA, Law GR, Staines A, Williams B, Bodansky HJ. 1997. Incidence of childhood diabetes mellitus in Yorkshire, northern England, is associated with nitrate in drinking water: an ecological analysis. Diabetologia 40(5):550–556.

Rademacher JJ, Young TB, Kanarek MS. 1992. Gastric cancer mortality and nitrate levels in Wisconsin drinking water. Arch Environ Health 47:292–294.

Raman DR, Williams EL, Layton AC, Burns RT, Easter JP, Daugherty AS, et al. 2004. Estrogen content of dairy and swine wastes. Environ Sci Technol 38:3567–3573.

Rao PV, Gupta N, Bhaskar AS, Jayaraj R. 2002. Toxins and bioactive compounds from cyanobacteria and their implications on human health. J Environ Biol 23:215–224.

Rapala J, Lahti K, Rasanen LA, Esala AL, Niemela SI, Sivonen K. 2002. Endotoxins associated with cyanobacteria and their removal during drinking water treatment. Water Res 36:2627–2635.

Schets FM, During M, Italiaander R, Heijnen L, Rutjes SA, van der Zwaluw WK, et al. 2005. *Escherichia coli* O157:H7 in drinking water from private water supplies in the Netherlands. Water Res 39:4485–4493.

Seffner W. 1995. Natural water contents and endemic goiter. Zantralblatt Hyg Umwelt 196:381–398.

Sengelov G, Agerso Y, Halling-Sorensen B, Baloda SB, Andersen JS, Jensen LB. 2003. Bacterial antibiotic resistance levels in Danish farmland as a result of treatment with pig manure slurry. Environ Int 28:587–595.

Sharpe RR and Harper LA. 1997. Ammonia and nitrous oxide emissions from sprinkler irrigation applications of swine effluent. J Environ Qual 26:1703–1706.

Sharpley A, Moyer B. 2000. Phosphorus forms in manure and compost and their release during simulated rainfall. J Environ Qual 29:1462–1469.

Soto AM, Calabro JM, Prechtl NV, Yau AY, Orlando EF, Daxenberger A, et al. 2004. Androgenic and estrogenic activity in water bodies receiving cattle feedlot effluent in eastern Nebraska, USA. Environ Health Perspect 112:346–352.

Steindorf K, Schlehofer B, Becher H, Hornig G, Wahrendorf J. 1994. Nitrate in drinking water: a case-control study on primary brain tumours with an embedded drinking water survey in Germany. Int J Epidemiol 23:451–457.

Stone KC, Hunt PG, Coffey SW, Matheny TA. 1995. Water quality status of A USDA water quality demonstration project in the Eastern Coastal Plain. J Soil Wat Conserv 50:567–571.

Sumpter JP, Johnston AC. 2005. Lessons from endocrine disruption and their application to other issues concerning trace organics in the aquatic environment. Environ Sci Technol 39:4321–4332.

Tajtakova M, Semanova Z, Tomkova Z, Szokeova E, Majoroa J, Radikova Z, et al. 2006. Increased thyroid volume and frequency of thyroid disorders signs in schoolchildren from nitrate polluted area. Chemosphere 62:559–564.

Thiele-Bruhn S, Beck IC. 2005. Effects of sulfonamide and tetracycline antibiotics on soil microbial activity and microbial biomass. Chemosphere 59:457–465.

Thouez J-P, Beauchamp Y, Simard A. 1981. Cancer and the physicochemical quality of drinking water in Quebec. Soc Sci Med 15D:213–223.

University of Iowa and Iowa State Study Group. 2002. Iowa Concentrated Animal Feeding Operations Air Quality Study. Iowa City, IA:The University of Iowa College of Public Health.

U.S. EPA. 1998. Environmental Impacts of Animal Feeding Operations. Washington, DC:U.S. Environmental Protection Agency, Office of Water, Standards and Applied Sciences Division. Available: http://www.epa.gov/ostwater/guide/feedlots/envimpct.pdf [accessed 26 September 2005].

U.S. EPA. 2000. Deposition of Air Pollutants to the Great Waters. 3rd Report to the U.S. Congress. (1) Section A. Washington, DC:U.S. Environmental Protection Agency.

U.S. EPA. 2006. Approved Methods for Unregulated Contaminants. U.S. Environmental Protection Agency. Available: http://www.epa.gov/ogwdw/methods/unregtbl.html [accessed 5 January 2007].

Van Loon AJM, Botterweck AAM, Goldbohm RA, Brants HAM, van Klaveren JD, van den Brandt PA. 1998. Intake of nitrate and nitrite and the risk of gastric cancer: a prospective cohort study. Br J Cancer 7:129–135.

Van Maanen JM, Albering HJ, de Kok TM, van Breda SG, Curfs DM, Vermeer IT, et al. 2000. Does the risk of childhood diabetes mellitus require revision of the guideline values for nitrate in drinking water? Environ Health Perspect 108(5):457–461.

Ward MH, Cantor KP, Riley D, Merkle S, Lynch CF. 2003. Nitrate in public water supplies and risk of bladder cancer. Epidemiology 14:183–190.

Ward MH, deKok TM, Levallois P, Brender J, Gulis G, Nolan BT, et al. 2005. Workgroup report: drinking-water nitrate and health—recent findings and research needs. Environ Health Perspect 113:1607–1614.

Ward MH, Mark SD, Cantor KP, Weisenburger DD, Correa-Villasenore A, Zahm SH. 1996. Drinking water and the risk of non-Hodgkin's lymphoma. Epidemiology 7:465–471.

Webb J, Archer JR. 1994. Pollution of soils and watercourses by wastes from livestock production systems. In: Pollution in Livestock Production Systems (Dewi IA, Axford RFE, Marai IFM, Omed HM, eds). Oxfordshire, UK:CABI Publishing, 189–204.

Webb S, Ternes T, Gibert M, Olejniczak K. 2003. Indirect human exposure to pharmaceuticals via drinking water. Toxicol Lett 142:157–167.

Weisenburger D. 1993. Potential health consequences of ground-water contamination of nitrates in Nebraska. Nebr Med J 78:7–10.

Westerman PW, Huffman RL, Feng JS. 1995. Swine-lagoon seepage in sandy soil. Transact ASAE 38(6):1749–1760.

Weyer P, Riley D. 2001. Endocrine Disruptors and Pharmaceuticals in Drinking Water. Denver, CO:AWWA Research Foundation and the American Water Works Association.

Weyer PJ, Cerhan JR, Kross BC, Hallberg GR, Kantamneni J, Breuer G, et al. 2001. Municipal drinking water nitrate level and cancer risk in older women: the Iowa Women's Health Study. Epidemiology 11:327–338.

WHO. 2003. Algae and cyanobacteria in fresh water. In: Guidelines for Safe Recreational Water Environments. Vol 1: Coastal and Fresh Waters. Geneva:World Health Organization, 136–138.

Wing S, Freedman S, Band, L. 2002. The potential impact of flooding on confined animal feeding operations in eastern North Carolina. Environ Health Perspect 110:387–391.

Wollenberger L, Halling-Sorensen B, Kusk KO. 2000. Acute and chronic toxicity of veterinary antibiotics to *Daphnia magna*. Chemosphere 40:723–730.

Yang C-Y, Cheng M-F, Tsai S-S, Hsieh Y-L. 1998. Calcium, magnesium, and nitrate in drinking water and gastric cancer mortality. Jpn J Cancer Res 89:124–130.

Zahn JA, Hatfield JL, Do YS. 1997. Characterization of volatile organic emissions and wastes from a swine production facility. J Environ Qual 26:1687–1696.

Appendix B-3

Minnesota Pollution Control Agency

West River Dairy Expansion
Environmental Assessment Worksheet (EAW)

Comment Letters Received and Attachments

Attachments to Letter 0158 David Jungst



Appendix B-3

Minnesota Pollution Control Agency

West River Dairy Expansion
Environmental Assessment Worksheet (EAW)

Comment Letters Received and Attachments

Attachments to Letter 1289 Minnesota Center for Environmental Advocacy

IFCN Top-10 List: Dairy Farming Companies Worldwide 2020

IFCN Dairy Research Network, Kiel, Germany
Milica Kocic, Torsten Hemme
milica.kocic@ifcndairy.org; torsten.hemme@ifcndairy.org

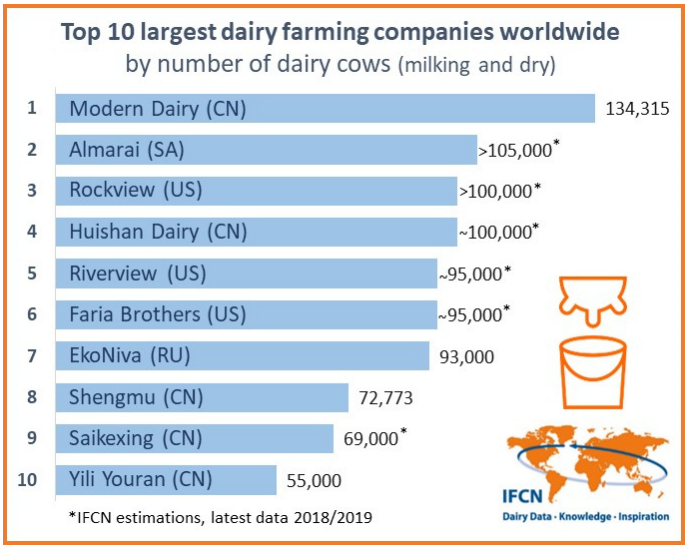
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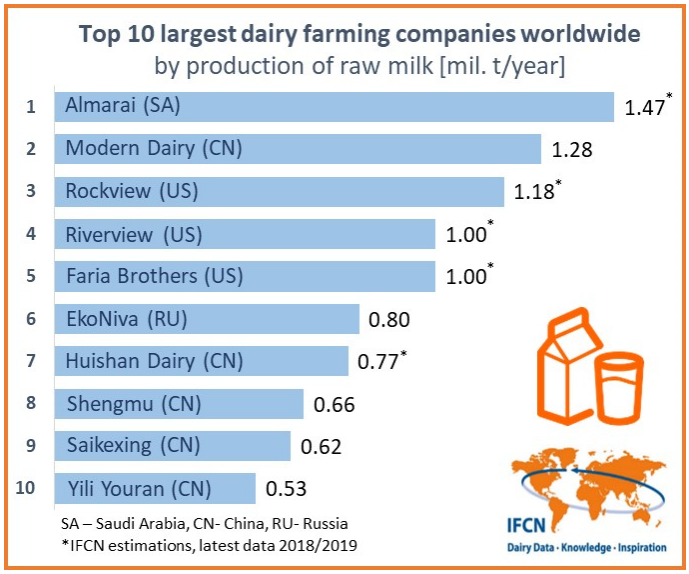
Summary: According to IFCN's latest research, Saudi Arabia and China have the largest dairy farming enterprises in the world. China holds half of the top 10 list, while the rest of the companies are located in Saudi Arabia, Russia and the USA. These top 10 companies, with multiple dairy farms, together produced 1.1% of world's milk output in 2018.

Almarai the largest "dairy farm" by milk volume
Almarai from Saudi Arabia has the largest milk production with 1.47 million metric tons per year. This volume is similar to the milk production of Indonesia or Norway. Almarai has over 100,000 dairy cows.

***Modern Dairy* the largest "dairy farm" by cow number**
Modern Dairy from China has the largest dairy herd in the world with 134,315 dairy cows. They recorded 1.28 million metric tons of milk in 2018. This company manages its herd in 26 locations located across seven different provinces.

Almarai, Mengnui and Yili the top 3 farming companies
The Chinese farms are often subsidiaries of large milk processors (e.g. *Mengniu, Yili*, etc.) or have long-term strategic partnerships with them in order to secure upstream supply chain and synergize the best of both producers and processors of milk. Based on this IFCN classifies the top 3 dairy farming companies Almarai, Mengnui and Yili.





US dairy farms driven by family ownership models

The three US farms have developed over generations out of single dairy farms. Currently they have a large number of dairy farms in different states. These farms are in many cases run by different family members.

***EkoNiva* the fastest growing dairy farm in the world**
Ekoniva is the largest milk producer in Europe and is the fastest growing farming company in this list. They expect to exceed 1,0 million tons of milk in 2020.

The myth of large vs small dairy farms: IFCN research of farming systems in over 50 countries shows that larger farms usually outperform smaller farms in various aspects of sustainability (environmental, social and economic). Source: IFCN Dairy Report 2019

Method: The research was conducted by the IFCN Dairy Research Network aiming to create a better understanding of the dairy world. The data is based on annual reports, publicly available information and experts' estimations. IFCN welcomes any feedback to improve this analysis.

IFCN is a global network for dairy economic research and consultancy in the supply chain. In 2020 dairy researchers from over 100 countries and over 140 dairy related companies are a member. For details: www.ifcndairy.org

Global dairy production: Top 10 largest dairy farms in the world

Ana Sofia Santos (Head of Research and Innovation at Feedinox CoLAB)

Updated: 2 Jun 2025 | 12 min read

Introduction

Global **dairy production** is increasingly driven by large-scale farms capable of producing hundreds of thousands of tonnes of raw milk annually. This article ranks the world's top 10 largest dairy farms based on annual milk output, highlighting how scale, technology, and productivity shape modern dairy production.

- Introduction
- Why is scale becoming the dominant factor in global dairy production?
- How were the world's largest dairy farms ranked?
- Where is large-scale dairy production geographically concentrated?
- Which farms lead global dairy production by scale and output?
- Which technologies drive efficiency in large-scale dairy production?
- Why are European dairy farms absent from the global top 10 ranking?
- Key Takeaways
- References

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Why is scale becoming the dominant factor in global dairy production?

Global **dairy production** is no longer defined by herd expansion alone. Instead, scale, productivity per cow, capital intensity and technology adoption are now the primary drivers of competitiveness.

According to the OECD–FAO Agricultural Outlook, global milk production is **projected to grow at 1.5–2% annually through 2031–2034**, with the majority of growth coming from higher yields, improved management, and technological innovation, rather than increases in animal numbers.



- Only farms or farm groups that own and directly manage dairy herds are included
- Dairy cooperatives, processors, and farmer networks are excluded
- The goal is structural consistency at the farm level, not market share or processing capacity

Where is large-scale dairy production geographically concentrated?

Mega-scale dairy farms are primarily concentrated in China, Saudi Arabia, Russia, the United States, and Southeast Asia. These regions combine access to capital, land, and regulatory frameworks that allow dairy operations to scale rapidly.

Rank	Farm / Farm Group	Country	Raw milk production (t/year)
1	Mudanjiang Mega Dairy Farm	China	+2,000,000
2	Almarai	Saudi Arabia	+1,470,000
3	Modern Dairy	China	+1,200,000
4	Ekolnica	Russia	+1,200,000
5	Riverview LLP	USA	+800,000–1,000,000
6	Rockview Family Farms	USA	+1,000,000
7	Huishan Dairy	China	+800,000
8	Al Safi Dairy Farm	Saudi Arabia	+350,000
9	Greenfields Dairy Farm	Indonesia	+400,000–450,000
10	Fair Oaks Farms	USA	+350,000–400,000

Which farms lead global dairy production by scale and output?

1. Mudanjiang Mega Dairy Farm (China)

At the top of the ranking stands Mudanjiang Mega Dairy Farm, producing an estimated **2 million tonnes of raw milk annually**. With a herd exceeding 135,000 **dairy cows**, it currently represents the most concentrated industrial dairy operation. With yields approaching 15,000 kg per cow per year reflect intensive genetic selection, precision nutrition, and fully controlled housing systems.

2. Almarai (Saudi Arabia)

Saudi Arabia features prominently, led by Almarai, whose dairy farms collectively produce close to **1.5 million tonnes of milk per year** under desert conditions. This output is enabled by heavy investment in cooling infrastructure, imported feed, and vertical integration. While highly resource-intensive, these systems demonstrate that climatic constraints can be overcome through capital and technology, achieving productivity levels comparable to temperate-zone mega farms.

3. Modern Dairy (China)

Modern Dairy ranks among the world's largest dairy producers, with an estimated annual production of around **1.20 million tonnes of raw milk**. The company operates multiple very large farms under centralized ownership, allowing them to capture economies of scale while spreading geographic and climatic risk.

4. Ekolnica (Russia)

Ekolnica is Russia's largest farm group, with annual milk production estimated at approximately **1.2 million tonnes**. The group's size and presence across multiple farming sites help balance production conditions across regions, limiting the impact of weather or regional disruptions on overall milk output.

5. Riverview LLP (United States)

In the United States, Riverview LLP has emerged as one of the largest dairy operators, with annual milk production estimated between **800,000 and 1 million tonnes**. Operating across multiple states, the company relies heavily on automation, genetic progress, feed efficiency, and data-driven management to remain competitive in a mature market characterized by rising labor, regulatory, and environmental costs.

6. Rockview Family Farms (United States)

Rockview Family Farms ranks among the world's largest dairy operations, with annual milk production close to **1 million tonnes**. It is recognized as the largest documented family-owned dairy farm group, highlighting the scale that can be reached under single-family ownership.

7. Huishan Dairy (China)

Huishan Dairy represents a centrally managed, multi-farm group in China, with total production of approximately **800,000 tonnes per year**. Its model emphasizes geographic dispersion, standardized management, and integration with domestic processing and retail markets.

8. Al Safi Dairy Farm (Saudi Arabia)

Al Safi Dairy Farm is one of the world's largest single-site, fully integrated dairy operations, with annual milk production of around **550,000 tonnes**. Located in Saudi Arabia, its performance is driven by extreme capital intensity and advanced cooling systems, enabling consistently high productivity despite harsh climatic conditions.

9. Greenfields Dairy Farm (Indonesia)

Greenfields Dairy Farm generates an estimated **400,000 to 450,000 tonnes of milk per year**, making it one of Southeast Asia's largest dairy operations.

Source: Greenfields

10. Fair Oaks Farms (United States)

Fair Oaks Farms, the largest documented single-site dairy farm in the U.S., rounds out the top 10 with **350,000 to 400,000 tonnes of annual milk production**.

Which technologies drive efficiency in large-scale dairy production?

Across all Top 10 farms, innovation is the common denominator. High-output dairy systems consistently deploy:

- Precision feeding and ration optimization
- Digital herd monitoring and health analytics
- Advanced reproductive and genetic programs
- Automation and standardized operating protocols

These technologies underpin the OECD–FAO projection that future milk supply growth will be driven primarily by productivity gains per animal, not by expanding herd sizes.

Why are European dairy farms absent from the global top 10 ranking?

One outcome of this ranking is the absence of European Union dairy farms from the global Top 10. This is not due to missing data, but to structural differences in production models.

European dairy farming is dominated by family-owned farms, operating under strict environmental, animal welfare, and land-use regulations. Scale is achieved primarily through cooperative aggregation, rather than through ultra-large, centrally owned farms. As a result, even Europe's largest individual farms fall well below the production thresholds required to be included in a global Top 10 ranking based on raw milk output per farm. Nonetheless, the EU's dairy sector is highly efficient and will be addressed in future articles.

Key Takeaways

- The world's largest dairy farms highlight a sector increasingly driven by scale, capital, and technology.
- Productivity gains—not herd expansion—will define future milk supply growth.
- Cooperative-based models are dominant in Europe and India, while mega-farms dominate in China and Saudi Arabia.
- Understanding these structural differences is essential for informed discussions on sustainability, competitiveness, and global food security.



References

OECD & FAO. (2025). OECD-FAO Agricultural Outlook 2025-2034: Dairy and dairy products chapter. OECD Publishing. https://www.oecd.org/en/publications/2025/07/oecd-fao-agricultural-outlook-2025-2034_b6d2591d/full-report/dairy-and-dairy-products_1b50d5e6.html

FAO. (2024). Dairy Market Review 2024: Overview of global dairy market developments in 2023. Food and Agriculture Organization of the United Nations. https://www.fao.org/markets-and-trade/publications/dairy-archive/en

Hemme, T., & Otte, J. (Eds.). (2022). *FCN Dairy Report 2021* (extended). International Farm Comparison Network. Retrieved from https://ifcndairy.org/wp-content/uploads/2022/10/Dairy-Report-22-Kapitel-extended.pdf

International Farm Comparison Network. (2022). *FCN Dairy Report 2021 farm comparison* (extract). IFCN. Retrieved from https://ifcndairy.org/wp-content/uploads/2022/10/Dairy-Report-22-Kapitel-extended.pdf

European Parliament Research Service. (2018). *EU livestock farming: Structure and trends*. https://www.europarl.europa.eu/thinktank/en/document/EPRS_BRI(2018)630385

Santos, A.S. (2025). World's largest integrated dairy farm: a look at innovation and scale. CEVA Ruminants Blog. Published May 2025. https://ruminants.ceva.com/dairy-farming

Sousa, A.V. (2025). Top 10 dairy farms in the world. In CEVA Ruminants Blog. Published August 2025. https://ruminants.ceva.com/dairy-production

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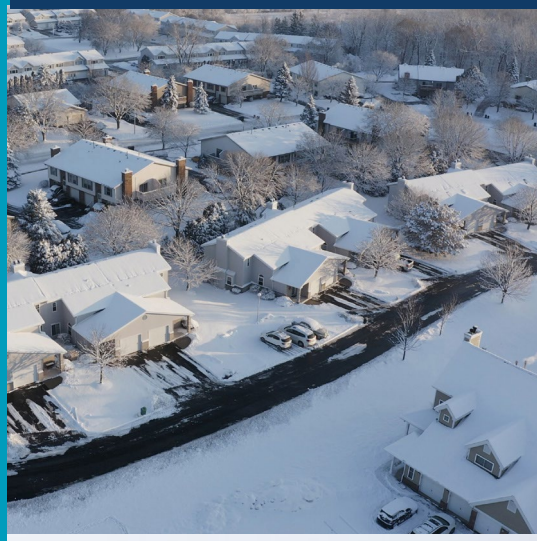
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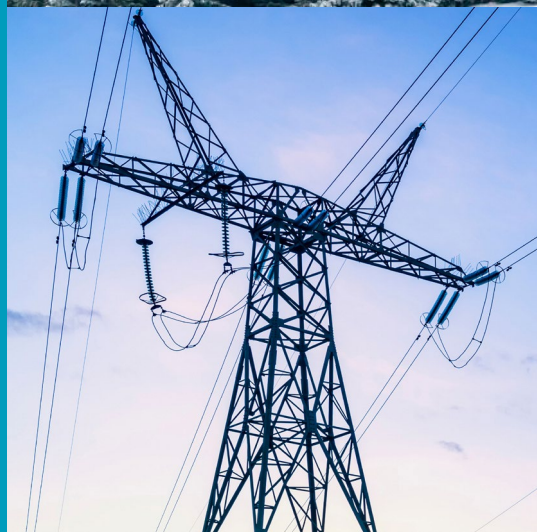
JANUARY 2025

Greenhouse gas emissions in Minnesota 2005-2022

Biennial inventory report tracking the state's greenhouse gas emissions contributing to climate change.







MINNESOTA

Pollution Control Agency
Department of Commerce

Greenhouse gas emissions in Minnesota 2005-2022:

Biennial inventory report tracking the state's greenhouse gas emissions contributing to climate change.

Report to Legislature, January 2025. Jointly submitted by the Pollution Control Agency and the Department of Commerce

Legislative charge

Minn. Stat. § 216H.02 Greenhouse gas emissions control.

Subd. 1. Greenhouse gas emissions-reduction goal. It is the goal of the state to reduce statewide greenhouse gas emissions across all sectors producing those emissions to a level at least 15% below 2005 levels by 2015, to a level at least 30% below 2005 levels by 2025, and to a level at least 80% below 2005 levels by 2050. The levels shall be reviewed based on the climate change action plan study.

Minn. Stat. § 216H.07 Emissions-reduction attainment; policy development process.

Subd. 3. Biennial report. (a) By January 15 of each odd-numbered year, the commissioners of commerce and the Pollution Control Agency shall jointly report to the chairs and ranking minority members of the legislative committees with primary policy jurisdiction over energy and environmental issues the most recent and best available evidence identifying the level of reductions already achieved and the level necessary to achieve the reductions timetable in section 216H.02. (b) The report must be in easily understood nontechnical terms.

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Introduction

The reality of climate change continues to have a profound impact on the lives of Minnesotans. The extreme conditions Minnesota experienced in 2023 and 2024, including an exceptionally warm winter and major spring rains, were consistent with ongoing climate change trends. The changes in our climate are being felt across Minnesota's communities, economy, cultures, and ecosystems.

More information about climate trends and the impacts of climate change is available from the **Department of Natural Resources** www.dnr.state.mn.us/climate

Heavy rains are now more common in Minnesota and more intense than at any time on record. Long-term observation sites have seen dramatic increases in 1-inch rains, 3-inch rains, and the size of the heaviest rainfall of the year. Frequent and intense storms are damaging homes, businesses, infrastructure, farms, and ecosystems.

Minnesota's winters are also becoming shorter and milder. This climate trend is called "cold weather warming," and it means that the average temperature of winter months is increasing faster than the average temperature of summer months. Over the last 50 years, Minnesota's winter has warmed an incredible 13 times faster than summer. Warmer winters allow some pests like ticks and certain invasive species to survive and multiply. Over those 50 years, Minnesota lakes have also lost an average of 10 to 14 days of ice, affecting lake and fish health, outdoor recreation opportunities, and business owners.

Simply put, Minnesota is getting warmer and wetter. Changes to our climate, such as heavier and more frequent rainfall events and warmer winters, are caused by human activities that release greenhouse gases (GHGs). Our changing climate has economic and environmental impacts for Minnesotans. Over the past decade, for instance, our state has been experiencing a much higher rate of natural disasters, with a higher number of individual storms that cause more than $1 billion in damage.

This report summarizes what we know about GHG emissions in Minnesota, including the major sources and trends over time. Tracking GHG emissions and identifying their sources are two important ways that state government can help Minnesotans understand how our actions contribute to our changing climate and how we can curb our climate pollution.

To guide our response to climate change, the State of Minnesota has developed a Climate Action Framework (mn.gov/framework). The Framework identifies immediate, near-term actions to reduce climate pollution and prepare Minnesota communities for the impacts of climate change. The Framework is currently being updated to include a comprehensive set of actions that help us achieve those goals. Analyzing Minnesota's emissions through this inventory allows us to track progress on the Framework goals and focus on actions with maximum impact to address climate change.

This inventory documents Minnesota's GHG emissions from 2005 through 2022 and shows the impact of actions taken by individuals, organizations, and governments across Minnesota to reduce climate pollution. The COVID-19 pandemic changed how Minnesotans lived and worked in 2020. As Minnesotans returned to regular activities, emissions that dropped steeply in 2020 rebounded, reflecting a similar trend nationally. Despite the rebound, emissions from sectors like transportation, electricity generation, industrial, agriculture, and waste remain below 2019 levels, indicating lasting changes toward increased energy efficiency and a low-carbon economy.

Billions of dollars in state and federal climate investments made between 2022 and 2024 will reduce GHG emissions in Minnesota. The impacts of these investments cannot yet be seen in the data of this report, and the

momentum of those investments will be felt for decades to come. While there is much work ahead to meet our climate goals, this inventory demonstrates that collaborative action and smart policy-making work.

Evaluating greenhouse gas emissions

Greenhouse gases (GHGs) warm the planet's atmosphere and surface. Human activity increases the amount of GHGs in the atmosphere, leading to changes in Earth's climate. The Minnesota Greenhouse Gas Emissions Inventory accounts for the six GHGs originally covered by the Kyoto Protocol of the United Nations Framework Convention on Climate Change: carbon dioxide (CO_2), nitrous oxide (N_2O), methane (CH_4), sulfur hexafluoride (SF_6), and two types of compounds called hydrofluorocarbons (HFCs) and perfluorocarbons (PFCs).

GHGs come from a variety of sources in our state:

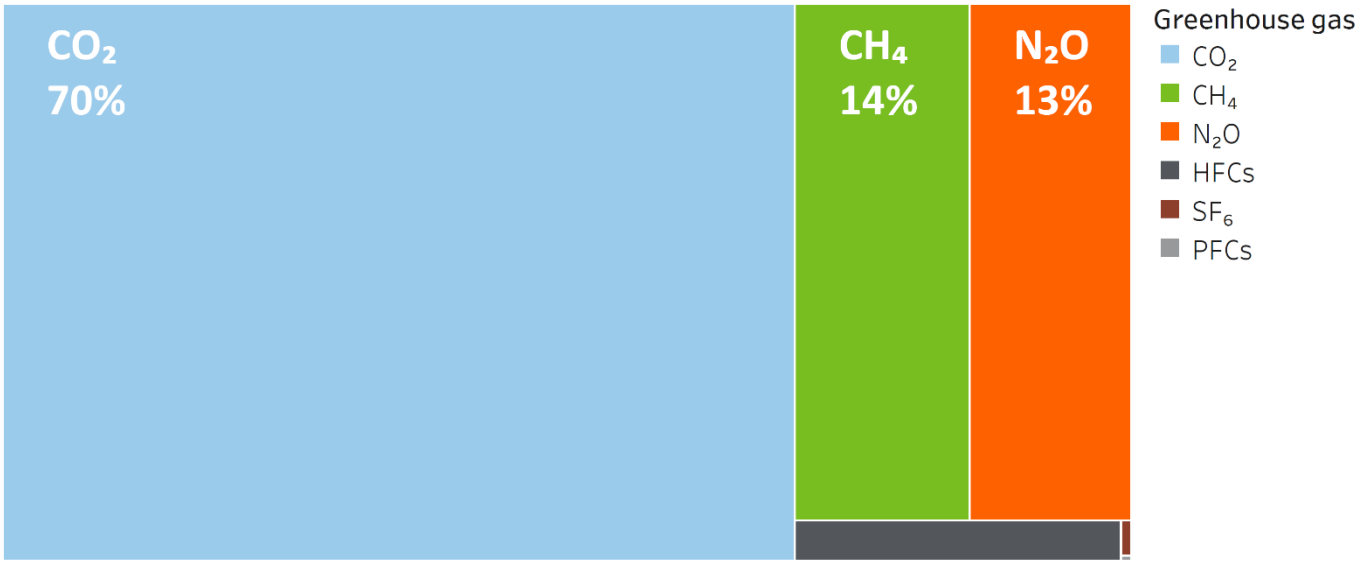
- Fossil fuel combustion is responsible for most carbon dioxide emissions in Minnesota and the United States. The majority of fossil fuels used today are burned to generate electricity, fuel vehicles, and provide heat for homes and industrial processes, all of which are significant sources of emissions.
- Animal agriculture is responsible for most methane emissions in Minnesota. Materials decomposing in landfills and in bodies of water also emit methane.
- Agricultural nutrient management practices, including fertilizer application and subsequent mineralization, cause over 50% of nitrous oxide emissions.
- Most hydrofluorocarbon emissions are from refrigerants used in vehicle and building air conditioners.
- Perfluorocarbons and sulfur hexafluoride account for a small portion of GHG emissions and are released from technical applications like semiconductor manufacturing and electricity transmission.

Carbon dioxide is the primary GHG emitted by human activities, followed by methane and nitrous oxide. Other GHGs are emitted in smaller amounts, but trap heat more effectively than carbon dioxide, and some stay in our atmosphere for a very long time, contributing more to climate change.

Global warming potential (GWP) is a relative measure of how much heat a GHG traps in the atmosphere. To compare different emissions and pollutants, we use the effect of carbon dioxide on our climate as a standard reference. In this report, emissions are reported as metric tons of carbon dioxide-equivalent (CO_2-e), meaning emissions are stated in relative terms that reflect their impact on global temperatures.

Minnesota's net GHG emissions in 2022 by gas

Emissions are expressed as percent of total CO_2-equivalent and includes carbon sequestration.



Greenhouse gases, their 100-year global warming potentials, and their persistence in Earth's atmosphere.

Greenhouse gas	Global warming potential (GWP)	Persistence in Earth's atmosphere
Carbon dioxide (CO_2)	1	Variable, up to thousands of years
Nitrous oxide (N_2O)	265	121 years
Methane (CH_4)	28	12 years
Sulfur hexafluoride (SF_6)	23,500	3,200 years
Hydrofluorocarbons (HFCs)	Up to 12,400	Up to 242 years
Perfluorocarbons (PFCs)	Up to 11,100	2,600 to 50,000 years

Source: IPCC Fifth Assessment Report, Working Group 1 Chapter 8

Tracking statewide emission reduction progress

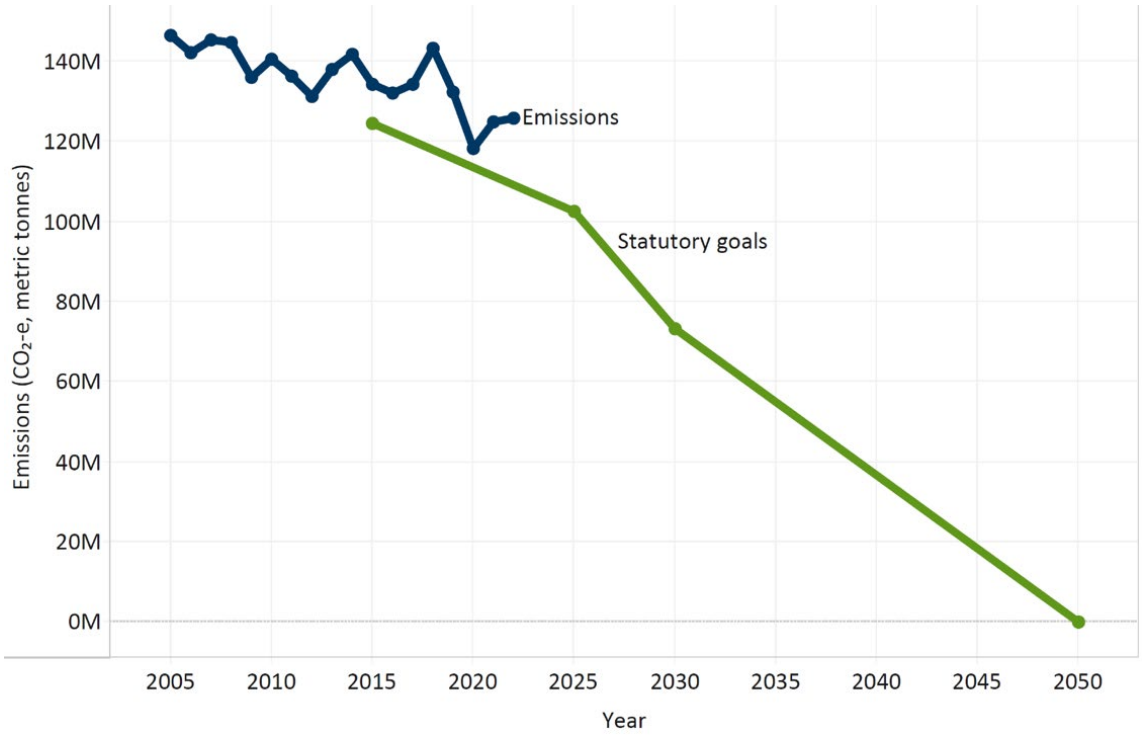
In 2007, the Minnesota Legislature passed the Next Generation Energy Act, setting our state's first science-based goals to reduce our GHG emissions in the state compared to our emissions in 2005.[1] Since then, Minnesota has reassessed and updated our state's GHG emissions goals in the Climate Action Framework, and subsequently in statute, based on current scientific evidence. Now, Minnesota's GHG emissions reduction goals are to reduce emissions by 15% by 2015, 30% by 2025, 50% by 2030 (from a 2005 baseline), and to reach net-zero by 2050.

Minnesota did not reach the statutory goal of reducing emissions by 15% by 2015. Between 2005 and 2022, Minnesota's GHG emissions fell by 14%, making it difficult to achieve our goals if we maintain current trends. Changes in fuels used for electricity generation have resulted in significant emission reductions from the electricity generation sector and are the most significant contributor to statewide emission reductions between 2005 and 2022.

Between 2020 and 2022, emissions rose due to economic activity resuming after the height of the COVID-19 pandemic, reflecting increased energy use and transportation demands. The emission increases in 2021 and 2022 are consistent with nationwide emission increases calculated by the US EPA. The good news is that 2022 emissions reflect a continuation of pre-pandemic long-term downward trends.

Recent emission reductions show that action can get us on track to achieve our statutory goals and reach net-zero emissions by 2050. The rate of reduction since 2005 shows that much work remains to achieve these ambitious and necessary goals.

Minnesota's greenhouse gas emissions and statutory goals

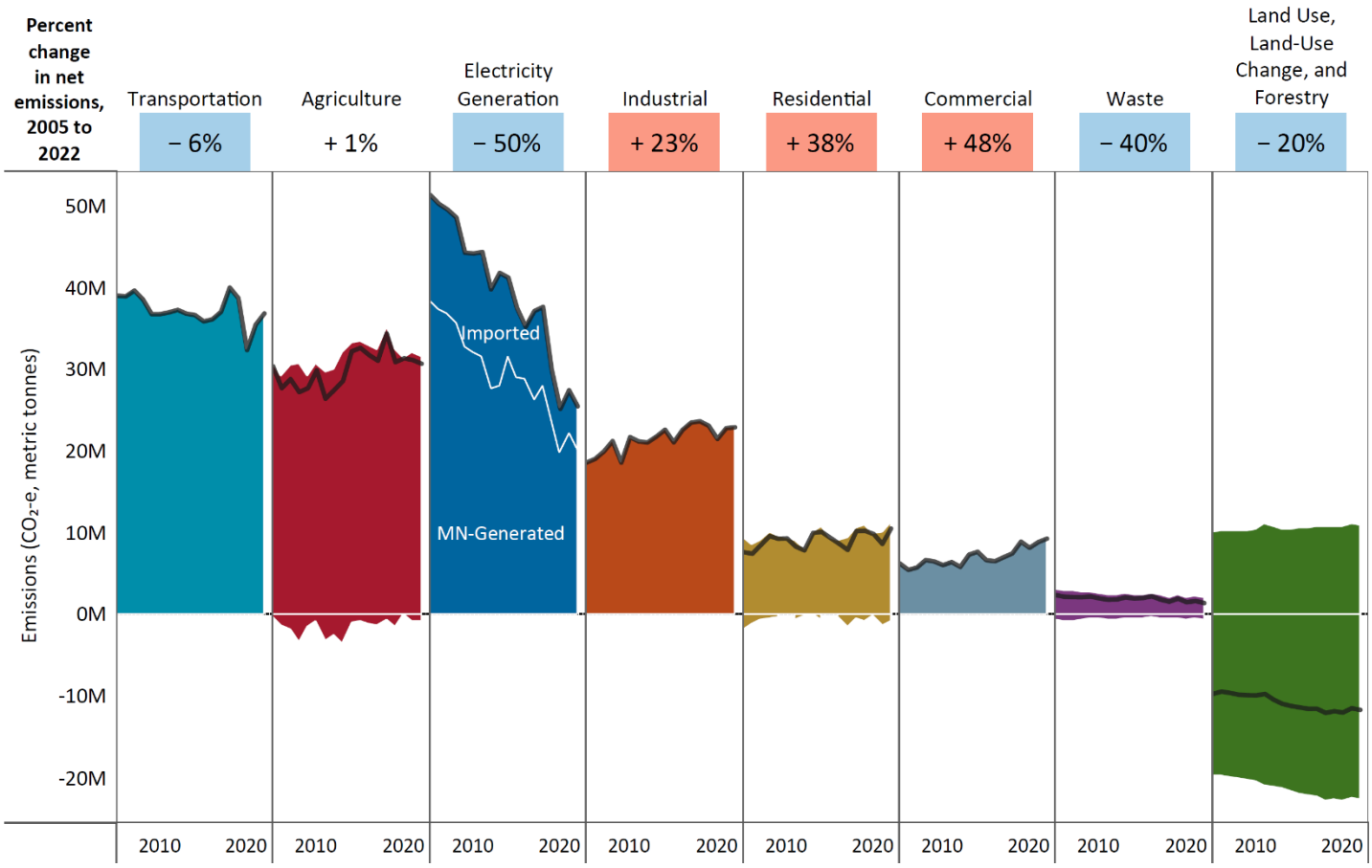


[1] Data revisions and changes in methodology can cause the baseline to change, but continuity is provided when making relative year-to-year emissions comparisons.

Sectoral greenhouse gas emissions

This section reports annual GHG emissions and terrestrial sequestration of carbon from 2005 through 2022 for the eight economic sectors in Minnesota: transportation; agriculture; electricity generation; industrial; residential; commercial; waste; and land use, land-use change, and forestry. The “agriculture” and “land use, land-use change, and forestry”sectors have replaced the “agriculture, forestry, and other land use” sector from previous inventories to allow for better alignment with the EPA's national GHG quantification approach and to provide greater detail than in previous reports. Interactive data visualizations are available at https://www.pca.state.mn.us/air-water-land-climate/climate-change-trends-and-data.

Minnesota’s GHG emissions across economic sectors from 2005 to 2022, ranked by net 2022 emissions.

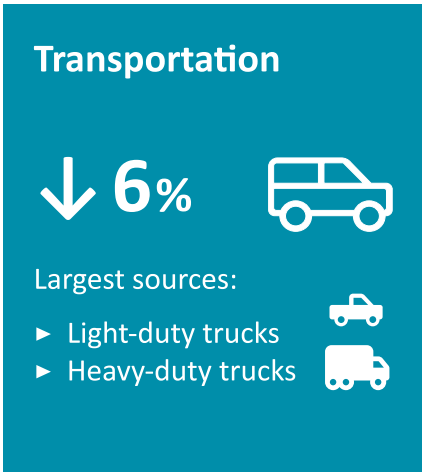


Dark lines represent the net emissions for each sector (gross emissions minus sequestration). Carbon sequestration is shown as negative emissions, present in the agriculture; residential; waste; and land use, land use change, and forestry sectors. The electricity generation sector differentiates emissions from electricity generated in Minnesota versus those from imported electricity. The percent change from 2005 to 2022 is shown above the chart by sector. Blue and red indicate reductions and increases in emissions, respectively.

Transportation

Minnesota's largest source of GHG emissions is the transportation sector, accounting for about 29% of the state's total emissions. Since the baseline year of 2005, total GHG emissions from transportation have decreased by about 6%. While emissions from aviation and light-duty trucks rebounded after the height of the pandemic in 2020, they remain below pre-pandemic levels. In contrast, emissions from heavy-duty trucks are now higher than pre-pandemic levels.

GHG emissions 2005-2022



Emissions sources in the transportation sector include:

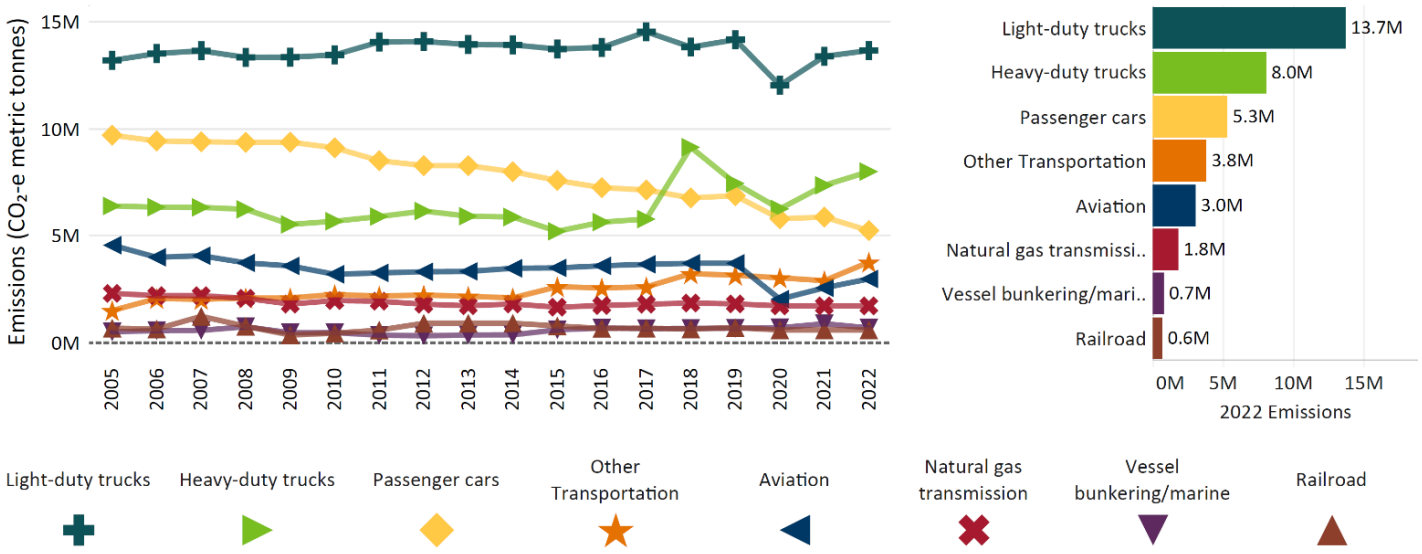
- on-road vehicles, including passenger vehicles, light-duty trucks, medium- to heavy-duty trucks, RVs, buses, and motorcycles
- airplanes and other aviation equipment
- trains
- marine vehicles
- off-highway gasoline vehicles and equipment, including military vehicles, ATVs, and snowmobiles
- vehicle air conditioning units
- natural gas transmission pipelines

Our personal choices have a significant impact on emissions, especially when it comes to how we move around. Passenger vehicles account for about 14% of emissions in this sector, while light-duty trucks (including pickup trucks, minivans, and SUVs) make up about 37%. Medium- to heavy-duty trucks (including delivery vans, large commercial vehicles, and tractor-trailers) produce about 22% of emissions in this sector.

While stronger federal vehicle emissions standards have helped reduce GHG emissions overall, long-term trends in consumer preferences for larger vehicles and the increasing number of miles driven (except during the pandemic) have slowed potential progress in reducing emissions. Although the adoption of electric vehicles is growing, the trend toward larger, higher-emitting vehicles challenges the pace at which electric vehicles and vehicle emissions standards can reduce emissions.

Continued investment in cleaner vehicles and expanding transportation options, such as public transit, biking, walking, and rolling, is essential to achieve further emission reductions in this sector. Also important to the reduction of transportation sector emissions are changes in land use development patterns that promote denser development and housing near amenities and transportation options. This type of development makes the use of transportation options other than cars more convenient and encourages shorter trips.

Transportation sector GHG emissions



Emissions by subsector from 2005 to 2022 (left) and only 2022 (right). “Other Transportation” includes bus, motorcycle, RV, mobile air conditioning, and miliary/other off-highway emissions.

Agriculture

Minnesota's second-largest source of GHG emissions is the agriculture sector, accounting for about 25% of the state's net emissions. Since 2005, net GHG emissions from agriculture are essentially unchanged.

In previous versions of this report, agriculture, forests, and other land uses were grouped into a single sector. Separating agriculture into its own sector results in better alignment with the US Environmental Protection Agency's (EPA) national approach to GHG quantification, allows more detail, and clarifies that sequestration in natural landscapes offsets emissions from all sectors, not only agriculture.

Emission sources and sequestration in the agriculture sector include:

- livestock digestion
- manure storage and land application
- fertilizer use
- methane emissions avoided due to the anaerobic digestion of manure (a process that captures methane that would otherwise be emitted to the atmosphere)
- emissions and sequestration of carbon within cropland soils*

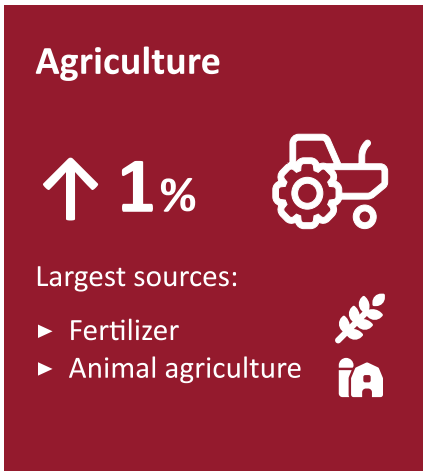
*Due to the difficulty of differentiating grazed from ungrazed grasslands, carbon stock changes within all grasslands are included in the land use, land-use change, and forestry sector

Within agriculture, GHG fluxes (i.e., emissions and sequestration) are largely driven by plants and the microbes in soils, manure storage areas, and cattle digestive systems. It is not possible to directly measure these fluxes across the state, so we use scientific models to estimate them. Models of GHG fluxes within agricultural systems continue to become more sophisticated, useful, and accurate. While coarse data on management decisions (e.g., aerial imagery, grower surveys, and product sales records) are sources of uncertainty in these estimates, models provide helpful estimates of the impacts of crop and livestock management practices, environmental conditions, and other variables on GHG emissions and sequestration.

Agricultural practices in Minnesota are responsible for 96% of the state's nitrous oxide emissions and 44% of the state's methane emissions. The largest sources of nitrous oxide are the land application of synthetic fertilizers and manure, and the subsequent mineralization and runoff of that nitrogen. Methane emissions are caused by cattle digestion and manure storage practices.

The largest source of carbon dioxide from the agricultural sector is the use of drained organic soils for crop production. Compared to other states, Minnesota is uniquely rich in organic soils, which form within peatlands (a class of wetlands that includes bogs) over thousands of years and have high soil carbon content. When left untouched, peatlands are massive stores of carbon. However, during the 20th century in Minnesota, there was significant drainage and tillage of peatlands for crop production. Lowering the water table exposes these large carbon stocks to the air,

GHG emissions 2005-2022



Minnesota agriculture summary

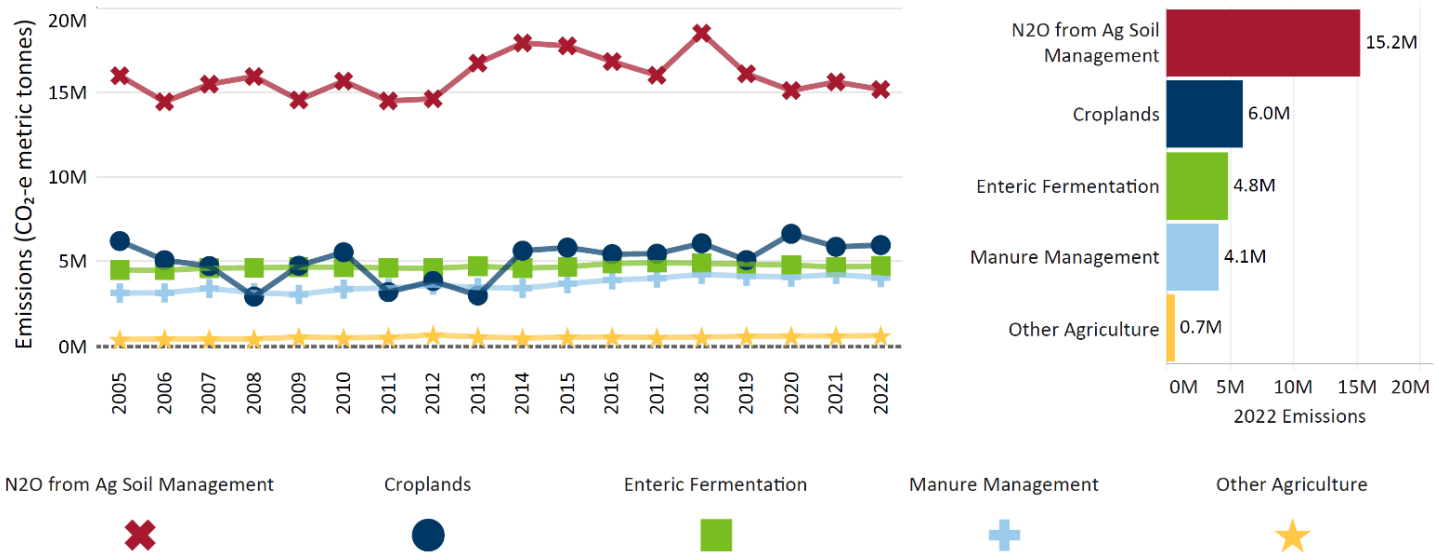
- Minnesota has over 65,000 farms operating on 21.5 million acres of cropland, 3% of which are irrigated.
- Minnesota has 650 organic farms on 164,000 acres.
- Minnesota ranks in the top 10 for over 20 agricultural products, including #1 in turkeys and sugar beets, #2 in hogs, #3 in soybeans, and #4 in corn.
- Minnesota has approximately 25,000 farms with animals, including 8.9 million hogs, 2.1 million cattle and calves, 14.9 million turkeys, 14.5 million laying hens, and 7.8 million broiler chickens.

Sources: US Department of Agriculture, Minnesota Department of Agriculture

which which allows them to decompose and release carbon dioxide for several decades unless they are rewetted. Regardless of the soil health practices employed, drained organic soils lose more carbon than they can gain. In contrast, there are approximately 20 million acres of croplands on mineral soils (i.e., non-peat soils) in Minnesota, which, on average, are sequestering soil carbon. The carbon sequestered by Minnesota's approximately 20 million acres of croplands on mineral soils is outweighed by the carbon dioxide emissions from the roughly 405,000 acres of croplands on drained organic soils. This area, approximately equivalent to the size of Hennepin County, represents a significant source of greenhouse gas emissions. The most effective way to reduce these emissions is to restore drained organic soils where practicable to their natural state as peatlands. In addition to curbing emissions, restored peatlands provide critical habitat for unique native species and help protect downstream water quality. Efforts to rewet peatlands are already underway on private, public, and tribal lands, with additional public funding for this work becoming available soon.

While net emissions from Minnesota agriculture have not changed significantly since 2005, improved efficiency and more sustainable agricultural management practices have resulted in our farms producing more food, biofuel, and fiber than ever before. Agriculture is the second-highest emitting sector in the state, as emissions from electricity generation have declined substantially since 2005. Significant opportunities remain for emission reductions and additional carbon sequestration while maintaining agricultural productivity. Investments are being made at the state and federal levels to support sustainable agricultural practices and on-farm energy and efficiency projects, such as the recent EPA-awarded $200 million grant to cut climate pollution from our state's food systems through the federal Climate Pollution Reduction Grants program.

Agriculture sector GHG emissions



Emissions by subsector from 2005 to 2022 (left) and only 2022 (right). "Other Agriculture" includes field burning of agricultural residues, CO_2 from carbon containing fertilizers, and rice cultivation.

Reducing emissions and sequestering carbon through crop agriculture

Within crop agriculture, nitrous oxide emissions can be reduced through the efficient use of nitrogen fertilizers. Successful nitrogen use results from applying the right source of nitrogen at the right rate, time, and place to maximize plant uptake and minimize losses to the environment. To enhance nitrogen efficiency, timing strategies can be complemented with the use of nitrification inhibitors, urease inhibitors, and other controlled-release fertilizers. These products extend the duration of nitrogen availability to growing crops, reducing nitrogen losses and GHG emissions by about 21 metric tons of CO_2-equivalent per 100 acres per year. If applied to 10 million acres per year, these products could reduce agricultural soil emissions by about 2 million metric tons of CO_2-equivalent annually, equivalent to removing about 500,000 gasoline-powered passenger vehicles from the road for one year.

Actions aimed at improving soil health and water quality can also boost carbon sequestration in plants, soil, and aquatic ecosystems. Examples include planting perennial field borders; incorporating trees and shrubs; retiring marginal lands into conservation easements; and the long-term adoption of reduced tillage, perennials in crop rotations, and cover crops. Cover cropping has been shown to prevent soil erosion, reduce nutrient losses, suppress weeds, and accumulate organic carbon in soil. According to United States Department of Agriculture surveys, from 2012 to 2022, the number of acres in Minnesota with cover crops increased from about 408,000 to 760,000. Although results vary, a typical implementation of cover crops in Minnesota results in a net reduction of about 15 metric tons of CO_2-equivalent per 100 acres per year. Therefore, in 2022, cover crops likely reduced net emissions by over 113,000 metric tons of CO2-equivalent, comparable to removing about 26,000 gasoline-powered passenger vehicles from the road for one year. There is potential to significantly increase cover cropping in Minnesota. If cover cropping was implemented and maintained on about 13 million of the 20 million acres of crop agriculture in Minnesota, this could also reduce net GHG emissions from agriculture by up to 2 million metric tons of CO_2-equivalent per year, comparable to removing about 500,000 gasoline-powered passenger vehicles from the road for one year.

Reducing emissions from animal agriculture

Within animal agriculture, methane is the dominant GHG and is produced through cattle digestion and manure storage. An important long-term action to limit methane from cattle digestion (or "enteric fermentation") is to incorporate relevant genetics into herds to increase feed conversion efficiency, reduce cull rates, and influence other aspects of digestion, including the rumen microbial community. Increasing feed digestibility also helps, though Minnesota cattle already feed on high-quality forage compared to much of the globe. A variety of feed additives can also reduce enteric methane production by up to 30% during certain life stages, but research is ongoing and cost is currently a barrier to adoption.

Another source of avoidable methane emissions is manure stored as a liquid under anaerobic conditions, such as in open lagoons. Where manure is stored as a liquid, managed anaerobic digestion systems can capture the resulting methane and sell or use it as a replacement for fossil fuels. Anaerobic digestion systems work better for some species and types of manure infrastructure than others. They are most economical at large farms or in cooperative models (with manure from multiple farms combined in a single system), where market incentives promote renewable fuels (e.g., via low carbon fuel standards), and where other materials can be co-digested. Alternatively, managing manure as a solid and grazing livestock in pastures generates little methane because the manure is broken down by aerobic microbes. Other methane-reducing manure management interventions include composting and avoiding land application during wet field conditions.

Electricity generation

Electricity generation is the third-largest source of GHG emissions in Minnesota, accounting for about 20% of the state's net emissions. Burning fossil fuels, especially coal, to generate electricity for Minnesotans, whether produced in-state or out-of-state, is this sector's primary source of GHG emissions. Other smaller sources include:

- methane from coal storage
- carbon dioxide from scrubbing other air pollutants from facility emissions
- sulfur hexafluoride from electricity transmission and distribution

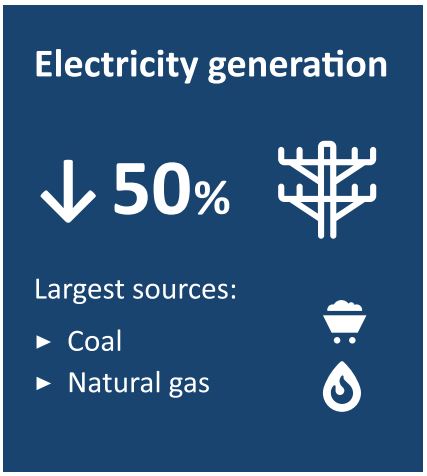
Since 2005, emissions from the electricity generation sector have declined by 50%. The significant decrease is mainly a result of the transition away from coal toward renewable energy sources to generate electricity. Renewable sources produced 32% of Minnesota-generated electricity in 2022.

Previously, Minnesota's electricity generation sector was the largest source of GHG emissions, and the greatest emissions reductions have been made here.

In Minnesota, we use more electricity than we generate inside our borders. As required by the statute, this report measures total GHG emissions from electricity generation, including emissions from electricity generated at facilities within the state, and provides an estimate of the electricity used here in Minnesota that is generated outside of our state borders (imported). Emissions from both Minnesota-generated and imported electricity generation have decreased since 2005.

Emissions per kilowatt-hour from electricity imported from the regional electrical grid are higher than in-state generation because some neighboring states haven't reduced their emissions as much as Minnesota. The amount of electricity imported into Minnesota continues to decrease as in-state generation increases, reducing the amount of estimated imported electricity and associated GHG emissions.

GHG emissions 2005-2022



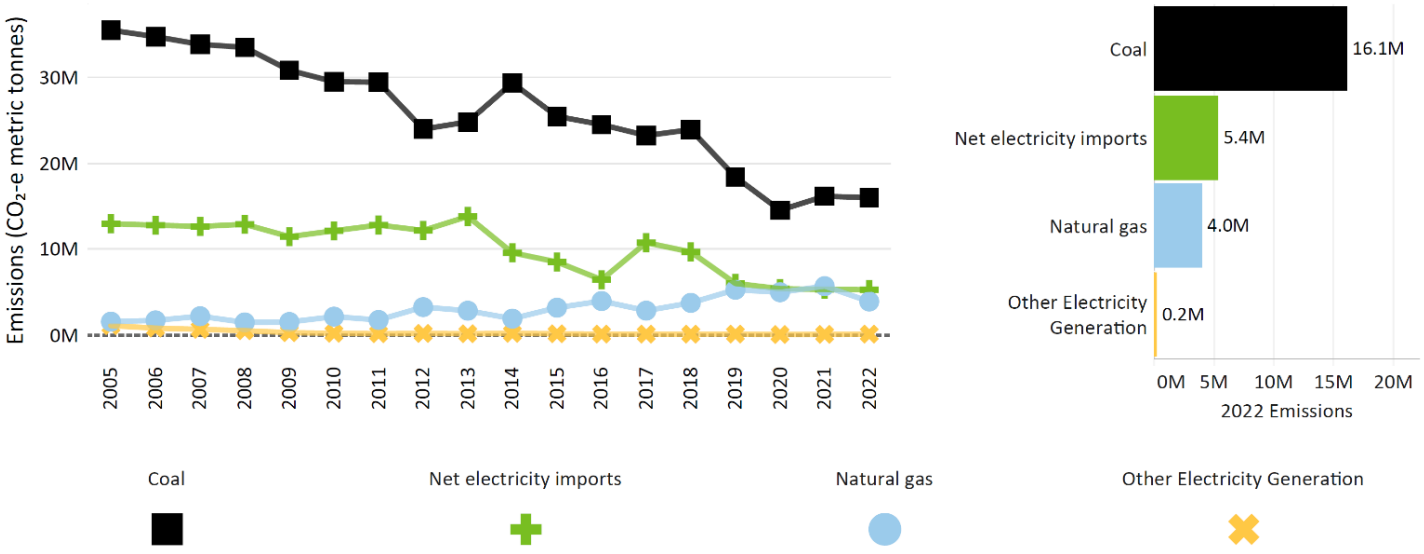
Percentage of Minnesota electricity utility generation (resource mix), 2022

Coal	27.4%
Wind	25.6%
Nuclear	24.9%
Gas	14.8%
Solar	3.2%
Biomass	2.0%
Hydroelectric	1.6%
Other fossil	0.4%

Source: eGRID

GHG emission reductions will continue in the electricity generation sector as a result of planned closures of coal-fired power plants in Minnesota, as indicated in the table below. In addition, in 2023, the Minnesota Legislature adopted a new Clean Electricity Standard that requires electric utilities to provide net-zero, or 100% carbon-free, electricity by 2040. Carbon-free electricity is important to help the state reduce emissions through electrification of other uses of fossil fuel combustion, such as vehicles and building heating. Continued focus on thoughtful transition to support an electric grid that is reliable, safe, affordable, and increasingly clean is vital to achieving economy-wide GHG emission reduction goals.

Electricity generation sector GHG emissions



Emissions by subsector from 2005 to 2022 (left) and only 2022 (right). "Other Electricity Generation" includes oil, SF6 emissions related to transmission, non-CO2 emissions from biofuels, coal storage, and flue-gas desulfurization.

Utility-owned coal-fired electricity generating units in Minnesota (as of December 2024)

Facility	Size (MW)	Status
Hibbing Public Utilities Commission		
Hibbing 3	10	Standby/backup: available for service but not normally used
Hibbing 5	20	Standby/backup: available for service but not normally used
Hibbing 6	6	Standby/backup: available for service but not normally used
Minnesota Power		
Boswell Unit 3	365	Operating: Cease coal-fired operations by year-end 2029
Boswell Unit 4	558	Operating: Proposed to cease coal-fired operations by 2035
Hibbard Energy Center Unit 3	30	Operating
Hibbard Energy Center Unit 4	32	Operating
Xcel Energy		
Sherburne County 1	680	Operating: full retirement by 2026
Sherburne County 3	876	Operating: full retirement by 2030
Allen S King	511	Operating: full retirement by 2028

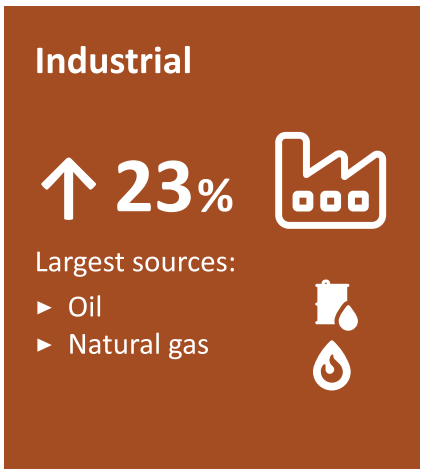
Industrial

The industrial sector is the fourth-largest source of GHG emissions in Minnesota, accounting for about 18% of the state's net emissions. The industrial sector includes direct emissions from industrial facility processes and fossil fuel combustions. Emissions from electricity use in the industrial sector are accounted for under the electricity generation sector. Since 2005, emissions have increased in this sector by 23%.

Emissions sources in the industrial sector include:

- fossil-fuel combustion
- petroleum refining
- taconite processing
- lead recycling
- industrial wastewater treatment
- solvent use
- manufacturing of steel, glass, and semiconductors

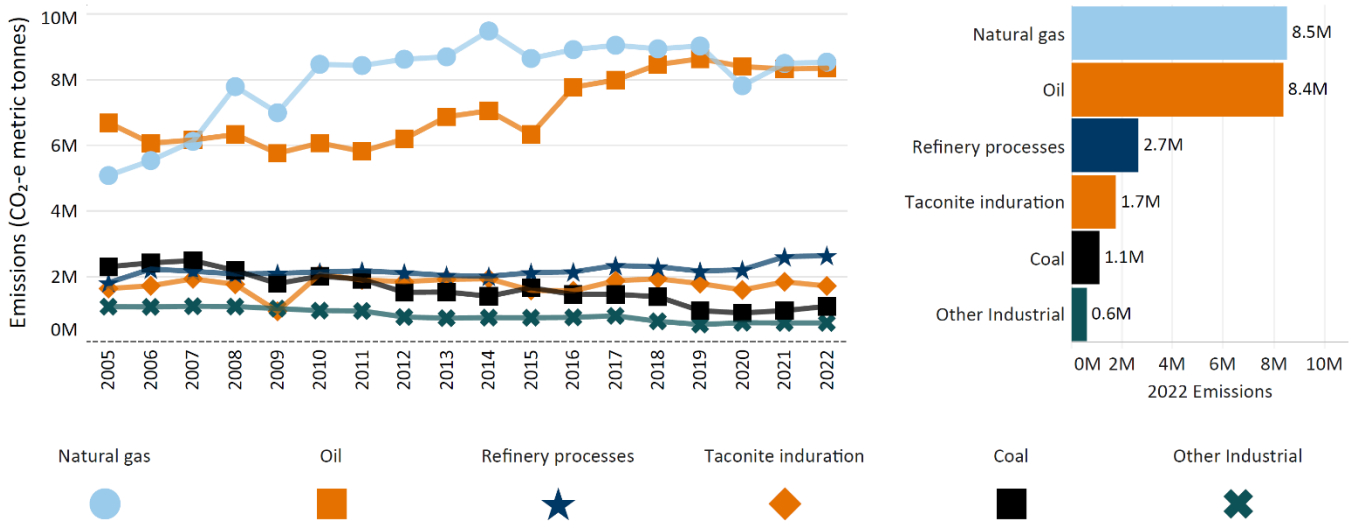
GHG emissions 2005-2022



While total GHG emissions from the industrial sector have declined since a peak in 2018, they are still higher than the 2005 baseline. The trends in emissions from specific fuels used are more varied. Industrial emissions from coal have declined since the 2005 baseline, while emissions from natural gas and oil (e.g. fuel oil, waste oils, propane, etc.) have increased relative to the 2005 baseline.

Changes are needed in industrial activities to meet statutory goals. Emissions from the industrial sector are closely tied to economic activity, but reductions in emissions do not require that our growth and productivity slow or decline. The Climate Action Framework includes a focus on transforming Minnesota's economy through innovation. With federal funding and technical assistance, industrial businesses can be national leaders in changing operations to increase efficiency and reduce fossil fuel use through electrification or the use of other greener fuels. The state is embarking on a study of the specific types of industrial and manufacturing processes that generate GHG emissions in the state. This study and the facility GHG emission data the MPCA receives will inform the development of a strategy to reduce emissions in the industrial sector and Minnesota's Climate Action Framework.

Industrial sector GHG emissions



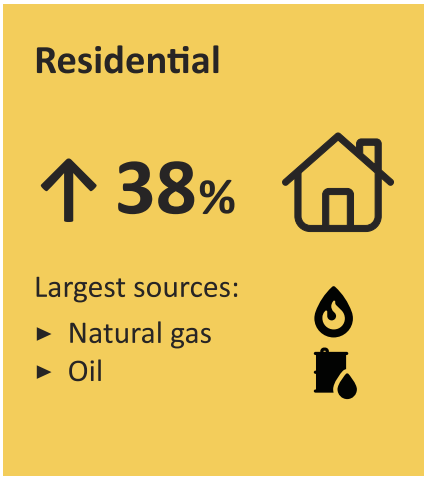
Emissions by subsector from 2005 to 2022 (left) and only 2022 (right). “Other Industrial” includes VOCs and toxics release, industrial wastewater treatment, semiconductor manufacturing, non-CO_2 emissions from biofuels, industrial solvent release, oil refining, and several sources related to specific manufacturing processes.

Residential

The residential sector is the fifth-largest source of GHG emissions in Minnesota, accounting for about 8% of the state's net emissions. The residential sector includes direct combustion of fossil fuels for heating and appliances, emissions from consumer products, and carbon stored in structural materials.

Since 2005, net emissions from the residential sector have increased by 38%. The largest residential emissions source is natural gas used for home heating and appliances. Emissions from residential natural gas and oil (e.g. propane and fuel oil) use have exceeded pre-pandemic levels. Annual variation in weather influences heating demand, affecting the GHG emissions in this sector. Improving home energy efficiency through weatherization and switching to electric technologies like heat pumps and appliances can significantly reduce residential emissions.

GHG emissions 2005-2022



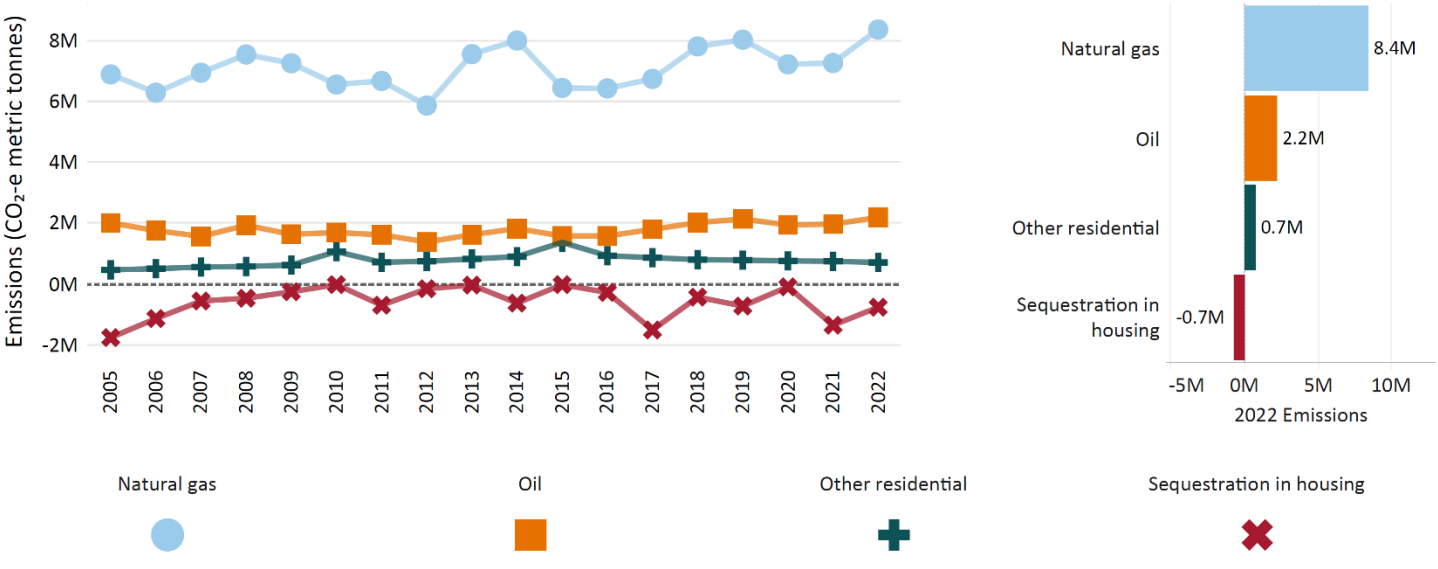
It's important to note that emissions from electricity use in residences are not included in the residential sector; they are accounted for under the electricity generation sector.

Emissions sources in the residential sector include:

- fossil-fuel combustion for heating and in-home appliances, such as furnaces, water heaters and clothes dryers
- home-product use
- food additives
- refrigerant leakage from air conditioners and refrigerators

This category includes carbon sequestered in wood construction materials. Over the lifetime of a house, carbon is stored and effectively removed from the atmosphere for decades, which offsets some emissions.

Residential sector GHG emissions



Emissions by subsector from 2005 to 2022 (left) and only 2022 (right). "Other Residential" includes non-CO_2 emissions from wood burning, aerosols, soaps/detergents, HFC emissions from air conditioning and refrigeration, carbon loss from wood in housing, and food additives.

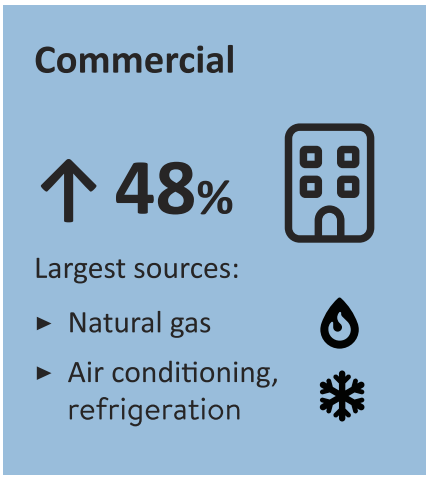
Commercial

The commercial sector is the sixth-largest source of greenhouse gas emissions in Minnesota, accounting for about 7% of the state's net emissions. Emissions from the commercial sector are predominantly derived from fuel combustion to provide buildings with heating, in addition to refrigerant leakage from air conditioning and refrigeration equipment. This sector includes buildings that house businesses, institutions, and government facilities. Business buildings include retail stores, offices, and food service establishments. Institutional buildings include schools, corrections facilities, and hospitals. As with the residential sector, emissions from electricity use in the commercial sector are not included in this inventory sector; they are accounted for under the electricity generation sector. Since 2005, emissions from the commercial sector increased by 48%.

Emissions sources in this sector include:

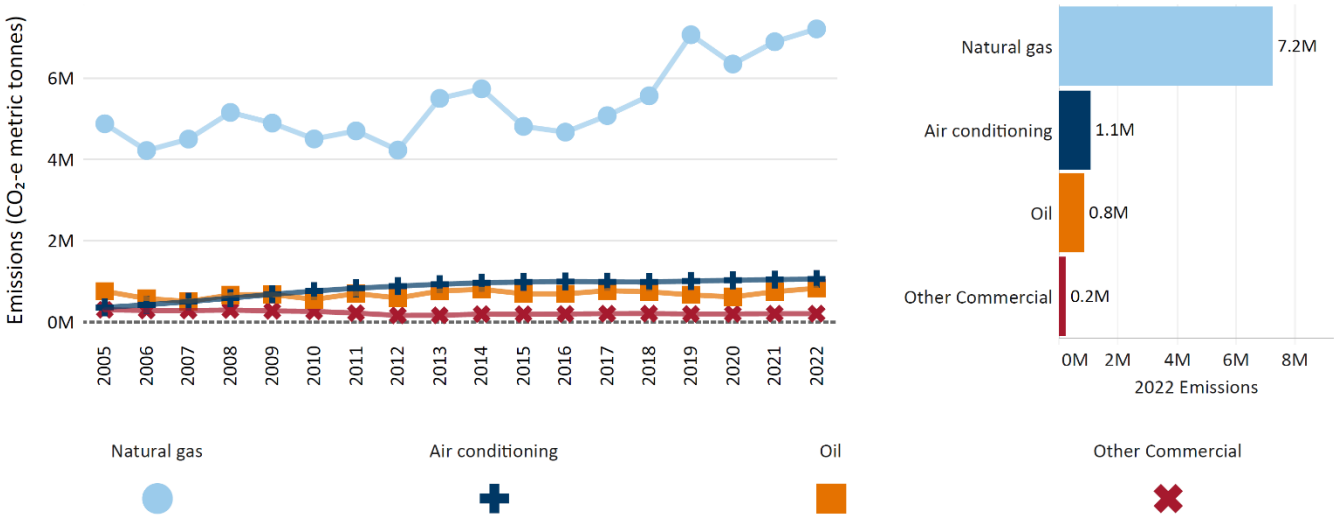
- fossil-fuel combustion
- air conditioning
- solvent use
- medical N_2O emissions

GHG emissions 2005-2022



The increase in emissions from the commercial sector is predominantly driven by the increase in combustion of natural gas. Natural gas emissions in this sector have increased by nearly 50% since 2005, with 2022 being the highest year on record. Emissions from air conditioning and refrigeration chemical leakage have continued to increase, though their growth has slowed since 2015. Investments in energy efficiency, electrification, and building efficiency will help commercial and institutional sources reduce fossil fuel use and energy consumption. The scheduled phase-down of high global warming potential hydrofluorocarbons refrigerants will also reduce the total GHG emissions from this sector.

Commercial sector GHG emissions



Emissions by subsector from 2005 to 2022 (left) and only 2022 (right). "Other Commercial" includes coal, solvent use, medical uses of nitrous oxide, non-CO2 emissions from biofuels, and limestone use.

Waste

The waste sector produces about 1% of GHG emissions annually in Minnesota. Compared to the 2005 baseline, GHG emissions from the waste sector have decreased by about 40%.

Emissions sources in the waste sector include:

- fossil fuel combustion in waste processing
- incinerator fuels
- waste incineration
- methane from landfill gas and wastewater treatment

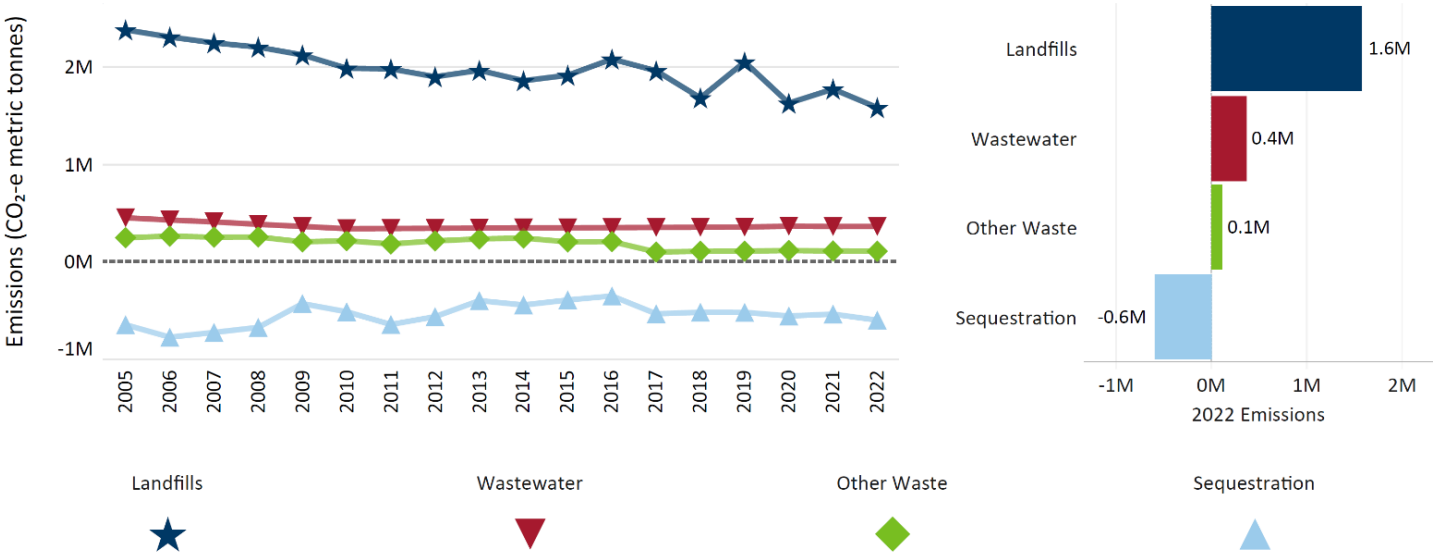
GHG emissions 2005-2022



The waste sector includes one emissions sink, which is the landfilling of wood construction materials. Although reuse and recycling of lumber and wood products is preferable, construction waste disposed of within construction and demolition landfills stores carbon for many years. In Minnesota, more construction waste is landfilled than the amount that decays within landfills each year, resulting in carbon sequestration that partially offsets other waste emissions.

Gradually decreasing methane emissions from landfills drives this sector's overall GHG reduction trend. This decline in methane emissions is due to a combination of factors. Aging waste in operating landfills results in lower emissions because older waste emits less methane as the organic fraction decomposes and becomes more stable. Also, gas capture technologies used at landfills reduce methane emissions by combusting it in a flare or using it to produce usable energy. As the closed landfill program administrator, the Minnesota Pollution Control Agency (MPCA) is working to address methane emissions from these facilities.

Waste sector GHG emissions



Emissions by subsector from 2005 to 2022 (left) and only 2022 (right). "Other Waste" includes processing-related emissions from waste-related facilities and incineration-related emissions from waste facilities and rural open burning

Land use, land-use change, and forestry

Minnesota's land use, land-use change, and forestry (LULUCF) sector sequesters more GHGs than it emits, resulting in net negative emissions of 11.6 million metric tons of CO_2-e in 2022, offsetting 8.4% of all other emissions in the state. The rate of net sequestration has increased by about 20% since 2005, a trend that has largely been driven by growth within and expansion of Minnesota's forests.

The LULUCF sector consists of non-agricultural lands and waters. In the context of GHG accounting, "land use" refers to categories of land surfaces based on vegetation, hydrology, and human activities; it does not refer to land use planning and zoning in urban and suburban contexts, which is another common use of this term. International GHG reporting standards recommend quantifying land-use-related GHG emissions and sequestration if they occur on managed lands or are associated with human activity. In practice, all lands and waters in Minnesota are managed or influenced by humans to some extent, so we aim to include all land use types for which robust accounting methodology exists.

The "land-use change" component of this sector accounts for emissions and sequestration caused by conversions between forest lands, grasslands, surface waters, and settlements. Lands converted from croplands to any of these uses are included. However, lands remaining in, or converted to, croplands are included in the agriculture sector. We use the same land use definitions as the US Environmental Protection Agency[2] (EPA) and lands are considered remaining within a given use type if in continuous use for more than 20 years.

Rates of plant growth and decay, weather, and management decisions influence the exchanges of GHGs between lands, waters, and the atmosphere. While the science of land-use-related GHG accounting has developed rapidly, some land-use types do not yet have quantification methods or require input data that are not readily available. Wetlands have particularly complex GHG exchanges, so the only wetland-associated estimates currently included are emissions caused by peat harvesting. Trees outside of forests and developed areas (e.g., between crops or along rivers and streams) and carbon stored in harvested wood products are also not yet included due to limitations in data and methods.

GHG emissions 2005-2022

Land use, land-use change, and forestry

↓ **20%** **8.4% offset**

Largest carbon sinks:

- Existing forests
- Land converted to forest



Minnesota land use summary

Minnesota's total surface area is approximately 54 million acres and more than 70% of the land is privately-owned.

Percent of Minnesota's surface area by land use:

- Croplands: 39%
- Forests: 34%
- Grasslands: 8%
- Wetlands: 8%
- Open water: 6%
- Settlements: 5%
- Barren/other: <1%

Sources: US Geological Survey, MN DNR

Different land-use types store carbon and exchange greenhouse gases with the atmosphere at different rates. Conversion from carbon-rich natural systems, like forests, grasslands, and wetlands, to intensively managed croplands or developed lands, results in carbon emissions. Conversely, restoration of natural lands typically results in carbon sequestration. For lands remaining in a given land use, rates of sequestration and emissions depend on factors such as time since establishment, soil type, hydrology, and local management (e.g., timber harvest, grazing, fire, and fertilizer use).

[2] https://www.epa.gov/ghgemissions/methodology-report-inventory-us-greenhouse-gas-emissions-and-sinks-state-1990-2022

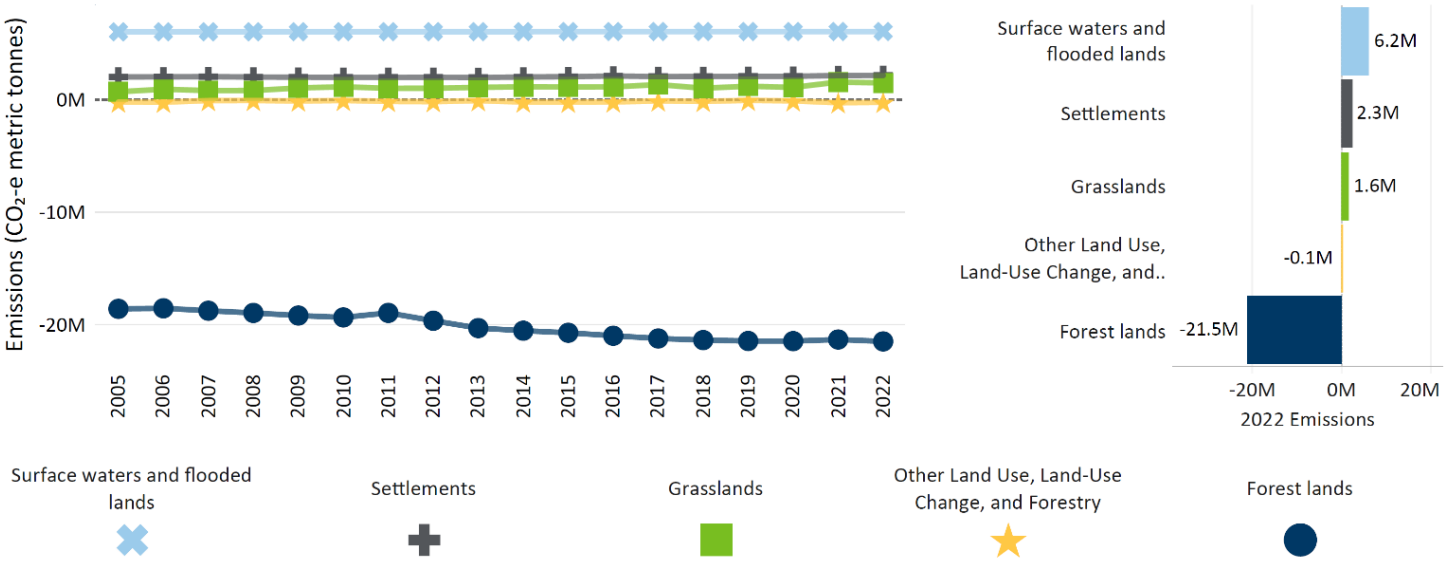
Forests in Minnesota sequester significant amounts of carbon dioxide each year (about 15% of total statewide emissions in 2022). The strength of Minnesota's forest carbon sink is attributable to multiple factors, including continued regrowth following the decades of widespread forest clearing for agriculture and unsustainable forest management practices throughout the 19th century. In addition, adopting sustainable timber harvesting practices in the 20th century played an important role in enhancing Minnesota's forest carbon sink.

Surface waters are the largest source of emissions in this sector. Reservoirs, canals, and ditches are significant human-caused sources of methane emissions. While lakes and rivers are natural water bodies, human contributions of nutrients to these waters increase their methane emissions above natural levels.

Settlements (which include cities, roads, and other developed lands and both categories of converted and remaining settlements) are the second largest net source of GHGs in this sector in 2022. The conversion of natural and working lands to settlements results in emissions, especially when organic soils are drained to allow for development. Many urban, suburban, and ex-urban communities in Minnesota also have robust tree canopies, however, which offset about a third of settlements' gross annual emissions.

Minnesota's grasslands are the third largest net source of emissions in 2022. Grasslands contain large stores of soil carbon, but the characteristics of the soils beneath these grasslands largely determine whether a given site emits or sequesters carbon. Ungrazed or moderately grazed grasslands on mineral soils typically sequester carbon, but a relatively small acreage of grasslands on drained organic soils (i.e., former peatlands) releases more carbon each year than is stored by grasslands on mineral soil. See the agriculture sector for further explanation of emissions from drained organic soils.

Land use, land-use change, and forestry sector GHG emissions



Emissions by land use type from 2005 to 2022 (left) and only 2022 (right). Several types of surface waters have been combined into "Surface waters and flooded lands." Lands remaining in and converted to a given land use (i.e. settlements, grasslands, and forest lands) have also been combined for this figure. See the interactive online data vizualizations for more details.

Harvested wood products

Harvested wood products store carbon—sometimes for long periods of time—and can also substitute for fossil-fuel-intensive products such as concrete and steel. The statewide GHG inventory currently does not include the net emissions associated with carbon stored in and emitted from wood products harvested from Minnesota's forests, except as estimates of wood used in residential construction and stored in construction and demolition landfills (see Residential and Waste sectors). A more complete accounting of the exchange of GHGs between Minnesota's forests and the atmosphere would include comprehensive annual estimates of carbon stored in and emitted from all harvested wood products, such as lumber, plywood and particleboard, and pulp and paper products.

When forests are managed with timber harvest, a large portion of the wood absorbed and stored in trees is transferred into wood products where it is stored for variable amounts of time. Long-lived wood products such as engineered wood and lumber are typically disposed of in landfills, where decomposition proceeds slowly.

Nationally, harvested wood products, both in use and in solid waste disposal sites, represent a consistent carbon sink that is roughly 12% of the magnitude of the national forest carbon sink. If this nationwide proportion is roughly true for Minnesota, harvested wood products might represent an additional 2.5 million metric tons of CO_2-e of sequestration and increase Minnesota forests' net sink from -21.5 million to -24 million metric tons of CO_2-e. We are developing a methodology for accounting for harvested wood products in Minnesota's GHG inventory and plan to include harvested wood products in the next iteration of this report.

Increasing carbon sequestration and storage through land management

As the only sector that currently sequesters more GHGs than it emits, Minnesota's Land Use, Land Use Change, and Forestry sector will be critical to achieving the state's net-zero emissions goal. Fortunately, when our lands and waters are managed well, they not only release lower amounts of GHGs and absorb and store more carbon, they can also enhance climate resilience, support healthy plant and animal populations, and sustain our quality of life.

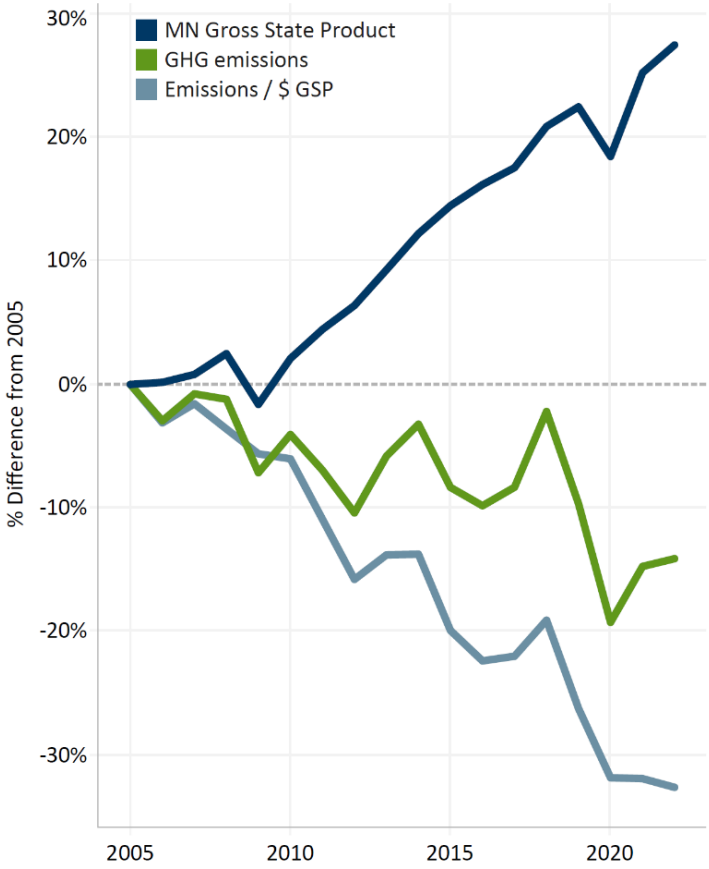
Examples of actions that support healthy landscapes and mitigate climate change:

- Forest managers can follow site-level guidelines and best practices to manage forests for wildlife habitat, recreation, clean water, timber, and climate resilience benefits over the long term.
- Grassland and prairie managers can establish a diverse mix of plant species – which has been demonstrated to enhance carbon storage – and adopt grazing practices that protect and enhance diversity and continuous cover.
- State, local, federal, and tribal governments can restore degraded lands, wetlands, and waterbodies to provide habitat, water quality, climate, economic, and recreational benefits.
- Residents, landowners, and communities can plant and care for native trees, wildflowers, and grasses.

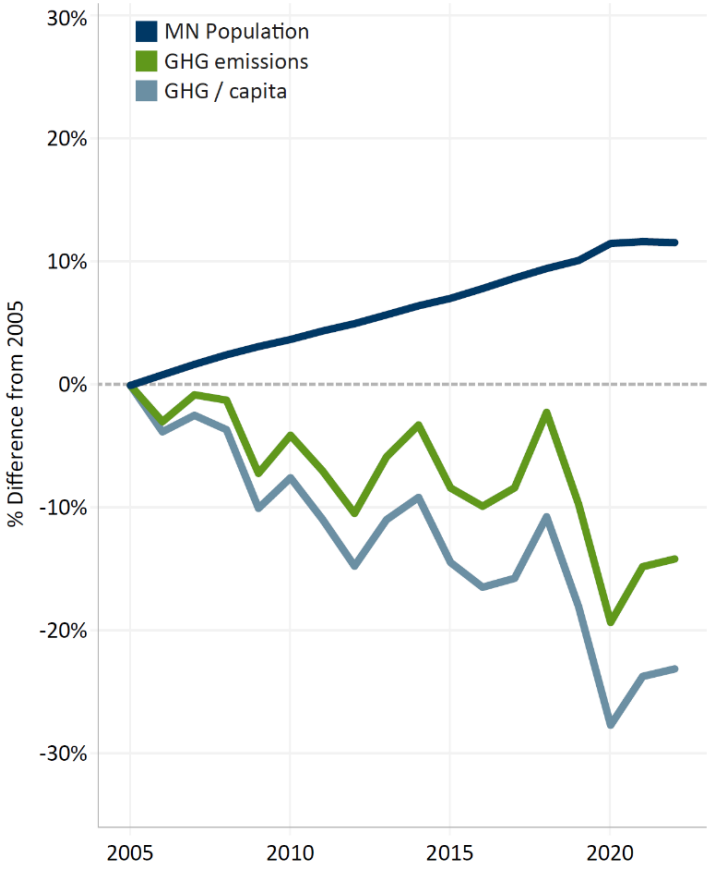
Greenhouse gas emissions and our economy

Measuring the amount of GHG emissions compared to other economic indicators is one way to understand how GHG emissions relate to the state's economy. Trends show that Minnesota has begun disconnecting economic growth from GHG emissions. Minnesota's gross state product has grown since 2005, while GHG emissions have generally decreased, demonstrating that the state economy can grow without increasing GHG emissions. Similarly, Minnesota's generally decreasing GHG emissions show that population growth can occur while reducing GHG emissions. Though the population in Minnesota is increasing, there is a growing decrease in emissions per person. The Climate Action Framework outlines initiatives to advance Minnesota's transition to a clean economy, helping to ensure greenhouse gas emissions reductions align with the goals in state law.

GHG emissions per dollar gross state product
2005 to 2022



GHG emissions per capita
2005 to 2022



Our path forward: Minnesota's Climate Action Framework

In September of 2022, Minnesota's Climate Action Framework was released. The Framework, developed with input from 3,000+ Minnesotans, sets a vision for how the state will address and prepare for climate change. It identifies near-term actions we must take to achieve the long-term vision of **a carbon-neutral, resilient, and equitable future for Minnesota**.



The Framework is organized around six climate action goals with specific steps and progress measures to guide and evaluate our work.

- **Clean transportation**
  Transportation represents the greatest opportunity to reduce climate pollution. The Framework aims to connect and serve all people through a safe, equitable, and sustainable transportation system.
- **Climate-smart natural and working lands**
  Minnesota can manage natural and working lands to address climate change by absorbing and storing carbon, reducing emissions, and sustaining local economies.
- **Resilient communities**
  Communities experience the impacts of climate change differently, and solutions must be tailored to local needs. The state can prepare communities with the resources they need to plan and build a more resilient future for themselves.
- **Clean energy and efficient buildings**
  Minnesotans can benefit from investments in clean energy and energy efficiency that will create jobs, lower energy costs, and contribute to a more stable climate.
- **Healthy lives and communities**
  Changes in Minnesota's climate threaten the health of every community, but not everyone experiences these impacts equally. The Framework's goal is to protect the health and well-being of all Minnesotans in the face of climate change.
- **Clean economy**
  Transitioning to a cleaner economy must include solutions that benefit everyone. Minnesota will build an economy that addresses climate change and equitably provides family-sustaining job opportunities.

The Framework will guide the state of Minnesota's priorities for addressing climate change in the coming years. Actions identified in the document will be developed into new policies, programs, and grants to reduce our greenhouse gas emissions. The Framework is currently being updated to include a more comprehensive set of actions that help us achieve those goals. Analyzing Minnesota's emissions through this inventory allows us to track progress on the Framework goals and focus actions for maximum impact to address climate change.

Learn more about our next steps to tackle climate change and how you fit into this work by visiting **mn.gov/framework.**

Conclusion

Since launching our Climate Action Framework in 2022, Minnesota has made significant progress on climate action, including historic climate funding and policies adopted in 2023. These state funds combined with billions of dollars federal funding have advanced dozens of programs to cut climate pollution and prepare our state for a warmer, wetter Minnesota.

Minnesota has successfully reduced emissions by approximately 14% since 2005, but we have significant work to do to meet our goal of being carbon-neutral by 2050. While emissions bounced back after the most disruptive period of the COVID-19 pandemic, our overall emissions have not returned to 2019 levels, indicating we are still on a downward trend.

This inventory report doesn't capture the impacts of historic climate action funding at the state and federal level since 2022, which will result emission reductions in the coming years and decade. To achieve our goals, we must continue Minnesota's commitment to climate action by government, businesses, institutions, and individuals that reduces climate pollution while fostering economic growth and jobs across Minnesota.

Minnesota is updating our Climate Action Framework in 2025 to include a more comprehensive set of actions with a stronger focus on collaboration, community benefits, and workforce needs. Though we have made progress, we must accelerate the pace and scale of our climate actions to achieve our long-term vision of a carbon-neutral, resilient, and equitable future.

Appendix: Methodology

Greenhouse gas emission inventory

The GHG inventory reports progress toward statutory goals and transparently provides information with high confidence in our results. The long record of emissions and high level of data disaggregation using the best available data and methods based on EPA and Intergovernmental Panel on Climate Change (IPCC) recommendations helps ensure the inventory is complete, consistent, transparent, accurate, and relevant. The EPA produces a national GHG inventory and a downscaled state-level GHG inventory. Both national and state EPA inventory versions are useful and incorporated in many parts of this inventory. However, there are differences between the MPCA inventory and others, such as the focus on activities like energy use or process emissions rather than on economic sectors, the division of electricity sector emissions, and the inclusion of imported electricity emissions. Inventories may present different details but are helpful as comparisons despite their differences.

Minnesota's state-level emission reduction goals are expressed as percentage reductions from estimated emissions in a historical baseline year (2005). Like most GHG inventories, the Minnesota GHG inventory has undergone substantial revisions since it was first built. It is continuously revised as methods and data improve and new emission sources are incorporated. When possible, these changes are applied to all inventory years to ensure consistency, including the 2005 baseline year. Developing a consistent time series of emissions estimates is essential to measure progress.

Not all emissions are included in statewide emission totals. Only those sources which can be included in the baseline year are evaluated. While it would be ideal to inventory and track all sources of GHG emissions from activities within Minnesota, in practice, the inventory consists of only those sources for which a well-developed scientific understanding of the physical and biological processes involved in the production and emission of GHGs exists. To include an emission source in the inventory, generally accepted protocols or methods must exist, and continuous data or reasonable quality must be available to support estimation.

Only emissions that occur within the geographical borders of the state are estimated, with two exceptions. Our estimate includes net electricity imports to meet Minnesota's electricity demand, which exceeds in-state electricity production. Emissions from the combustion of aviation fuel purchased in Minnesota but not necessarily combusted within Minnesota air space are also included.

GHG inventory protocols require accounting for photosynthetically-removed carbon dioxide stored in biomass in forests, landfills, and structures. Long-term storage of wood-carbon in residential structures and demolition and construction landfills is included in statewide GHG emission totals as sequestration because the materials will remain as carbon stores for a long time. Forest carbon fluxes are included from forest land that remains forest land and land converted to forest land following the EPA state methodology report (2022).

Within the agriculture and LULUCF sectors, some specific inclusions and exclusions are worthy of mention: Croplands enrolled in contract-based conservation programs (e.g., Conservation Reserve Program) are included in this sector because they are relatively likely to return to crop production, while former croplands that have been converted to wetlands, grasslands, forests, or settlements are instead included in the land use sector. Because grasslands are not exclusively used for agricultural purposes, grassland biomass and soil carbon fluxes are included in the land use sector, but any emissions from grazing livestock and manure are accounted for within the agriculture sector. Trees within croplands (e.g., windbreaks, agroforestry) are not included in the agriculture sector because quantification methods are not yet available. Finally, upstream emissions associated with the production of inputs such as fertilizers and equipment are out of scope for the agriculture sector; if these activities occur within Minnesota, their emissions are accounted for in the industrial sector.

Emissions are estimated from 1990 to 2020, though presented here in an abbreviated timeline. With a few exceptions, the methods used to develop these estimates are derived from the following sources:

- US Environmental Protection Agency (2022) Inventory of US greenhouse gas emissions and sinks: 1990-2020.
- US Environmental Protection Agency (2022) Methodology Report: Inventory of US greenhouse gas emissions and sinks by state: 1990-2020.
- US Environmental Protection Agency Motor Vehicle Emissions Simulator (MOVES) Models (versions 2014b and 3.1)
- Intergovernmental Panel on Climate Change (2006) IPCC guidelines for national greenhouse gas inventories. Vol. 1-4.
- Intergovernmental Panel on Climate Change (2019) 2019 Refinement to the 2006 IPCC Guidelines on National Greenhouse Gas Inventories.
- Radian Corporation (1996) Methane emissions from the natural gas industry. Volumes 1-15. Prepared for the US Environmental Protection Agency and the Gas Research Institute.
- California Air Resources Board, et al. (2010) Local government operations protocol for the quantification and reporting of greenhouse gas emissions inventories, version 1.1.
- The Climate Registry (2008) General reporting protocol, version 1.1.

Changes in methods and data sources

The methods used to develop the emission estimates are generally consistent from year to year, and changes made since the last report are discussed here.

Data collection methods implemented by the Minnesota Department of Transportation improved our accounting of vehicle miles traveled and the breakdown of miles traveled by vehicle type. However, these improved data are only available for recent years. Comparisons to 2005 details are therefore less accurate, but the overall trend in emissions is similar to the information reported in EPA's Inventory of US Greenhouse Gas Emissions and Sinks report and is still useful for tracking overall progress.

Since the last report, significant changes have been made to estimate GHG fluxes within the agriculture and land use, land-use change, and forestry sectors. In a shift from previous inventories, we now primarily use estimates provided by the EPA [3] for both of these sectors and have replaced historical estimates for consistency. The EPA inventory uses more sophisticated modeling with more complete coverage of both sectors than previously provided in this report.

Within the agriculture sector, this shift allows the inclusion of soil carbon fluxes in mineral soils (previous versions only included fluxes from organic soils). Other methods differ slightly from our previous approach, but estimates for each flux are generally similar to those derived using our previous methods.

Within the LULUCF sector, this shift to using EPA estimates allows us to include grasslands, settlements, and canals/ditches for the first time. EPA's estimates for lands converted to reservoirs were corrected for a known area overestimate. Lawn-applied nitrogen fertilizer emissions were previously accounted for within the residential sector but are now accounted for within settlements in the LULUCF sector. Estimates for emissions from lakes/ponds and rivers/streams are not included in the EPA inventory and are calculated using emission factors derived from peer-reviewed literature. For detailed definitions and methods of land use, see the

[3] US EPA's Inventory of US GHG Emissions and Sinks by State 1990-2022. https://www.epa.gov/ghgemissions/methodology-report-inventory-us-greenhouse-gas-emissions-and-sinks-state-1990-2022

associated Technical Supporting Document, which will be published shortly following this report and available on the same website: https://www.pca.state.mn.us/air-water-land-climate/climate-change-trends-and-data. We are committed to continuing to adopt the best available methods across all land use types and aim to include all GHG fluxes associated with wetlands, trees outside of forests and settlements, and harvested wood products in the future.

We strive to use the best available data and methods and are currently developing analyses using the US Department of Agriculture's Carbon Management & Emissions Tool (COMET) farm tool for potential future use to estimate fluxes from all of agriculture, as well as grasslands within LULUCF.

The Energy Information Administration (EIA) Fuel Oil and Kerosene Sales Report had previously been used to disaggregate fuel types and uses within economic sectors; however, that dataset has been discontinued. Now, the best available data is from the EIA State Energy Data System (SEDS), which is not as disaggregated with regard to fuel type or sector. As a result, we are no longer able to report agricultural diesel use nor distinguish biodiesel blends from total distillate fuel oil. This results in a small overestimate of CO_2 emissions from biodiesel in non-transportation uses. In addition, data derived from SEDS includes agriculture-related fuel combustion within industrial fuel combustion; therefore, these emissions are now included in the industrial sector totals.

In previous versions of this report, emissions related to peat harvesting were reported in the industrial sector. Those emissions are now reported in the land use, land-use change, and forestry sector, in alignment with the EPA's sectoral arrangement.

In previous versions of this report, methane emissions from hydroelectric reservoirs were duplicated in the electricity generation and the former agriculture, land use, and forestry sectors. These hydroelectricity-related emissions are now included only in land use, land-use change, and the forestry sector, which aligns with the EPA's sectoral arrangement.

Ozone-depleting substances (ODS) historically used as common refrigerants were replaced by other compounds, namely hydrofluorocarbons (HFCs) and perfluorocarbons (PFCs), collectively known as ODS substitutes. These ODS substitutes are high global warming potential GHGs whose emissions are included in this inventory. In previous reports, the procedure for estimating emissions from ODS substitutes in the commercial sector included scaling down national emissions to the population of Minnesota and subtracting emissions from state-level residential and transportation sectors. In this report, the estimation has been changed to leverage the state-level EPA GHG inventory, which estimates sector-specific emissions from ODS substitutes for Minnesota.

In the previous report, residual fuel oil was overestimated in the off-highway category of the transportation sector due to duplication in the railroad, marine, and military and other off-highway categories. It is now accounted for only in the marine category. An additional clerical error in the military and other off-highway category was corrected.

Finally, in the last report, commercial sector emissions associated with fuel oil combustion were overestimated. This error has been corrected in calculations for the current report.

The overall impact of these methodological changes is an improved understanding of Minnesota's progress toward statutory emissions reduction goals. Ongoing improvement in methodologies will continue to improve our understanding of Minnesota's historic emissions in future versions of this report.

Uncertainty of estimates and opportunities for improvements

It is difficult to calculate the precise amounts of GHG emissions; however, getting a reasonable estimate is still critical in understanding the general scope of emissions.

Several methods and data sources are used to estimate emissions from each activity within a sector to get a comprehensive view. Some of the methods for generating the estimates are very detailed and result from site-

specific measurements for both activity and emissions. In contrast, others use a model with only general data to characterize the source of emissions.

The accuracy of data for different economic sectors can vary:

- Fossil fuel combustion in each sector, such as electricity generation and industrial uses, has low uncertainty, especially when aggregated to state totals because the activity is regulated and tracked.
- Emissions from on-road transportation are estimated using the MOVES model, which depends on vehicle population and vehicle miles traveled data. Methods to measure vehicle miles traveled and types of vehicles on our roads have changed over time. This means that we understand current transportation activity much better than we did in the past, and it also means that there is more uncertainty in estimates for past years. However, our emissions trend is similar to other published estimates, such as the EPA state inventory.
- Methane generated from municipal solid waste in landfills is modeled. There is some uncertainty from data inputs and the model's underlying equations and assumptions.
- Emissions and sequestration from agriculture, forestry, and land use have a higher degree of uncertainty due to the multitude of factors influencing biological processes and the difficulty of obtaining accurate, relevant, detailed information.

STATE OF MINNESOTA
Executive Department

Governor Tim Walz

Executive Order 19-37

Establishing the Climate Change Subcabinet and the Governor's Advisory Council on Climate Change to Promote Coordinated Climate Change Mitigation and Resilience Strategies in the State of Minnesota

I, Tim Walz, Governor of the State of Minnesota, by the authority vested in me by the Constitution and applicable statutes, issue the following Executive Order:

Climate change is an existential threat that impacts all Minnesotans and our ability to thrive. Communities, farms, and industry face more frequent extreme weather events that threaten the infrastructure that we rely on to connect all parts of our state, cause undue economic stress, and place our communities and environment at risk. By increasing risks from vector-borne diseases and extreme weather, especially for vulnerable populations and individuals with pre-existing conditions, climate change threatens Minnesotans' health and wellbeing.

Climate change is a complex problem, and Minnesota recognizes that the impacts of climate change are disproportionally borne by disadvantaged communities. Disparities exist in Minnesota, including those based on race, gender, geography, and economic status, and they prevent us from reaching our full potential as a state. These disparities can be exacerbated by policies that do not reflect considerations of equity.

By working collaboratively, we can build resilient communities, promote community prosperity, mitigate risk to our farms and businesses, and create a homegrown clean economy. Currently, job growth in the clean energy sector is outpacing job growth in the overall economy. Continued leadership on climate change will position Minnesota for long-term economic success.

Minnesota's 2007 Next Generation Energy Act set statutory goals to reduce greenhouse gas emissions in the state by 30% of 2005 levels by 2025 and 80% by 2050. Minnesota fell short of its 2015 goal of 15% and is not on track to meet the 2025 goal. We must redouble our efforts to meet our future goals.

To fulfill Minnesota's statutory goals, avoid the severe economic, health, and ecological impacts associated with a changing climate, and fully realize the benefits of a healthy, sustainable, and resilient state, our state government must work across the enterprise in a coordinated approach to develop equitable strategies that will mitigate climate change and achieve greater resilience.

For these reasons, I order that:

1. A Climate Change Subcabinet ("Subcabinet") is established.

2. The purpose of the Subcabinet is to:

    a. Identify policies and strategies that will put Minnesota back on track to meet or exceed our goals, established under Minnesota Statutes 2019, section 216H.02, to reduce statewide greenhouse gas emissions across all sectors to a level at least 30% below 2005 levels by 2025, and to a level at least 80% below 2005 levels by 2050.

    b. Identify policies and strategies that will enhance the climate resiliency of Minnesota's natural resources, working lands, and communities.

3. The members of the Subcabinet are the Commissioner, Executive Director, or Chair of the following agencies and boards:

    a. Pollution Control Agency ("MPCA")

    b. Department of Commerce

    c. Department of Labor and Industry

    d. Department of Management and Budget

    e. Department of Employment and Economic Development

    f. Department of Agriculture

    g. Department of Public Safety

    h. Department of Natural Resources

    i. Department of Health

    j. Department of Transportation

    k. Board of Water and Soil Resources

    l. Department of Administration

    m. Metropolitan Council

    n. Environmental Quality Board

    o. Minnesota Housing Finance Agency

4. The Commissioner of the MPCA will serve as Chair of the Subcabinet.

5. The duties of the Subcabinet are as follows:

    a. **Climate Mitigation and Resilience Policy and Strategy Development.**

        i. Identify policies and strategies that the State may adopt to meet or exceed the economy-wide greenhouse gas emissions goals of the 2007 Next Generation Energy Act and achieve 100% clean energy by 2050.

        ii. Identify challenges and opportunities to mitigate climate change and consider how climate change mitigation policies intersect with the work of the Subcabinet members' agencies or boards.

        iii. Identify policies and strategies that will enhance the climate resiliency of Minnesota's natural resources, working lands, and communities and assist the state enterprise, families, businesses, and local communities to prepare for climate change impacts that cannot be avoided or mitigated.

        iv. Consider how climate change mitigation and resilience policies and strategies can reduce greenhouse gas emissions and energy waste; promote economic development, innovation, and job creation; ensure equitable distribution of benefits; and address disparities in current impacts related to climate change.

        v. Submit a written update to the Governor on December 1 of each year, with a first update due by December 1, 2020.

    b. **Public Engagement.** Successful policy and strategy development requires that those impacted, including frontline communities, indigenous peoples, industry, and workers, among others, have a voice and the opportunity to participate in the process. The Subcabinet will develop and implement a public engagement framework to ensure meaningful public engagement is conducted by the Subcabinet's agencies and boards. The purpose of the engagement framework is to:

        i. Build partnerships and shared understanding across Tribal Nations; local communities; and sectors including, but not limited to, agriculture, transportation, business, and conservation and environmental interests.

        ii. Provide a platform for dialogue about the strengths and challenges of climate change mitigation and resilience solutions, including policies and voluntary actions, and how these solutions will impact the lives of Minnesotans, including those who have been traditionally underrepresented in policy discussions, are disproportionately impacted by climate change, and are impacted by the transition to a clean energy economy.

iii. Highlight regional differences across Minnesota regarding the effects of climate change and locally relevant solutions.

iv. Share and gather ideas for how Minnesotans can get involved with, and stay informed about, climate change issues that matter to them.

6. The Governor's Advisory Council on Climate Change ("Advisory Council") is established to advise the Subcabinet in its duties.

7. The Advisory Council will be comprised of up to 15 members appointed by the Governor. The Governor will seek representation from community leaders, individuals with experience in the business sector, agriculture, conservation and environmental protection, and other relevant stakeholders.

8. The duties of the Advisory Council are as follows:

   a. Meet up to four times per year to identify opportunities for, and barriers to, the development and effective implementation of policies and strategies to reduce greenhouse gas emissions and promote climate change resiliency.

   b. Promote equity by examining how climate change impacts communities across the state and how potential solutions can address current disparities, incorporating the perspectives of people of color, indigenous people, rural Minnesotans, and other populations who experience disproportionate impacts from climate change.

   c. Promote a just transition for impacted workers and communities by examining the trade-offs that may accompany policies.

9. The MPCA, in coordination with other state agencies and boards, will provide staffing and administrative support to the Subcabinet and the Advisory Council.

This Executive Order is effective fifteen days after publication in the State Register and filing with the Secretary of State. It will remain in effect until rescinded by proper authority or until it expires in accordance with Minnesota Statutes 2019, section 4.035, subdivision 3.

Signed on December 2, 2019.

Tim Walz
Governor

Filed According to Law:

Steve Simon
Secretary of State

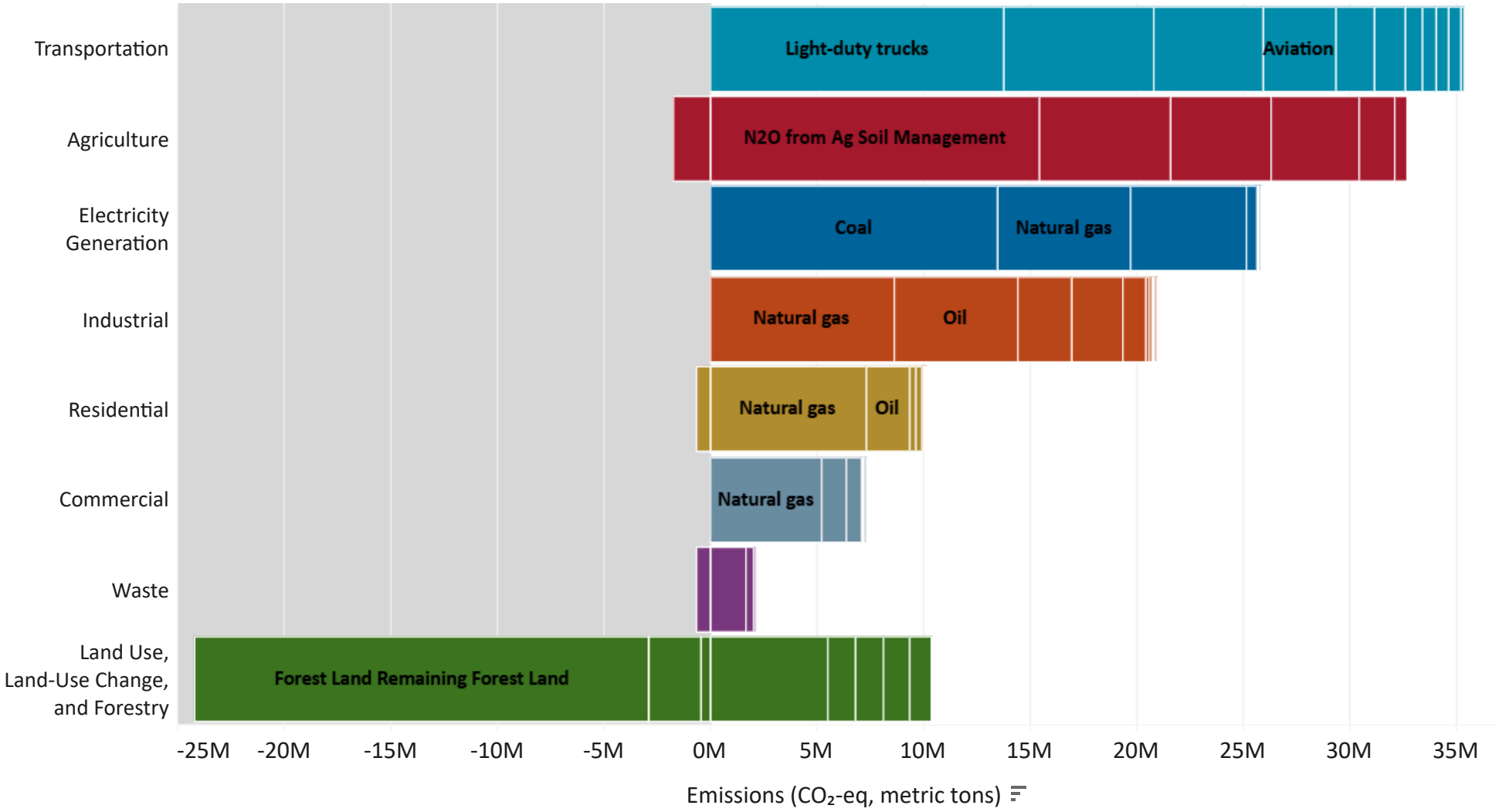
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Minnesota Greenhouse Gas Inventory

MINNESOTA POLLUTION CONTROL AGENCY

Main sources of GHG emissions and sequestration by sector in 2023

This figure shows the main sources of greenhouse gas emissions in each sector for 2023, the most recent year of available data. Mouse over each bar to see emissions by subsector for 2023. Negative emissions represent carbon sequestration.



Each sector includes the following emissions sources and sinks:

Transportation: Fuel combustion in gasoline and diesel vehicles, aviation, rail, air conditioning leakage, and natural gas pipelines

Minnesota Greenhouse Gas Inventory

MINNESOTA POLLUTION CONTROL AGENCY

Sector-level details

Subsector-specific GHG emissions from 2005 to 2023 are shown. Hover over the figures to view for details. Filter options to change plot type, sector, or the GHGs included. Line plots display trends for individual subsectors over time as separate lines and are paired with a legend differentiating the subsectors. The legend lists subsectors from largest to smallest emission sources in 2023.

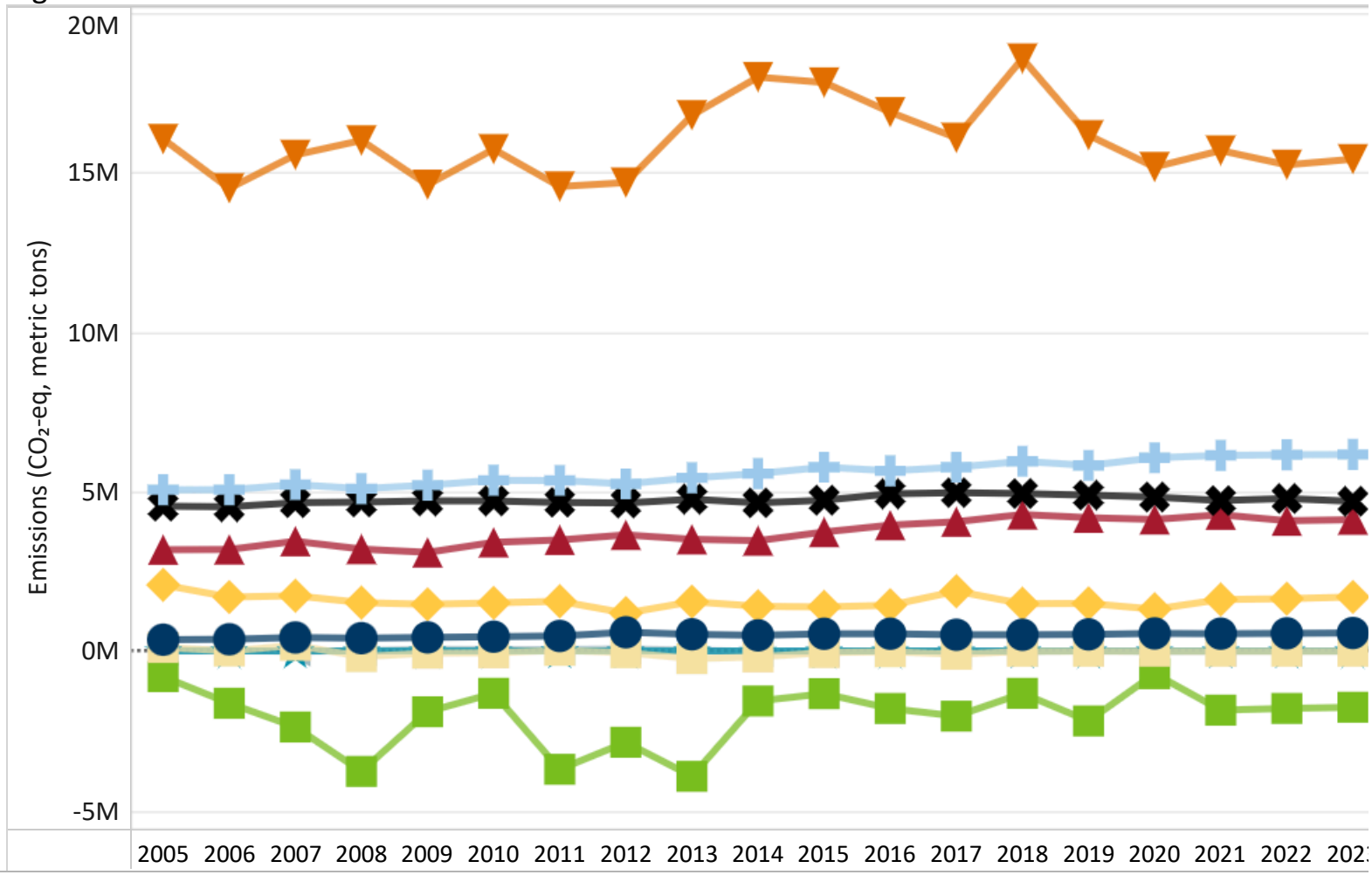
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- (•) Agriculture
- ( ) Commercial
- ( ) Electricity Generation
- ( ) Industrial
- ( ) Land Use, Land-Use Ch...
- ( ) Residential
- ( ) Transportation
- ( ) Waste

Greenhouse Gas

- [x] (All)
- [x] CH_4
- [x] CO_2
- [x] HFCs
- [x] N_2O
- [x] PFCs
- [x] SF_6

Agriculture sector



N2O from Ag Soil Management | Cropland Remaining Cropland, Organic Soil | Enteric Fermentation | Manure Management | Land Converted to Cropland

FARMING FOR OUR FUTURE

THE SCIENCE, LAW, AND POLICY OF CLIMATE-NEUTRAL AGRICULTURE

Peter H. Lehner & Nathan A. Rosenberg

ENVIRONMENTAL LAW INSTITUTE
Washington, D.C.

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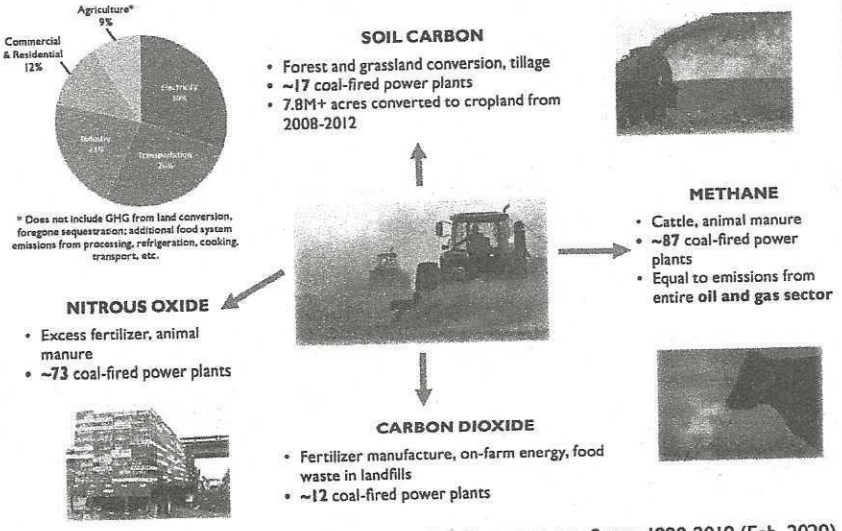
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Figure 3. Industrial Agriculture Contributes to Climate Change



Source: U.S. EPA, INVENTORY OF U.S. GREENHOUSE GAS EMISSIONS AND SINKS: 1990-2018 (Feb. 2020), https://www.epa.gov/sites/production/files/2020-02/documents/us-ghg-inventory-2020-main-text.pdf (tables 2-1 & 2-2, trends in U.S. greenhouse gas emissions; 2-4, energy; 2-5, combustion; 2-10, industrial; 5-1, agriculture; 6-1, land use and land use change; and 7-1, 7-3 & 7-6, waste & landfills); coal-fired power plants equivalencies from U.S. EPA, *Greenhouse Gas Equivalencies Calculator*, https://www.epa.gov/energy/greenhouse-gas-equivalencies-calculator. Percentages are of total gross U.S. anthropogenic GHG emissions.

countries are already investing significant sums into agroforestry research and production, yet the United States has lagged, despite robust research demonstrating its significant potential to sequester carbon while producing ample food. Moreover, food production needs will increase as the global population continues to grow. Thus, perhaps even more than agriculture's current contribution, its long-term determinative factor in climate stability demands careful policy attention.

2. U.S. Agricultural Greenhouse Gas Emissions

The U.S. Environmental Protection Agency (EPA) estimates that 2019 emissions from agricultural activities—growing crops and raising livestock and poultry—totaled about 629 million metric tons of carbon dioxide equiva-

lent (MMT CO_2 eq.), accounting for more than 10% of total U.S. greenhouse gas emissions.[12]

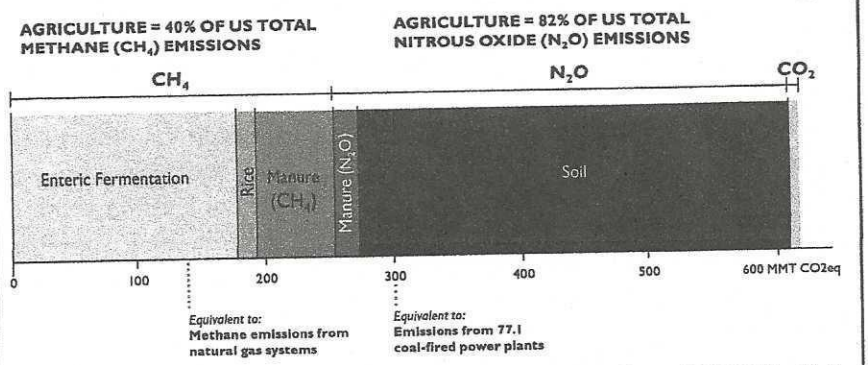
These agricultural emissions are at a minimum roughly equivalent to that produced by 136 million automobiles in a typical year.[13] However, unlike the greenhouse gas emissions of most other sectors of the economy, which consist of CO_2 released from the burning of fossil fuels, agriculture greenhouse gas emissions consist largely of nitrous oxide (N_2O) from soils and manure and methane (CH_4) from livestock and manure (as shown in Figure 3 on page 40). Agriculture also produces CO_2 from fossil fuel combustion (both on farms and off-site for on-farm electricity) and CO_2 from land conversion, neither of which are included in the EPA sector total. Agriculture is responsible for approximately 80% of U.S. N_2O emissions and 40% of U.S. CH_4 emissions—the same as the entire oil and gas sector's production emissions.[14]

The largest source of U.S. agricultural greenhouse gas emissions according to EPA is agricultural soil management. Activities by microorganisms in soil naturally result in emissions of N_2O, while agricultural practices, management, and land use can stimulate and accelerate these emissions by increasing the availability of nitrogen. Agricultural greenhouse gas emissions are dominated by emissions resulting from application of fertilizer as well as emissions associated with the breakdown of soil organic matter.[15] Soil management generates approximately half of all U.S. agricultural emissions and 93% of all U.S. N_2O emissions from agriculture.[16] Seventy-three percent of N_2O emissions from agricultural soil management come from cropland and 27% come from grazed grasslands.[17]

The next largest source of agricultural emissions is enteric fermentation, which results from the digestive process of ruminants (largely cows and sheep in the United States) (see Figure 4, page 42). Enteric fermentation creates CH_4, which animals subsequently release into the atmosphere through

12. U.S. EPA, Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2019, at 5-1 (2021), https://www.epa.gov/sites/production/files/2020-02/documents/us-ghg-inventory-2020-main-text.pdf. The 2019 emissions are more than 1% higher than those from just the prior year, 2018.
13. *Compare id., with* U.S. EPA, Greenhouse Gas Emissions From a Typical Passenger Vehicle (2018) (a typical passenger vehicle emits 4.6 metric tons of CO_2 annually).
14. *See* U.S. EPA, *Overview of Greenhouse Gases*, https://www.epa.gov/ghgemissions/overview-greenhouse-gases (last updated Sept. 8, 2020).
15. U.S. EPA, Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2018, Box 5-3 at 5-36 (2020) (EPA 430-R-20-002), https://www.epa.gov/sites/production/files/2020-04/documents/us-ghg-inventory-2020-main-text.pdf). In the methodology used by EPA to calculate nitrous oxide emissions, microorganisms in soil produce nitrous oxide at rates dependent on the availability of nitrogen, land use and management, weather, soil types, and other environmental conditions.
16. *See* U.S. EPA, *supra* note 15, at 5-2 tbl.5-1.
17. *See id.* at 5-25 tbl.5-15.

Figure 4. Major Sources of Agricultural Greenhouse Gas Emissions in the United States



Source: U.S. EPA, INVENTORY OF U.S. GREENHOUSE GAS EMISSIONS AND SINKS: 1990-2018, at 5-2 tbl.5-1 (Feb. 2020), https://www.epa.gov/sites/production/files/2020-02/documents/us-ghg-inventory-2020-main-text.pdf.

belching and exhalation.[18] Enteric fermentation is responsible for 32% of all agricultural emissions and 27% of CH_4 emissions in the United States.[19] (As discussed below, the relative impact of bovine exhalation would be much greater using more appropriate approaches for calculating CH_4 emissions.)

Manure management activities are the third major category of U.S. agricultural emissions, releasing N_2O and CH_4 in quantities that total 13% of total U.S. agricultural emissions.[20] The largest animal facilities—those with over 1,000 cattle on feed, 1,000 dairy cows, 2,000 finishing hogs, 100,000 turkeys sold, 300,000 broilers sold, or over 50,000 laying hens —generate the substantial majority of these emissions. Greenhouse gas emissions from enteric fermentation and manure are largely dependent on the number of animals raised in these facilities, which are heavily concentrated in a small proportion of the largest operations: over 50% of dairy cows in the United States are in the 4% of operations that stock 1,000 or more dairy cows.[21]

18. Andy Thorpe, *Enteric Fermentation and Ruminant Eructation: The Role (and Control?) of Methane in the Climate Change Debate*, 93 CLIMATE CHANGE 407, 411 (2009).
19. *See* U.S. EPA, *supra* note 15, at ES-7 tbl.ES-2, 5-2 tbl.5-1.
20. *See id.* at 5-2 tbl.5-1.
21. *See* NATIONAL AGRICULTURAL STATISTICS SERVICE, USDA, 2017 CENSUS OF AGRICULTURE, U.S. NATIONAL LEVEL DATA tbl.12 (2019). NASS uses different class sizes than does EPA in its definition of a "concentrated animal feeding operation" under the Clean Water Act. Pursuant to EPA rules, a large concentrated animal feeding operation (CAFO) is one with more than 1,000 animal units. An animal unit is defined as an animal equivalent of 1,000 pounds live weight and equates to 1,000 head of beef cattle, 700 dairy cows, 2,500 swine weighing more than 55 pounds, 125,000 broiler chickens, or 82,000 laying hens or pullets. *See* 40 C.F.R. §122.23(b)(4).

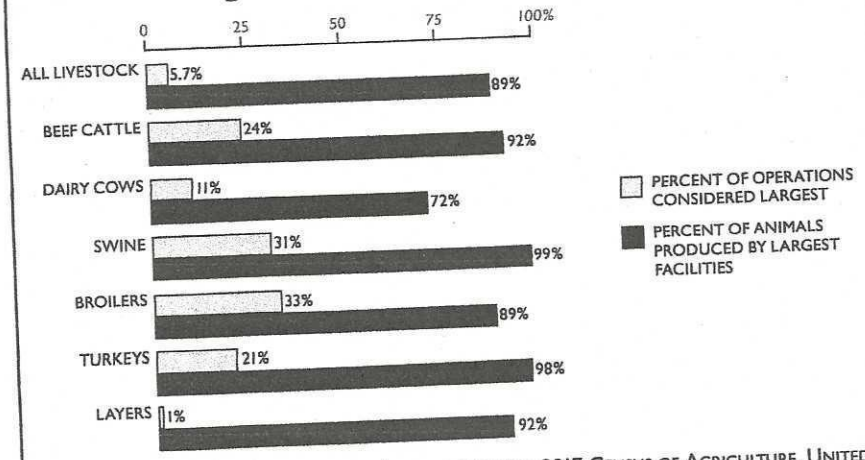
More than 90% of hogs in the United States are in the 12% of facilities that stock 2,000 or more hogs,[22] and more than three-quarters of all cattle on feed in the United States are in the 5% of facilities that stock 1,000 or more cattle.[23] As shown in Figures 5 and 6 (see page 44), the climate footprint of animal agriculture is directly correlated to this concentration of inventory, with a few large facilities responsible for the majority of greenhouse gas emissions.

Methane emissions released from soils flooded for rice cultivation and the field burning of crop residues make up more than 2% of total U.S. greenhouse gas emissions from agriculture.[24] In addition, CO_2 emissions from urea fertilization and liming—included by EPA in its estimate of agricultural emissions for the first time in 2015[25]—account for just under 2% of agricultural emissions.[26] We compare emissions of various agricultural activities in Figure 4.

The vast majority of agricultural emissions are from animal production, particularly beef and dairy. In the United States, meat and dairy production—including emissions related to production of their feed (which is about half of U.S. crop production), grazing, enteric fermentation, and manure—accounts for almost 80% of agriculture's greenhouse gas emissions.[27] If the global cattle population were a country, it would constitute the second largest greenhouse gas emitter after China.[28] Both the grazing stage for cows and the feedlot stage for beef, dairy, swine, and poultry production, as practiced now, produce substantial greenhouse gas emissions.[29] Because cows produce only one calf at a time, which nurse for months and then must graze until their bodies can take a grain diet in a feedlot, there are about five cows grazing for each of the close to 30 million cows in feedlots.[30] This requires vast amounts of land—almost 800 million acres or about 40% of the contiguous United States is devoted to grazing.[31]

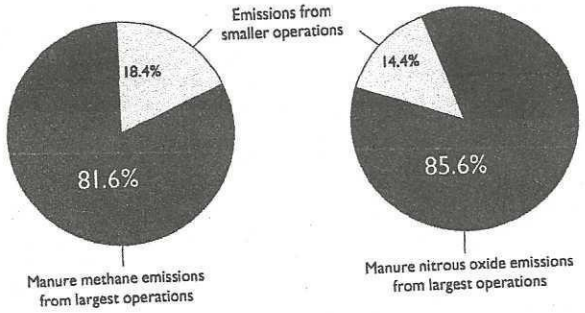
22. *See* National Agricultural Statistics Service, *supra* note 21, at tbl.25.
23. *See id.* at tbl.12.
24. *See id.*
25. *See id.*
26. *See id.*
27. These sources were responsible for 421.8 MMT CO_2 eq. or 78% of agricultural emissions in 2017. *Compare* U.S. EPA, *supra* note 15, at 5-2 tbl.5-1 (showing annual emissions from agriculture by source), *with infra* note 35 (calculating emissions from agricultural soils devoted to feed crop production or grazing).
28. Justin Ahmed et al., McKinsey & Co., Agriculture and Climate Change: Reducing Emissions Through Improved Farming Practices 5 (2020).
29. *See* C. Alan Rotz et al., *Environmental Footprints of Beef Cattle Production in the United States*, 169 Agric. Systems 1 (2019).
30. Matthew N. Hayek & Rachael D. Garrett, *Nationwide Shift to Grass-Fed Beef Requires Larger Cattle Population*, 13 Env't Res. Letters 0845005 (2018).
31. *See* Bigelow & Borchers, *supra* note 6.

Figure 5. Concentration and Production of Largest Animal Producton Operations



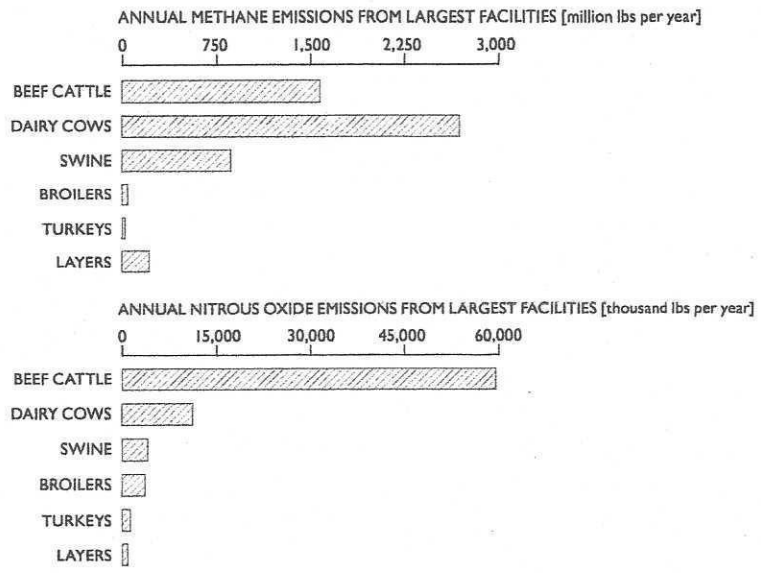
Source: USDA, National Agriculture Statistics Service, 2017 Census of Agriculture, United States Summary and State Data, tbls.12-30 (April 2019); Claire Huang, Earthjustice, Air and GHG Emissions CAFOs: Quantifying a National Estimate 25 (Aug. 19, 2020). For purposes here, the largest facilities are those with over 1,000 cattle on feed, 1,000 dairy cows, 2,000 finishing hogs, 100,000 turkeys sold, 300,000 broilers sold, or over 50,000 laying hens.

Figure 6. Share of Manure Emissions From Largest Animal Production Operations



Sources: USDA, National Agriculture Statistics Service, 2017 Census of Agriculture, United States Summary and State Data, tbls.12-30 (April 2019); Claire Huang, Earthjustice, Air and GHG Emissions CAFOs: Quantifying a National Estimate 23 (Aug. 19, 2020).

Figure 7. Annual Greenhouse Gas Emissions From Largest Animal Facilities



Source: CLAIRE HUANG, EARTHJUSTICE, AIR AND GHG EMISSIONS CAFOS: QUANTIFYING A NATIONAL ESTIMATE 25 (Aug. 19, 2020).

In addition, approximately half of all harvested cropland is devoted to animal feed crop production, adding to animal agriculture's already capacious footprint.[32] This cropland is often cultivated more intensely than cropland growing human food and often emits more nitrous oxide per acre than the production of crops for human consumption.[33] However, only a fraction of those crop calories is delivered to humans because the feed-to-meat ratio is so inefficient. For example, the production of one pound of beef from feedlot

32. There were approximately 310 million acres of harvested cropland in 2007 according to the Census of Agriculture. NATIONAL AGRICULTURAL STATISTICS SERVICE, U.S. DEPARTMENT OF AGRICULTURE, 2007 CENSUS OF AGRICULTURE: U.S. NATIONAL LEVEL DATA 16 tbl.8 (2009). The U.S. Department of Agriculture (USDA) estimates that approximately 165 million of those acres were devoted to feed crops; however, up to 10% of the feed was diverted to biofuels. CYNTHIA NICKERSON ET AL., USDA, MAJOR USES OF LAND IN THE UNITED STATES, 2007, at 20 (2011) (EIB-89). This total does not include soybeans, which USDA considers a "food crop," despite the fact that soybean meal is typically used as animal feed. TANI LEE ET AL., USDA, MAJOR FACTORS AFFECTING GLOBAL SOYBEAN AND PRODUCTS TRADE PROJECTIONS (2016).

33. Conventionally grown feed crops, such as corn, soybean, and hay, generally result in high N_2O emissions. *See* EPA, *supra* note 15, at 5-23.

cattle requires 15 pounds of grain.[34] As a result, grazing and feed crop production contribute almost two-thirds of N_2O emissions from agricultural soils.[35]

Not only does animal agriculture overall have an outsized impact on climate change, but this impact is—under current production methods—particularly influenced by beef, dairy, and to a lesser extent, swine production. This impact is all the more striking given that Americans receive only 30% of their calories from animal products.[36]

3. State-Level Agricultural Greenhouse Gas Emissions

While virtually all U.S. states have important agricultural sectors, their agricultural emission rates vary significantly due to climate differences and the type and intensity of agriculture within the state. A major factor is the amount of livestock. The top 10 highest overall greenhouse gas emitters (including fossil fuel emissions) account for nearly 50% of national emissions, with Texas and California in the lead. (See total emissions listed below state names in Figures 8 and 9 on pages 47 and 48.) However, the states with the largest total agricultural greenhouse gas emissions are Iowa (63 MMT CO_2 eq./yr.) with more than 10% of all U.S. agricultural greenhouse gas emissions, Texas (38 MMT CO_2 eq./yr.), Nebraska (33 MMT CO_2 eq./yr.), and California (29 MMT CO_2 eq./yr.). All of these states have both very high numbers of livestock and extensive cropland.

States also vary in the significance of agricultural emissions, accounting for more than 50% of total state emissions in South Dakota, and more than 30% of state emissions in Idaho, Nebraska, and Iowa. Finally, agricultural greenhouse gas emissions also vary when scaled by total cropland acres, indicating the relative intensity of the agricultural practices and the portion of

34. The feed conversion ratio expresses the number of pounds of grain necessary to increase the "live weight" of a head of cattle by one pound. At industrial feedlots, a feed conversion ratio of 6:1 is common. Dan W. Shike, Beef Cattle Feed Efficiency 3 (2013). About 40% of the live weight of a head of cattle is sold as beef, which means that 15 pounds of grain is necessary to yield one pound of beef. *See* Rob Holland et al., University of Tennessee Institute of Agriculture, How Much Meat to Expect From a Beef Carcass 9 (2016) (PB-1822).

35. This includes grassland emissions, which account for 73.3 MMT CO_2 eq., as well as 48% of cropland emissions—the approximate percentage of harvested cropland devoted to feed crop production in 2007—which adds an additional 92.7 MMT CO_2 eq. *Compare* U.S. EPA, *supra* note 15, at 5-2 tbl.5-1, 5-25 tbl.5-15 (showing annual emissions from agriculture by source), *with supra* note 32(explaining how the percentage of harvested cropland devoted to feed crop production was calculated). Together, they were responsible for 166 MMT CO_2 eq. or 62% of all emissions from agricultural soils in 2016. This total does not include the approximately 16.5 million acres devoted to the production of biofuel feedstock. *See supra* note 32.

36. USDA Economic Research Service, *Seventy Percent of U.S. Calories Consumed in 2010 Were From Plant-Based Foods*, https://www.ers.usda.gov/data-products/chart-gallery/gallery/chart-detail/?chartId=81864 (last updated Jan. 6, 2017).



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Niron Magnetics Manufacturing Plant Environmental Assessment Worksheet

Proposer: Niron Magnetics
RGU: City of Sartell

February 2026

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Niron Magnetics Manufacturing Plant
Environmental Assessment Worksheet

Proposer: Niron Magnetics
RGU: City of Sartell

February 2026

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December 2022 version

Environmental Assessment Worksheet

This most recent Environmental Assessment Worksheet (EAW) form and guidance documents are available at the Environmental Quality Board's website at**:** https://www.eqb.state.mn.us/ .The EAW form provides information about a Project that may have the potential for significant environmental effects. Guidance documents provide additional detail and links to resources for completing the EAW form.

Cumulative potential effects can either be addressed under each applicable EAW Item or can be addressed collectively under EAW Item 21.

Note to reviewers: Comments must be submitted to the RGU during the 30-day comment period following notice of the EAW in the *EQB Monitor*. Comments should address the accuracy and completeness of information, potential impacts that warrant further investigation and the need for an EIS.

1. Project Title

Niron Magnetics Manufacturing Plant

2. Proposer

Proposer:	Niron Magnetics
Contact person:	Dave Bance
Title:	Principal Environmental Engineer
Address:	650 Taft Street NE
City, State, ZIP:	Minneapolis, MN 55413
Phone:	612-327-9488
Email:	dave.bance@nironmagnetics.com

3. Responsible Governmental Unit (RGU)

RGU Agency:	City of Sartell
Contact person:	Kari Haakonson
Title:	Director of Community and Economic Development
Address:	125 Pinecone Road N
City, State, ZIP:	Sartell, MN 56377
Phone:	320-258-7312
Email:	kari.haakonson@sartellmn.com

4. Reason for EAW Preparation

Required:	Discretionary:
☐ EIS Scoping	☐ Citizen petition
X Mandatory EAW	☐ RGU discretion
	☐ Proposer initiated

If EAW or EIS is mandatory give EQB rule category subpart number(s) and name(s):

4410.4300 Subp. 14 (B)(2):

B. For construction of a new or expansion of an existing industrial, commercial, or institutional facility, other than a warehousing or light industrial facility, equal to or in excess of the following thresholds, expressed as gross floor space, the local governmental unit is the RGU:

(1) unincorporated area, 100,000 square feet;
(2) third or fourth class city, 200,000 square feet;
(3) second class city, 300,000 square feet; and
(4) first class city, 400,000 square feet.

5. Project Location

County: Stearns

City/Township: City of Sartell

PLS Location (¼, ¼, Section, Township, Range): NW1/4 S28 T125 R28

Watershed (81 major watershed scale): Mississippi River – Sartell (070120201)

GPS Coordinates (centroid): 94.2046514°W 45.6096918°N

Tax Parcel Number:
92.56577.0809 (Niron-owned. Facility site.)
92.56577.0808 (Niron-owned. Outlot.)
92.56577.0802 (City-owned. Temporary construction staging)
92.56577.0803 (City-owned. Temporary construction staging).

At a minimum attach each of the following to the EAW:

- U.S. Geological Survey 7.5 minute, 1:24,000 scale map indicating Project boundaries (photocopy acceptable); and
  See Figure 1, Appendix A
- County map showing the general location of the Project;
  See Figure 2, Appendix A
- Site plans showing all significant Project and natural features. Pre-construction site plan and post-construction site plan.
  Draft civil design drawings in Appendix B.
- List of data sources, models, and other resources (from the Item-by-Item Guidance: *Climate Adaptation and Resilience* or other) used for information about current Minnesota climate trends and how climate change is anticipated to affect the general location of the Project during the life of the Project (as detailed below in item 7. Climate Adaptation and Resilience).

6. Project Description

a. Provide the brief Project summary to be published in the EQB Monitor, (approximately 50 words).

Niron Magnetics proposes to develop a portion of an approximately 63-acre site in Sartell, MN to construct a manufacturing facility in two phases with a finished square footage of approximately 287,000 square feet. The facility will produce rare earth-free permanent magnets using Niron's novel process and material.

b. Give a complete description of the proposed Project and related new construction, including infrastructure needs. If the Project is an expansion include a description of the existing facility. Emphasize: 1) construction, operation methods and features that will cause physical manipulation of the environment or will produce wastes, 2) modifications to existing equipment or industrial processes, 3) significant demolition, removal or remodeling of existing structures, and 4) timing and duration of construction activities

Proposed Project

Niron Magnetics (Niron) proposes to construct a manufacturing facility on an undeveloped site located on 4th Avenue South between Heritage Drive and 3rd Street South in Sartell, MN (PID 92.56577.0809). See Figure 1 and Figure 2, Appendix A).

The Project area is a 63.02-acre undeveloped set of parcels within Sartell's city limits, located near the City of Sartell's Public Works facility and a landfill currently operated by the City of Sartell. The Project area contains a mixture of brushy grassland, recently fallowed cropland, two wetlands, and a historic constructed stormwater feature. Niron intends to permanently develop 25.8 acres of the site.

The proposed facility would produce Niron's patented rare earth-free high-performance permanent magnets. Pressed magnets will be cut to size and shape, then coated either in an enclosed spray booth or in a plating line. Finished magnets are then packaged and sent to customers. At full build-out, the facility would consist of six staffed buildings and three unoccupied structures. See the draft civil design drawings in Appendix B.

Production would occur in the Oxide building, Milling building, and Finishing/Warehouse building, as well as the Nitriding structure. All production activity to create the iron nitride magnet material or material transfer would be located inside sealed, inerted equipment or closed piping. Automated processes would be monitored inside the Control Room building. The facility would be accessed through a gate controlled from the Guard House building. An Electrical building would securely house electrical distribution to the facility. A Methanol Column structure would collect and purify solvents for reuse within plant processes. A Flare structure would serve to mitigate any emergency releases from relief devices. The Flare equipment would be contained within a structure that blocks light emitted from the flare. A Hot Oil Heater would be located onsite for process heating. The burner would be configured to combust multiple types of gases and would contain a stack with ports for performance testing. A Cooling Tower would be located onsite for process cooling. See Table 1 below for select details.

Permits for land disturbance, construction stormwater management, and air emissions were previously obtained, and site preparation work was initiated in October 2025. A design change was implemented in January 2026 that increased the gross square footage above 200,000 square feet, triggering the need for an EAW per MN 4410.4300 Subp. 14 (B)(2). The increase in proposed gross square footage was the result of adding a second floor to some buildings and did not expand the originally proposed and permitted ground disturbance footprint. Already completed disturbance activities include limited preliminary grading and stockpiling of imported fill soil. All site work has been paused until completion of the EAW process.

Initial site preparation and grading would create a level construction site using clean fill from an offsite local source. Minimal excavation or grading within native soil would be needed. Construction activities would re-commence upon completion of the environmental review process. Facility construction would commence upon issuance of remaining Project permits (see EAW Section 9). Construction is anticipated to take up to four years and would be completed in two phases.

The Project would result in 25.8 acres of permanent disturbance from grading and construction of the facility structures, two access drives, a parking lot, stormwater management features, utilities, and landscaped lawn space. Permanent disturbance would occur within parcel 92.56577.0809 and the 4th Avenue right-of-way. See Figure 3, Appendix A and draft civil design drawings in Appendix B.

The Project would also result in 8.5 acres of temporary disturbance. Temporary construction easements would be obtained for two City of Sartell parcels (92.56577.0802 and 92.56577.0803) to use them for construction trailers, contractor parking, materials staging, and construction stormwater management. To minimize topsoil compaction or other damage, approximately eight inches of existing topsoil would be stripped from the temporary disturbance area, then stockpiled and stabilized. Gravel fill would replace the removed topsoil to serve as a base pad for trailers, parking, and equipment staging. After construction, the gravel would be removed and replaced with the stockpiled topsoil. The disturbed area would be revegetated using an approved native seed mix.

c. **Project magnitude**

Table 1 summarizes the Project magnitude.

Table 1. Project Magnitude

Description	Value
Total Project Area Acreage	63.02
Temporary Ground Disturbance Acreage	8.5
Permanent Ground Disturbance Acreage	25.8
Number and type of residential units	0
Residential building area (in square feet)	0
Commercial building area (in square feet)	0
Industrial building area (in square feet)	286,971 (Phase 1: 135,871. Phase 2: 151,100)
Institutional building area (in square feet)	0
Roads/Parking Lots (acres)	5.2
Structure height(s)	
Oxide Building	43 ft
Nitriding Structure	105 ft
Milling Building	41 ft
Finishing/Warehouse Building	48 ft
Electrical Building	20 ft
Control Room Building	18 ft
Guard House Building	12 ft
Methanol Column Structure	64 ft
Hot Oil Heating Unit	40 ft
Cooling Tower	34 ft
Flare Structure	82 ft

d. Explain the Project purpose; if the Project will be carried out by a governmental unit, explain the need for the Project and identify its beneficiaries.

The purpose of this project is to establish a first-of-its-kind, full-scale U.S. manufacturing facility for rare-earth-free high-performance permanent magnets, supporting both local economic development and national supply chain resilience. Through a public–private partnership between Niron Magnetics and the City of Sartell, the project would meet a critical need: rebuilding the city's industrial tax base, restoring high-quality manufacturing jobs after the 2012 closure of the Verso paper mill, and positioning Minnesota as a leader in advanced materials innovation.

Niron Magnetics' technology represents the first major breakthrough in permanent magnet materials in decades. Developed at the University of Minnesota and refined in Minneapolis, Niron's Iron Nitride magnets are produced without any rare earth elements—using abundant, domestically sourced materials such as iron and nitrogen. This rare-earth-free magnet platform not only eliminates exposure to environmentally damaging mining practices abroad but also reduces U.S. dependence on foreign supply chains that have historically constrained production of electric vehicles, electronics, renewable energy systems, and defense technologies.

The Sartell project would be one of Minnesota's largest construction and manufacturing projects, with a planned investment of over $550 million. The project would be built in two phases. Phase 1 would support construction of a projected 136,000-square-foot manufacturing facility. Phase 2 is estimated to add an additional 151,000 square feet, bringing the total facility to approximately 287,000 square feet. Upon completion, the facility is anticipated to create 175 full-time jobs.

A local benefit of the project to the city is creating new jobs, broadening the tax base, and investing in workforce development and educational initiatives designed in partnership with local institutions. Nationally, the facility would address an urgent and growing need for domestically produced permanent magnets. Global demand is projected to exceed supply by 55,000 tons by 2040, threatening production timelines for EVs, wind turbines, and essential defense systems. By producing up to 1,500 tons of Iron Nitride magnets annually, the Sartell facility will help close that gap while establishing Minnesota as the epicenter of next-generation magnet manufacturing.

This project represents a long-term investment in economic vitality, technological leadership, and supply chain security, benefiting the City of Sartell, the State of Minnesota, and industries across the United States.

e. Are future stages of this development including development on any other property planned or likely to happen? ☐ **Yes** **X No**

If yes, briefly describe future stages, relationship to present Project, timeline and plans for environmental review.

f. Is this Project a subsequent stage of an earlier Project? ☐ **Yes** **X No**

If yes, briefly describe the past development, timeline and any past environmental review.

7. Climate Adaptation and Resilience

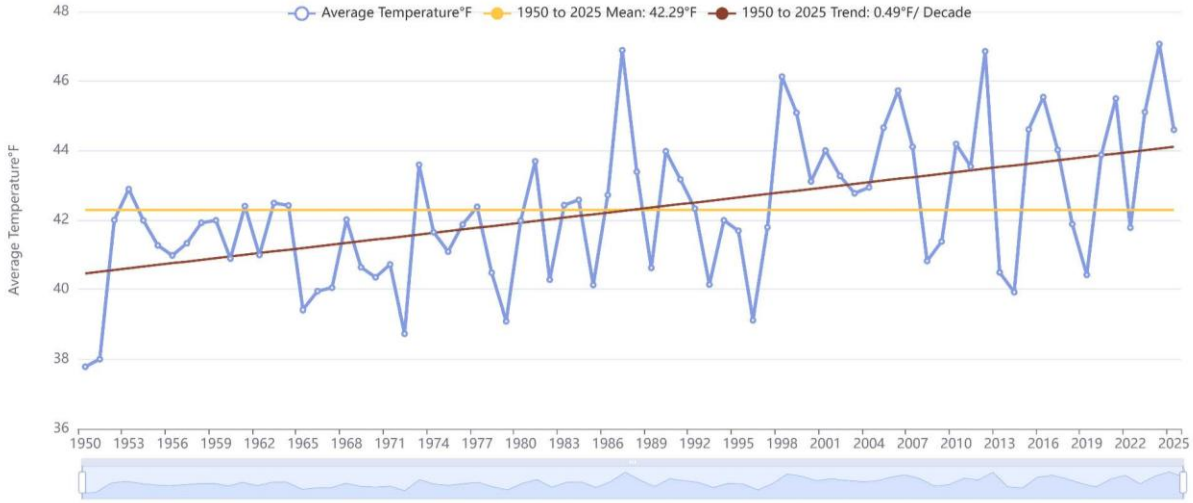
a. *Describe the climate trends in the general location of the Project (see guidance: Climate Adaptation and Resilience) and how climate change is anticipated to affect that location during the life of the Project.*

In general, Minnesota is anticipated to experience an increase in temperature, precipitation, and more frequent extreme precipitation events resulting from climate change. Between 1895 and 2020, annual average temperatures have risen three degrees Fahrenheit and precipitation has increased by an average of 3.4 inches in Minnesota.[1] The highest average temperature increases have occurred during the winter. Since 1895, temperatures during the winter have increased at a rate two to three times higher than during the summer. [2] In particular, winter warming rates have risen more sharply in recent decades. Current climate warming trends, most notably during the winter, are anticipated to continue.

Heavy rain events have become more frequent in Minnesota and more intense. From 1973 to 2021, Minnesota experienced 16 mega-rain events[3] with a notable increase since 2000. Of these 16 events, three occurred in the 1970s, one in the 1980s, one in the 1990s, six mega-rain events occurred in the 2000s, four in the 2010s, and one in 2020. Between 2000 to 2021, more than twice as many mega rain events occurred compared to the prior 27 years (1973 to 1999).[4]

Climate trends in Stearns County parallel the overall statewide trends, indicating Minnesota's climate is becoming warmer and wetter. Exhibit 1 and Exhibit 2 illustrate historical average annual temperature and precipitation trends from 1950 to 2025, respectively. During this time period, the County experienced an average annual temperature increase of 0.49 degrees Fahrenheit (°F) per decade and an annual precipitation increase of 0.45 inches per decade.

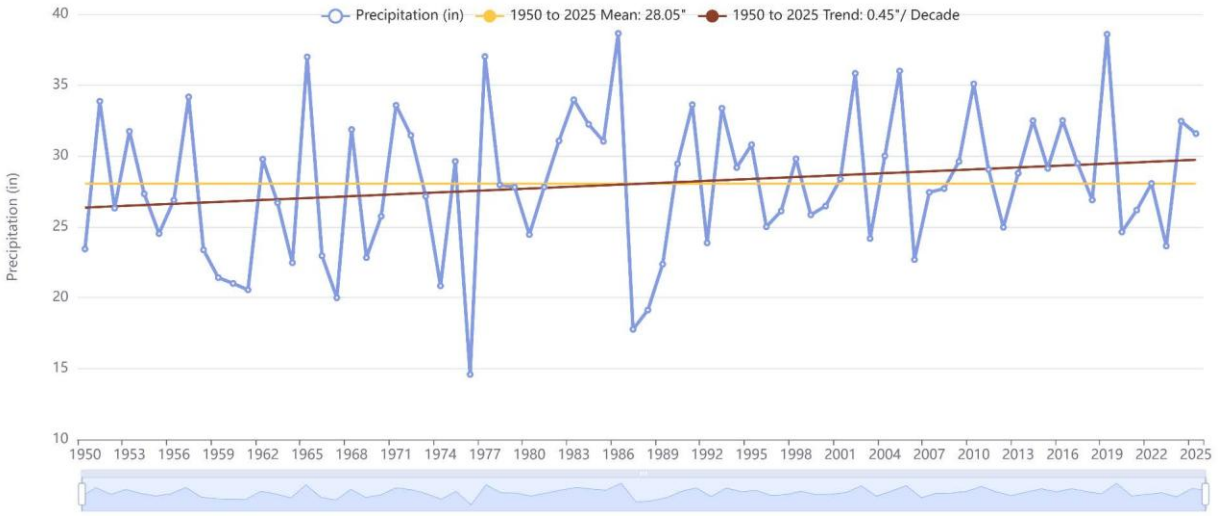
Exhibit 1. Historical Annual Average Temperature in Stearns County (1950 – 2025)



Source: DNR Climate Explorer available at https://climate-explorer.dnr.state.mn.us/main/historical

[1] DNR, undated(a). Climate Trends. Available at: https://www.dnr.state.mn.us/climate/climate_change_info/climate-trends.html. Accessed November 2025.
[2] Ibid.
[3] Mega-rain events are defined as events in which six inches of rain covers more than 1,000 square miles and the core of the event tops eight inches.
[4] MnDNR, 2024(a). Historic Mega-Rain Events in Minnesota. Available at: https://www.dnr.state.mn.us/climate/summaries_and_publications/mega_rain_events.html.

Exhibit 2. Historical Annual Average Precipitation in Stearns County (1950 – 2025)

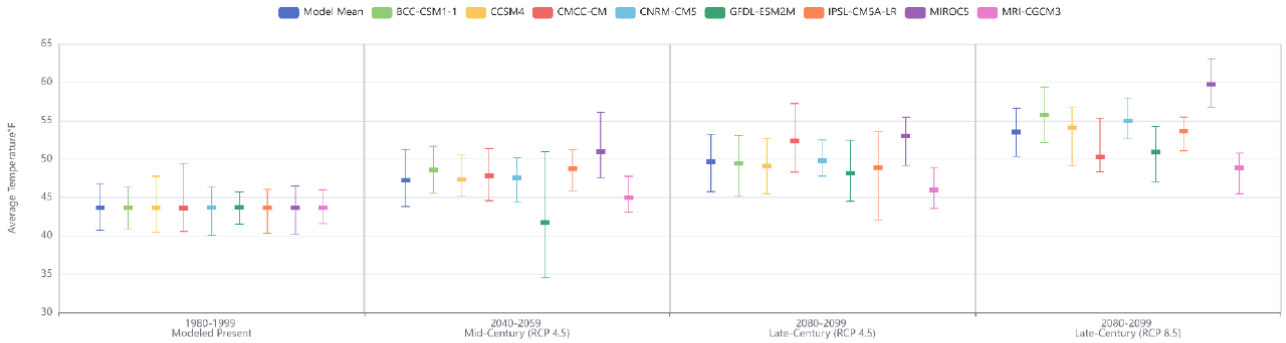


Source: DNR Climate Explorer available at https://climate-explorer.dnr.state.mn.us/main/historical

Projected climate trends indicate that temperatures within the County would continue to increase. Exhibit 3 illustrates Projected temperatures for the County. Several climate models are shown in the projected temperature analysis. The model mean, shown in blue on the first boxplot to the left in each model category, illustrates the average of all models included in the analysis. Exhibit 3 shows the modeled present condition, mid-century (2040-2059) at Representative Concentration Pathway (RCP) 4.5, late-century (2080-2099) at RCP 4.5, and late-century (2080-2099) at RCP 8.5. RCP is a greenhouse gas concentration scenario used by the Intergovernmental Panel on Climate Change in the fifth assessment report. RCP 4.5 is an intermediate scenario in which emissions decline after peaking around 2040 and RCP 8.5 represents a worst-case scenario in which emissions continue rising through the 21st century.

Under the RCP 4.5 scenario, the annual temperature is anticipated to increase within the County from a modeled present mean of 43.7°F (1980-1999) to a mid-century (2040-2059) model mean of 47.2°F and a late-century (2080-2099) model mean of 49.6°F. Under the RCP 8.5 worst-case scenario, the County would experience a late-century (2080-2099) model mean temperature of 53.5°F. In comparison to the modeled present mean (1980-1999), the late-century (2080-2099) modeled mean annual temperature would increase by approximately 12.6 percent under the RCP 4.5 scenario and increase by approximately 20.2 percent under the RCP 8.5 scenario.

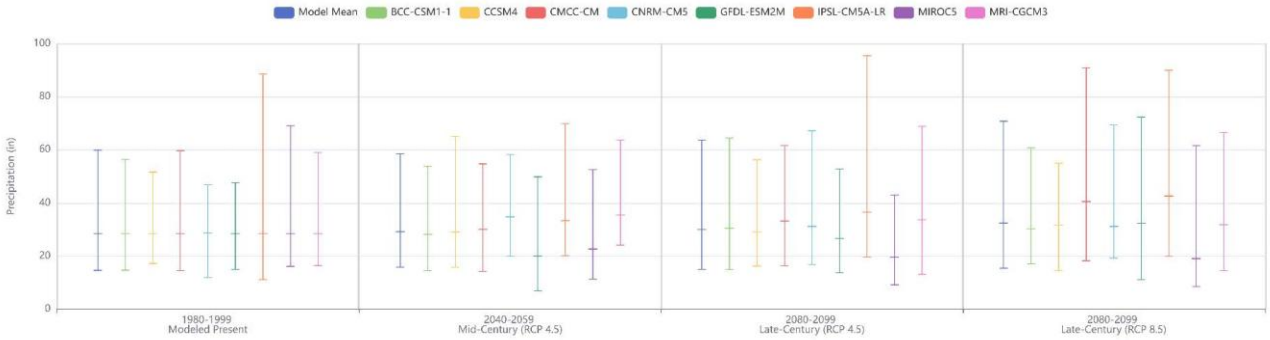
Exhibit 3. Projected Temperatures in Stearns County



Source: DNR Climate Explorer available at https://climate-explorer.dnr.state.mn.us/main/historical

Exhibit 4 presents Projected average annual precipitation for Stearns County. Under the RCP 4.5 scenario, the annual precipitation is anticipated to increase within the County from a modeled present mean of 28.5 inches (1980-1999) to a mid-century (2040-2059) model mean of 29.2 inches and a late-century (2080-2099) model mean of 30.1 inches. Under the RCP 8.5 worst-case scenario, the County would experience a late-century (2080-2099) model mean precipitation of 32.5 inches. In comparison to the modeled present mean (1980-1999), the late-century (2080-2099) modeled mean annual precipitation would increase by approximately 5.5 percent under the RCP 4.5 scenario and increase by approximately 13.1 percent under the RCP 8.5 scenario.

Exhibit 4. Projected Precipitation in Stearns County



Source: DNR Climate Explorer available at https://climate-explorer.dnr.state.mn.us/main/historical

b. For each Resource Category in the table below: Describe how the Project's proposed activities and how the Project's design will interact with those climate trends. Describe proposed adaptations to address the Project effects identified.

Table 2 summarizes climate considerations related to the Project and adaptation considerations.

Table 2. Climate Considerations and Adaptations

Resource Category	Climate Considerations	Project Information	Adaptations
Project Design	Projected climate trends include increasing temperatures, precipitation, and frequency of heavy rainfall events. Minnesota is trending towards warmer temperatures. Urban heat islands occur when impervious surfaces, such as roofs and paved surfaces, absorb heat during the day and release it at night, amplifying the warming trend.	Conversion from undeveloped land to developed land including construction of buildings, roadways, and parking areas would increase impervious surface area. Increased impervious surfaces would increase volume of stormwater runoff and potential flooding risk during heavy rain events. Impervious surfaces may create local heat island effects by absorbing heat during daytimes hours and radiating it at night leading to an increase in surface temperatures.	The Project would follow proposed and recommended actions for impervious surface coverage outlined by the City of Sartell in their Zoning Regulations. Additional measures to minimize heat island effects can include strategically planting trees to increase shading near buildings to reduce energy use. The Project area contains coarse, well-drained soils that significantly limit the potential for localized flooding.

Resource Category	Climate Considerations	Project Information	Adaptations
Land Use	Heavier rainfall is expected to bring a higher risk of localized flooding. Increased temperatures may create public health crises primarily for vulnerable communities such as children and the elderly.	The Project area currently consists of fallow cropland, brush/grassland, deciduous tree canopy and some wetlands. Conversion from undeveloped land to industrial development would increase impervious surfaces and may contribute to local heat island effects.	The Project does not propose critical facilities such as hospitals, daycare centers, public utilities, or schools within the Project area that would have heightened sensitivity to the climate considerations identified. Wetlands would be preserved within the Project area, and avoidance and minimization of impacts to tree canopy within the Project area would occur where feasible. Local heat island effects from adding impervious surface to the Project area may be mitigated by avoiding removal of existing tree canopy where feasible and the planting of new trees to increase shade in developed areas.
Water Resources	Addressed in Item 12.		
Contamination/ Hazardous Materials/Wastes	The Project area is projected to experience an increase in precipitation and heavy rainfall events.	The Project is anticipated to involve the use of chemical/ hazardous materials in their manufacturing process. The Project would include the use of Aboveground Storage Tanks. All hazardous materials would be stored indoors or inside Aboveground Storage Tanks and not exposed to storm events.	Facilities for storing and using hazardous materials would be constructed to building codes, fire codes, and industry best practices. Chemical inventories are expected to exceed EPA's Risk Management Program thresholds, and a Risk Management Program and Plan would be developed and submitted to the EPA. Aboveground Storage Tanks would be designed and registered in accordance with MPCA requirements. A Spill Prevention, Control, and Countermeasures (SPCC) plan would be developed for oil storage.

Resource Category	Climate Considerations	Project Information	Adaptations
			Waste generated during construction and operations would be properly managed and disposed of in accordance with Minnesota Pollution Control Agency (MPCA) requirements. The facility would operate under an MPCA Large Quantity Generator License and would develop a Contingency Plan to manage risks.
Fish, wildlife, plant communities, and sensitive ecological resources (rare features)	Addressed in Item 14.		

8. Cover Types

Estimate the acreage of the site with each of the following cover types before and after development.

The following tables and Figure 4, Appendix A summarize cover types within the Project area.

Table 3. Cover Types

Cover Types	Before(acres)[1]	After (acres)
Wetlands and shallow lakes (<2 meters deep)	7.88	7.88
Deep lakes (>2 meters deep)	0.0	0.0
Wooded/forest	11.51	9.51
Brush/grassland/fallowed cropland	43.50	12.0
Lawn/landscaping	0.0	5.70
Green infrastructure total (from table below*)	0.0	0.0
Impervious surface	0.0	23.60
Stormwater Basins	0.13	4.33
Total	**63.02**	**63.02**

[1] *Before" Acreages are approximate and based on geospatial observation of Stearns County 2024 aerial imagery (see Figure 4, Appendix A) and 2023 wetland delineation data.*

Table 4. Green Infrastructure

Green Infrastructure*	Before (acreage)	After (acreage)
Constructed infiltration systems	0	0
Constructed tree trenches and tree boxes	0	0
Constructed wetlands	0	0
Constructed green roofs	0	0
Constructed permeable pavements	0	0
Other (describe) Landfill-based geothermal system	0	0
Total	**0**	0

Table 5. Tree Canopy

Trees	Percent	Number
Percent tree canopy removed, or number of mature trees removed during development	18%	261
Number of new trees planted	TBD*	TBD*

*City of Sartell's tree preservation rules state that developers must plant at least 1 tree per 1,000 square feet of building floor square footage or per 100 feet of lot perimeter, whichever is greater. The number of new required trees can be reduced based on the number of existing mature trees not removed by the Project. Niron must submit a Landscaping Plan to the City for approval.

9. Permits and Approvals Required

List all known local, state and federal permits, approvals, certifications and financial assistance for the Project. Include modifications of any existing permits, governmental review of plans and all direct and indirect forms of public financial assistance including bond guarantees, Tax Increment Financing and infrastructure. All of these final decisions are prohibited until all appropriate environmental review has been completed. See Minnesota Rules, Chapter 4410.3100.

Table 6. Permits and Approvals

Unit of Government	Type of Application	Status
Federal		
U.S. Environmental Protection Agency	Risk Management Plan submittal	Pending
U.S. Internal Revenue Service	Qualified Advanced Energy Project Tax Credit (48C)	Complete
State		
Minnesota Pollution Control Agency	Air Emission Registration Permit, Option D	Complete (#14500196-101)
Minnesota Pollution Control Agency	Construction Stormwater Permit	Complete (#C00073325)
Minnesota Pollution Control Agency	Industrial Stormwater Permit	Pending
Minnesota Pollution Control Agency	Aboveground Storage Tank Registrations	Pending
Minnesota Pollution Control Agency	Large Quantity Generator License	Pending
Minnesota Department of Natural Resources	Water Appropriation Permit (new well)	Pending
Minnesota Department of Natural Resources	Water Appropriation Permit (construction dewatering)	To be applied for, if needed
Minnesota Department of Employment and Economic Development	Minnesota Forward Fund financial assistance	Received
Local		
City of Sartell	Environmental Assessment Worksheet	Pending
City of Sartell	Wetland Conservation Act wetland delineation approval	Complete
City of Sartell	Land Disturbance Permit	Complete (#25-LD00004)
City of Sartell	Construction Permits (Site Plan, Building, Plumbing, Electrical)	Pending
City of Sartell	Certificate of Occupancy	Pending
City of Sartell	Tank Permit	Pending
City of Sartell	Industrial Wastewater Permit	Pending
City of Sartell	Tax Increment Financing Development Agreement	Complete

10. Land use

a. Describe:

i. Existing land use of the site as well as areas adjacent to and near the site, including parks and open space, cemeteries, trails, prime or unique farmlands.

The Project area currently consists of vacant grassland and brushland, recently fallowed crop land, a large wetland, and scattered groves of mixed trees. Adjacent land uses include residential areas to the north and east, light industrial and vacant land to the west, and a closed landfill to the south. The Mississippi River is approximately 350 feet to the east of the Project area.

There are several public parks within ½-mile of the Project area, including Rotary Regional Park, Natures Edge Park, Sabre Park, Watab Regional Park, Veteran's Regional Park, and Val Smith Regional Park. A City of Sartell public trail runs north-south along 4th Avenue South. See Figure 5, Appendix A.

There are mapped Prime Farmland soils within the Project area. The property was converted to non-farming use prior to this proposed Project and the Project requires no federal funding or federal permitting, thus the federal Farmland Protection Policy Act (FPPA) does not apply.

ii. Plans. Describe planned land use as identified in comprehensive plan (if available) and any other applicable plan for land use, water, or resources management by a local, regional, state, or federal agency.

The 2016 City of Sartell Comprehensive Plan (Comp Plan) Future Land Use map indicates the Project area was anticipated to be utilized for a mix of Medium Density Residential and Office/Warehouse uses.[5] See Figure 6, Appendix A.

iii. Zoning, including special districts or overlays such as shoreland, floodplain, wild and scenic rivers, critical area, agricultural preserves, etc.

The Project area is currently zoned for Light Industrial by the City of Sartell.[6] See Figure 7, Appendix A. The Project area is not within a Shoreland, Wild and Scenic River, or Floodplain overlay district.

iv. If any critical facilities (i.e. facilities necessary for public health and safety, those storing hazardous materials, or those with housing occupants who may be insufficiently mobile) are proposed in floodplain areas and other areas identified as at risk for localized flooding, describe the risk potential considering changing precipitation and event intensity.

The proposed facility would not be within a floodplain area or an area otherwise at risk for flooding.

b. Discuss the Project's compatibility with nearby land uses, zoning, and plans listed in Item 9a above, concentrating on implications for environmental effects.

The proposed Project is compatible with City of Sartell zoning and current land use planning.

c. Identify measures incorporated into the proposed Project to mitigate any potential incompatibility as discussed in Item 10b above and any risk potential.

Not applicable.

[5] City of Sartell. 2016. "2026 Comprehensive Plan". Available at https://www.sartellmn.com/services/community_development___planning2/comprehensive_plan.php.

[6] City of Sartell. 2026. "Sartell Zoning Map". Available at https://sartellmn.com/services/community_development___planning2/maps.php.

11. Geology, Soils and Topography/Land Forms

a. Geology - Describe the geology underlying the Project area and identify and map any susceptible geologic features such as sinkholes, shallow limestone formations, unconfined/shallow aquifers, or karst conditions. Discuss any limitations of these features for the Project and any effects the Project could have on these features. Identify any Project designs or mitigation measures to address effects to geologic features.

The surficial geology in the Project area has been mapped by the Minnesota Geological Survey's (MGS) Geologic Atlas of Stearns County as being sediments consisting of glacial till, specifically deposits associated with the Superior Lobe (Figure 9, Appendix A). These deposits consist of predominantly sandy loam soil, unsorted sediment, with pebbles, cobbles, and boulders. The till in this area is mapped as being water-washed, and may be mantled by silt, sand, or gravel in some places. [7] The relief in the Project area is generally subdued, forming a gently undulating surface around 1,050 feet above mean sea level (AMSL) with minor rises to about 1,060 feet AMSL in the northwest and 1,070 feet AMSL in the northeast.

The bedrock geology in the Project area has been mapped by the MGS Geologic Atlas of Stearns County as being Reformatory granodiorite from the Early Proterozoic Period. The unit is characterized by grey to pinkish-gray, medium grained, weakly porphyritic and trachytic hornblende-biotite granodiorite.[8] The bedrock topography[9] within the Project area is mapped to be approximately 960 to 1,020 feet AMSL and the depth to bedrock[10] is estimated to be approximately 50 to 100 feet. According to the Minnesota Department of Health (MDH) Minnesota Well Index (MWI), no wells were identified within the Project area and six wells were identified within one quarter mile of the Project area.[11] These wells were drilled to depths between 14 and 76 feet and do not record the presence of bedrock. The well log reports and stratigraphic records are available in Appendix B.

According to the MNDNR, Karst Feature Inventory, there are no known karst or sinkhole features within the Project area or within the vicinity of the Project area.[12] Further, the US Geological Survey (USGS) does not identify the Project area as being within a known or potential karst area.[13] The nearest known feature is a sinkhole located approximately 50 miles southeast of the Project area in Ramsey, Minnesota. The first encountered bedrock in the Project area is the Reformatory granodiorite, which is an insoluble crystalline igneous rock not known for karst development. Due to the lack of soluble carbonate bedrock, the formation of karst within the Project area is unlikely.

b. Soils and topography - Describe the soils on the site, giving NRCS (SCS) classifications and descriptions, including limitations of soils. Describe topography, any special site conditions relating to erosion potential, soil stability or other soils limitations, such as steep slopes, highly permeable soils. Provide estimated volume and acreage of soil excavation and/or grading. Discuss impacts from Project activities (distinguish between construction and operational activities) related to soils and topography. Identify measures during and after Project construction to address soil limitations including stabilization, soil corrections or other measures. Erosion/ sedimentation control related to stormwater runoff should be addressed in response to Item 12.b.ii.

The Project area features gently undulating topography with minor rises in the northwest and northeast.

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[7] Meyer, G.N. (1995). Minnesota Geological Survey. C-10 Geologic Atlas of Stearns County. Plate 3 – Surficial Geology. Available at: https://conservancy.umn.edu/items/f86ea182-8341-4f4f-9ac9-124b2ed03052. Accessed January 2026.
[8] Meyer, G.N. (1995). Minnesota Geological Survey. C-10 Geologic Atlas of Stearns County. Plate 2 – Bedrock Geology. Available at: https://conservancy.umn.edu/items/f86ea182-8341-4f4f-9ac9-124b2ed03052. Accessed January 2026.
[9] Meyer, G.N. (1995). Minnesota Geological Survey. C-10 Geologic Atlas of Stearns County. Plate 6 – Bedrock Topography. Available at: https://conservancy.umn.edu/items/f86ea182-8341-4f4f-9ac9-124b2ed03052. Accessed January 2026.
[10] Meyer, G.N. (1995). Minnesota Geological Survey. C-10 Geologic Atlas of Stearns County. Plate 5 – Depth to Bedrock. Available at: https://conservancy.umn.edu/items/f86ea182-8341-4f4f-9ac9-124b2ed03052. Accessed January 2026.
[11] MDH (2025). Minnesota Well Index. Available at: https://www.health.state.mn.us/communities/environment/water/mwi/index.html. Accessed January 2026.
[12] MDNR (undated). Karst Feature Inventory. Available at: https://arcgis.dnr.state.mn.us/portal/apps/webappviewer/index.html?id=9df792d8f86546f2aafc98b3e31adb62. Accessed January 2026.
[13] Weary, D.J. and Doctor, D.H. (2014). Karst in the United States: A digital map compilation and database: U.S. Geological Survey Open-File Report 2014-1156, 23 p. Available at: https://pubs.usgs.gov/publication/ofr20141156. Accessed January 2026.

Elevation ranges from approximately 1,050 feet AMSL to 1,060 feet AMSL in the northwest and 1,070 feet AMSL in the northeast. The Project area was used for agricultural purposes from the 1930's until the late 2010s. The Project area also contains a large wetland in the center-east, a small wetland in a small grove of trees in the southwest corner, a human-made drainage ditch in the southwest corner, and two small stormwater ponds along 4th Avenue.

According to the U.S. Department of Agriculture (USDA) Natural Resource Conservation Services (NRCS) soil survey data, there are five soil map units within the Project area. The upland soil units predominantly consist of fine and loamy sands with mucky soil in surface depressions associated with wetland areas. The mapped soils range from moderately well drained to very poorly drained. The upland soil units are expected to feature relatively high susceptibility to wind erosion, while wetland soils are expected to feature very low susceptibility to wind erosion. The mapped soil units are expected to feature low to moderate susceptibility to water erosion and mixed permeability. See Figure 9, Appendix A for USDA-NRCS soil mapping and Table 7 below for a summary of select attributes for each of the mapped soil units.

Based on soil borings conducted and summarized in the 2025 Preliminary Geotechnical Investigation, the general soil profile of undisturbed areas consisted of sandy topsoil overlying glacially deposited sand and gravel materials. The topsoil samples consisted of fine-grained silty sand and clayey sand and ranged from about 1 to 2 feet thick. Samples of glacial deposits consisted mainly of silty sand with gravel, but contrast was found in different boring locations. One of the soil borings encountered a blockage, likely a buried boulder. There was also a large boulder observed at the surface, therefore, cobbles and boulders should be anticipated during excavation of the Project area.

The Project would significantly alter the existing soil and topographic conditions through grading and construction activities. It is anticipated that approximately 25.8 acres of the Project area would be permanently disturbed by grading and filling activities (see Figure 3, Appendix A). The disturbance area would generally be graded flat to prepare the site for facility construction. Approximately 121,377 cubic yards of clean imported fill soil would be needed. Most grading activity would utilize the imported fill material to level the construction area, as opposed to cutting into native soil.

The Project would adhere to erosion and sediment control practices during construction and operations per conditions of the Project's Stormwater Pollution Prevention Plan (SWPPP), National Pollution Discharge Elimination System (NPDES) Construction Stormwater Permit, and any local permitting conditions. See EAW Item 12.b.ii for details on stormwater management and erosion and sediment control.

Table 7. NRCS Soil Map Units within the Project area

Map Unit Symbol	Map Unit Name	Hydrologic Group	Wind Erodibility Group	Water Erodibility Factor (K*f*)	Acres	% of Project area
325	Prebish sandy loam, depressional	B/D	3	0.20	4.50	7.1%
163B	Brainerd fine sandy loam, 1 to 4 percent slopes	C/D	3	0.24	0.46	0.7%
1113	Haslie, Seelyeville, and Cathro soils, frequently ponded, 0 to 1 percent slopes	B/D	8	*not rated*	3.90	6.2%
119B	Pomroy fine sand, 1 to 6 percent slopes	A	1	0.10	24.95	39.6%
218	Watab loamy fine sand	C/D	2	0.17	29.21	46.4%
				Total	**63.02**	**100.0**

The hydrologic soil groups are:

- **Group A**: Soils having a high infiltration rate (low runoff potential) when thoroughly wet. These consist mainly of deep, well drained to excessively drained sands or gravelly sands. These soils have a high rate of water transmission.
- **Group B**: Soils having a moderate infiltration rate when thoroughly wet. These consist chiefly of moderately deep or deep, moderately well drained, or well drained soils that have moderately fine texture to moderately coarse texture. These soils have a moderate rate of water transmission.
- **Group C**: Soils having a slow infiltration rate when thoroughly wet. These consist chiefly of soils having a layer that impedes the downward movement of water or soils of moderately fine texture or fine texture. These soils have a slow rate of water transmission.
- **Group D**: Soils having a very slow infiltration rate (high runoff potential). These consist chiefly of soils with high clay content, soils that have a high-water table, soils that have a claypan or clay layer at or near the surface, and soils that are shallow over nearly impervious material. These soils have a very slow rate of water transmission.
- **Dual Groups**: Dual Group designations (A/D, B/D, or C/D) are used to indicate wet soils that belong to Group D due to a high water table but would meet the drainage or textural criteria for Group A, B, or C if drained. Dual Group soils should be treated as Group D soils in the absence of effective artificial drainage.

The soil erodibility factors are:

- **Wind Erodibility Group**: Soils are assigned a Wind Erodibility Group (WEG) rating based on their inherent vulnerability to soil particle detachment from wind forces. Values range from 1 (most erodible) to 8 (least erodible).
- **Water Erodibility Factor (K*f*):** The Soil Erodibility Factor (K*f*) is a unitless quantitative description of the inherent vulnerability of a soil to water erosion. It provides a measurement of soil particles' susceptibility to detachment from rain drops or surface runoff. Values range from 0.02 (least erodible) to 0.69 (most erodible).

12. Water Resources

a. Describe surface water and groundwater features on or near the site in a.i. and a.ii. below.

i. Surface water - lakes, streams, wetlands, intermittent channels, and county/judicial ditches. Include any special designations such as public waters, shoreland classification and floodway/floodplain, trout stream/lake, wildlife lakes, migratory waterfowl feeding/resting lake, and outstanding resource value water. Include the presence of aquatic invasive species and the water quality impairments or special designations listed on the current MPCA 303d Impaired Waters List that are within 1 mile of the Project. Include MnDNR Public Waters Inventory number(s), if any.

Surface Waters
There are no streams, lakes, or Minnesota Public Waters within the Project area. See Figure 10, Appendix A. The closest surface water is the Mississippi River, which is approximately 350 feet east of the eastern Project property boundary. The Watab River is approximately 2,100 feet north of the Project area. Table 8 below lists the named Public Waters basins within one mile of the Project area. Table 9 provides details on MPCA-listed 303d impaired waters.

Table 8. Public Waters within One Mile of the Project area[14]

Water Resource	Type	PW ID/ Kittle No.	On Impaired Waters List?
Within Project area			
No surface waters within the Project area.			
Within One Mile of the Project area			
Mississippi River	River	103383	Y
Watab River, South Fork	River	110522	Y
Davenport Lake	Lake	18877	N
Unnamed	Public Waters Wetland	18878	N

Table 9. 303d Impaired Waters within One Mile of the Project area[15]

Waterbody Name	AUID*	Affected Designated Use	Pollutant or Stressor	TMDL² ID
Mississippi River	07010201-631	Aquatic Consumption	Mercury in Fish Tissue	PRJ07770-001
Watab River, South Fork	07010201-554	Aquatic Life, Aquatic Recreation	Fish bioassessments, E. coli bacteria	PRJ06864-001

**Assessment Unit Identification (AUID)*

[14] MPCA. Undated. Minnesota Public Waters Inventory. Access via ESRI ArcGIS Online, January 2025.
[15] MPCA. 2024. Minnesota Impaired Waters List. wq-iw1-81.xlsx. Access January 2025

[2]*Total Maximum Daily Load (TMDL)*

Wetland Resources

A wetland delineation was conducted within and adjacent to the Project area in 2023 by Short Elliot Hendrickson (SEH) and approved by the local Wetland Conservation Act (WCA) authority, the City of Sartell. The investigation identified one constructed stormwater pond and two natural wetlands within the Project area. A total of 8.01 acres of wetland were delineated. See Table 10 below and Figure 11, Appendix A.

Table 10. Wetlands Within the Project Area

Wetland ID	Circular 39	Cowardin	Eggers and Reed	Acres within Project area
Wetland 3	Type 3	PEM1C	Shallow Marsh	0.198
Wetland 4	Type 2, 5, and 6	PEM1B, PUBG, PSS1C	Fresh (wet) Meadow, Shrub-Carr, Shallow Open Water	7.68
Pond 1	n/a	n/a	n/a	0.13

Floodplain

The Project area is within a Federal Emergency Management Agency (FEMA) Flood Hazard Zone X, which indicates minimal annual risk of flooding.

ii. Groundwater – aquifers, springs, seeps. Include: 1) depth to groundwater; 2) if Project is within a MDH wellhead protection area; 3) identification of any onsite and/or nearby wells, including unique numbers and well logs if available. If there are no wells known on site or nearby, explain the methodology used to determine this.

There are no known springs, seeps, or karst features present in the Project area, and the Project area is not within a wellhead protection area.

Groundwater can be expected to be within 20 feet of the surface depending on the time of year and regional groundwater conditions. A review of the MDH MWI[16] identified no verified wells within the Project area and six verified wells within a quarter-mile radius of the Project area. These wells are presented in Table 11 and Figure 12, Appendix A. The depth to static water level in the MWI well log reports ranges from approximately seven to 27 feet. Well log reports are included in Appendix C. A geotechnical investigation was commissioned by Niron in March 2025. Six borings were conducted, each between 15 to 20 feet below ground level. Static water table was observed within 20 feet of the surface in two of the borings.[17]

[16] MDH. 2025. MWI. Available at: https://www.health.state.mn.us/communities/environment/water/mwi/index.html. Accessed January 2026.
[17] SEH. 2025. “Preliminary Geotechnical Investigation”. Available upon request.

Table 11. Verified MWI Wells Near the Project Area

Well ID	Use Type	Distance from Project	Status	Depth (ft.)	Static Water Level (ft.)
135955	Domestic	Approximately 200 feet east	Active	76	Not reported
472168	Monitoring	Approximately 600 feet west of southwest corner	Sealed	14	7
472169	Monitoring	Approximately 600 feet west of southwest corner	Sealed	62	22
594766	Monitoring	Approximately 200 feet southwest	Active	30	20
594767	Monitoring	Approximately 200 feet southwest	Active	60	27
680557	Monitoring	Approximately 800 feet south of southwest corner	Active	22	16

According to the MDH Source Water Protection Map[18], the Project area is not within an MDH Wellhead Protection Area or Drinking Water Supply Management Area (DWSMA). However, as shown in Figure 12, Appendix A, the Fischers Garden Mobile Home Park Wellhead Protection Area and DWSMA limits are located approximately 1,000 feet and 500 feet east of the Project area, respectively. This DWSMA has a vulnerability ranking of high.

b. Describe effects from Project activities on water resources and measures to minimize or mitigate the effects in Item b.i. through Item b.iv. below.

i. Wastewater - For each of the following, describe the sources, quantities and composition of all sanitary, municipal/domestic and industrial wastewater produced or treated at the site.

1) If the wastewater discharge is to a publicly owned treatment facility, identify any pretreatment measures and the ability of the facility to handle the added water andwaste loadings, including any effects on, or required expansion of, municipal wastewater infrastructure.

At full production upon completion of both phases, the Proposed facility would generate an estimated 290,400 gallons per day (GPD) of industrial wastewater related to manufacturing processes and includes 16,400 GPD of residential strength wastewater from an estimated 175 full time daily employees. Table 12 below breaks down the estimated wastewater flow by facility source.

[18] MDH (2025). Source Water Protection Map Web Viewer. Available at: https://www.health.state.mn.us/communities/environment/water/swp/mapviewer.html. Accessed January 2026.

Table 12. Estimated Wastewater Flows

Source	Waste Strength	Estimated Daily Flow (gal)	Estimated Yearly Flow (gal)	Pre-Treatment Required?
Employees (175)	Domestic	16,438	6,000,000	No
Plating Process	Industrial	21,918	8,000,000	Yes (pH, metals)
Cooling Towers	Industrial	57,534	21,000,000	No
Reverse Osmosis Reject	Industrial	35,616	13,000,000	No
Oxide Building	Industrial	95,890	35,000,000	Yes (pH)
All other industrial discharges	Industrial	63,014	23,000,000	No
TOTAL		**290,410**	**106,000,000**	

The proposed facility's wastewater would discharge to an existing public sanitary sewer in the 4th Avenue right-of-way and the west-east public sanitary sewer between the south edge of the Project site and the Sartell landfill. Wastewater would be conveyed to the St. Cloud Nutrient, Energy, and Water Recovery Facility (WRF) in St. Cloud, MN for final treatment. The St. Cloud WRF discharges to the Mississippi River per the conditions of their MPCA NPDES permit requirements (permit #MN0040878). The St. Cloud WRF has a permitted design flow capacity of 17.9 million GPD (6.5 billion gallons per year) and has affirmed to Niron that the treatment facility has existing capacity to accept the estimated flows.

All wastewater conveyed from the proposed facility to the public sanitary system must meet effluent quality standards from the St. Cloud WRF. Niron anticipates that some industrial wastewater sources would need pH adjustment prior to discharge to the public sanitary sewer, and the plating process wastewater would pass through its own pre-treatment process to reduce metals concentrations. Chloride would be the primary constituent of concern for the wastewater discharged to the public system, with an estimated maximum concentration of 8,000 parts per million. The facility's oxide process system would be the primary source of excess chloride. Niron is currently in discussions with St. Cloud WRF authorities regarding the anticipated chloride concentrations.

2) *If the wastewater discharge is to a subsurface sewage treatment systems (SSTS), describe the system used, the design flow, and suitability of site conditions for such a system. If septic systems are part of the Project, describe the availability of septage disposal options within the region to handle the ongoing amounts generated as a result of the Project. Consider the effects of current Minnesota climate trends and anticipated changes in rainfall frequency, intensity and amount with this discussion.*

Not applicable.

3) *If the wastewater discharge is to surface water, identify the wastewater treatment methods and identify discharge points and proposed effluent limitations to mitigate impacts. Discuss any effects to surface or groundwater from wastewater discharges, taking into consideration how current Minnesota climate trends and anticipated climate change in the general location of the Project may influence the effects.*

   Not applicable.

ii. Stormwater - Describe changes in surface hydrology resulting from change of land cover. Describe the routes and receiving water bodies for runoff from the Project site (major downstream water bodies as well as the immediate receiving waters). Discuss environmental effects from stormwater discharges on receiving waters post construction including how the Project will affect runoff volume, discharge rate and change in pollutants. Consider the effects of current Minnesota climate trends and anticipated changes in rainfall frequency, intensity and amount with this discussion. For Projects requiring NPDES/SDS Construction Stormwater permit coverage, state the total number of acres that will be disturbed by the Project and describe the stormwater pollution prevention plan (SWPPP), including specific best management practices to address soil erosion and sedimentation during and after Project construction. Discuss permanent stormwater management plans, including methods of achieving volume reduction to restore or maintain the natural hydrology of the site using green infrastructure practices or other stormwater management practices. Identify any receiving waters that have construction-related water impairments or are classified as special as defined in the Construction Stormwater permit. Describe additional requirements for special and/or impaired waters.

Under existing conditions, the Project area primarily consists of grassland, recently fallowed cropland, wetlands, and several groves of trees. There are no impervious surfaces present. The site's topography is generally bowl-shaped, and slopes from most directions toward a large wetland that runs north-south across the center-eastern side of the Project area. A topographic ridge on the east side of the Project area limits surface runoff.

Under proposed conditions, most of the Niron-owned property west of the large wetland would be graded and partially leveled for facility construction. Imported fill would be used to level the work area. See Figure 3, Appendix A and draft civil design drawings in Appendix B. The Project would result in approximately 23.6 acres of new impervious surface. Increased impervious surface area can result in different runoff rates and volumes compared to the existing conditions, and a change in potential runoff pollutants. For a 100-year storm, Niron estimated a pre-development peak surface runoff rate of 125 cubic feet per second (cfs), and a post-development peak runoff rate of 48 cfs.

A Stormwater Pollution Prevention Plan (SWPPP) would be prepared as part of the Project's National Pollutant Discharge Elimination System (NPDES) Construction Stormwater Permit issued by MPCA (permit #C00073325). The SWPPP would conform to permit requirements and address sediment and erosion control Best Management Practices (BMPs) during construction. The Project must also adhere to the City of Sartell's Land Disturbance Permit requirements and the Erosion and Sediment Control Ordinance.[19] Sediment and erosion control BMPs may include bio-rolls, silt fence, rock construction entrances, inlet protection devices, erosion control blankets, erosion stabilization mats, and/or other similar devices to prevent soil erosion and sediment transport. Temporary sedimentation basins would be utilized during construction to store runoff and capture sediment. Per City of Sartell rules, all disturbed soils would be stabilized within seven days of inactivity, and seeded areas must show proper vegetation establishment within three weeks. All construction erosion and sediment control BMPs must be inspected by the permit holder within 24 hours of a significant rain event (>0.5 inches). Inspections and repairs must be documented in writing. City staff may also conduct inspections at their discretion.

[19] Sartell City Code, Title 10, Chapter 21. Erosion and Sediment Control Ordinance: https://cms5.revize.com/revize/sartell/Title%2010%20Zoning%20Regulations%20RV%202025%20KH%20Edits.pdf?t=202511251020390&t=202511251020390.

Per the MPCA's General Stormwater Permit conditions, permittees must utilize infiltration BMPs to reduce the volume of stormwater runoff discharged from the site, unless infiltration practices are prohibited due to certain site conditions described in the Permit. Infiltration BMPs are prohibited for this Project due to unfavorable soil conditions. Infiltration basins must feature at least 36 inches of vertical separation between the basin floor and seasonal groundwater (General Permit Section 16.17), and the soils in the vicinity of the stormwater management system are rated as Hydrologic Group C/D (see EAW Question 11b). Hydrologic Group C/D soils feature poor infiltration rates due to shallow groundwater. MPCA rules also explicitly prohibit infiltration practices within Hydrologic Group D soils (General Permit Section 16.18). In addition, infiltration practices are prohibited if they could adversely impact the hydrology of wetlands on site and there was concern that significantly reducing the overall volume of runoff to the wetland could starve it of water during dry years (General Permit Section 16.3).

If infiltration BMPs are not allowed, filtration systems are the next preferred type of BMP for volume control per MPCA guidance, if feasible. It was determined that a filtration basin for this Project would require a significantly larger footprint in terms of area and elevation to handle the anticipated flows from large storm events than the proposed wet sedimentation basin. In addition, filtration systems require intense maintenance to preserve the efficiency and effectiveness of the filtration which can lead to increased risk of reduced water quality.

During operations, stormwater runoff would be directed to an approximately 4.2-acre wet sedimentation stormwater pond system along the south and east sides of the facility. See draft civil design drawings in Appendix B. The pond system would consist of a forebay and a wet sedimentation basin. At a minimum, a sedimentation basin must be able to store the equivalent volume of a 1-inch rainfall across all impervious surfaces. The wet sedimentation basin is designed to provide live runoff storage of 136,900 cubic feet, which is more than double the estimated runoff generated by a one-inch rainfall (66,066 cubic feet). Any overflow would be discharged to the adjacent wetland through a control structure. The control structure would feature a skimmer device designed to reduce total suspended solids by up to 90%.

Due to the proposed facility type, an MPCA Industrial Stormwater Permit would be required prior to commencement of facility operations. This permit addresses stormwater that may come in contact with industrial materials, equipment, or supplies that may be stored outside. The facility would not store any harmful materials outdoors.

There would be no direct discharge of managed stormwater to a lake or stream. The Mississippi River is 1,000 feet east of the receiving wetland, but due to the site's topography there is no direct surface drainage connection to the river. The Mississippi River is not listed for any construction stormwater-related impairments. All site stormwater would be contained within the project area.

iii. Water appropriation - Describe if the Project proposes to appropriate surface or groundwater (including dewatering). Describe the source, quantity, duration, use and purpose of the water use and if a MnDNR water appropriation permit is required. Describe any well abandonment. If connecting to an existing municipal water supply, identify the wells to be used as a water source and any effects on, or required expansion of, municipal water infrastructure. Discuss environmental effects from water appropriation, including an assessment of the water resources available for appropriation. Discuss how the proposed water use is resilient in the event of changes in total precipitation, large precipitation events, drought, increased temperatures, variable surface water flows and elevations, and longer growing seasons. Identify any measures to avoid, minimize, or mitigate environmental effects from the water appropriation. Describe contingency plans should the appropriation volume increase beyond infrastructure capacity or water supply for the Project diminish in quantity or quality, such as reuse of water, connections with another water source, or emergency connections.

Construction excavation into native soil would be limited to buried utilities and pits for those pieces of equipment that need to extend below the facility's floor elevation. Depending on the time of year and

groundwater conditions, construction dewatering may be needed within these excavations. The construction contractor would obtain a dewatering permit from MNDNR as needed.

The facility would require an estimated 429,000 gpd of water during Phase 2 operations. The City of Sartell has affirmed the municipal water treatment system has both physical and permit capacity to support the Project's water needs. The municipal water supply is drawn from nine wells owned by the City of Sartell. Alternatively, Niron is considering construction of their own private water supply well for the Project to mitigate the increased draw on the City of Sartell's water infrastructure. The well would be located on Niron's property, outside of Sartell's wellhead protection areas. Prior to securing a water appropriation permit from MNDNR or drilling a well, a Well Construction Assessment and aquifer test would be conducted to evaluate potential groundwater impacts. The well driller would notify Minnesota Department of Health prior to drilling the well. The Project area is not within a drinking water supply management area (DWSMA), though the Fischer's Garden Mobile Home Park DWSMA's western boundary is approximately 500 feet east of the Project area.

As described in EAW Item 7a, Stearns County (and much of Minnesota) is expected to see a moderate increase in average annual precipitation and large storm events. This trend should result in greater groundwater recharge rates compared to current conditions.

iv. Surface Waters

a) Wetlands - Describe any anticipated physical effects or alterations to wetland features such as draining, filling, permanent inundation, dredging and vegetative removal. Discuss direct and indirect environmental effects from physical modification of wetlands, including the anticipated effects that any proposed wetland alterations may have to the host watershed, taking into consideration how current Minnesota climate trends and anticipated climate change in the general location of the Project may influence the effects. Identify measures to avoid (e.g., available alternatives that were considered), minimize, or mitigate environmental effects to wetlands. Discuss whether any required compensatory wetland mitigation for unavoidable wetland impacts will occur in the same minor or major watershed and identify those probable locations.

The Project may result in approximately 300 square feet of fill impact to Wetland 4 related to the stormwater basin's outlet structure. By design, the basin would discharge treated stormwater to the wetland. The discharge outlet would utilize approximately 300 square feet of riprap (or other energy dissipation materials) to prevent scour erosion around the outlet. This feature may be moved out of the wetland if feasible. If not, Niron would submit a WCA No-Loss application under a "de minimis" exemption, which allows for up to 1/10th acre of permanent impact to the affected wetland type without the need for mitigation.

b) Other surface waters- Describe any anticipated physical effects or alterations to surface water features (lakes, streams, ponds, intermittent channels, county/judicial ditches) such as draining, filling, permanent inundation, dredging, diking, stream diversion, impoundment, aquatic plant removal and riparian alteration. Discuss direct and indirect environmental effects from physical modification of water features, taking into consideration how current Minnesota climate trends and anticipated climate change in the general location of the Project may influence the effects. Identify measures to avoid, minimize, or mitigate environmental effects to surface water features, including in-water Best Management Practices that are proposed to avoid or minimize turbidity/ sedimentation while physically altering thewater features. Discuss how the Project will change the number or type of watercraft on any water body, including current and Projected watercraft usage.

No other waters would be impacted by the Project.

13. Contamination/Hazardous Materials/Wastes

a. Pre-Project site conditions - Describe existing contamination or potential environmental hazards on or in close proximity to the Project site such as soil or ground water contamination, abandoned dumps, closed landfills, existing or abandoned storage tanks, and hazardous liquid or gas pipelines. Discuss any potential environmental effects from pre-Project site conditions that would be caused or exacerbated by Project construction and operation. Identify measures to avoid, minimize or mitigate adverse effects from existing contamination or potential environmental hazards. Include development of a Contingency Plan or Response Action Plan.

A Phase 1 Environmental Site Assessment (ESA) was conducted on behalf of Niron in March, 2025 by Short Elliott Hendrickson (SEH). The ESA did not identify any onsite contamination risks. The nearest identified potential contamination risk was the closed landfill immediately south of the Project area. SEH prepared a Landfill and Groundwater Quality Review report in November 2025 related to the landfill site. The report states "…*based on the landfill's design with liners, leak detection systems, leachate collection, and groundwater monitoring systems, the potential for future landfill-related groundwater impacts to the Site is minimal. Because [the] landfills are regulated facilities with active, ongoing monitoring with more than 30 years of water quality data, no additional investigation to establish existing groundwater quality on the Site [was] warranted*."

Soil or groundwater contamination is not anticipated within the Project area. However, due to the close proximity of the landfill site, Niron Magnetics commissioned SEH to prepare a Soil and Groundwater Management Plan (Plan) for the proposed Project. The Plan provides guidance for identifying contaminated soils or groundwater and provides detailed plans for the handling and testing of any potentially contaminated materials encountered during construction.[20]

A review of MPCA's *What's in My Neighborhood* (WIMN) database was conducted to identify documented potentially contaminated sites within or in the vicinity of the Project area.[21] No known contaminated sites were identified within the Project area, though the Project's approved Construction Stormwater Permit is included in the WIMN database. Eleven WIMN sites were identified within one-quarter mile of the Project area. Table 13 summarizes these findings and Figure 13, Appendix A, illustrates the location of WIMN sites in close proximity to the Project.

Table 13. MPCA WIMN Sites within One-Quarter Mile of the Project area

Site ID	Site Name	Activity	Status	Location
264817	Niron Magnetics	Construction Stormwater	Active	310 4th Ave South
6838	Sartell Heights South Improvements	Construction Stormwater	Inactive	No street address
265782	Sartell Public Works	Aboveground Tanks	Active	306 4th Ave South
191371	Brown Residence	Petroleum Remediation, Leak Site	Active	1909 High View Drive

[20] The SEH reports cited above are available upon request.
[21] MPCA, 2026. What's in My Neighborhood. Available at: What's in My Neighborhood | Minnesota Pollution Control Agency (state.mn.us). Accessed January 2026.

Site ID	Site Name	Activity	Status	Location
220938	Sartell Holdco	Construction Stormwater	Active	4th Ave South
8440	O'Reilly Auto Parts - 1572	Hazardous Waste, Minimal quantity generator	Active	216 Riverside Ave South
11150	Sartell Auto Service	Hazardous Waste	Inactive	5 Riverside Ave South
4599	Grede Saint Cloud Industrial SW Landfill	Multiple Activities	Active	4th St South
145918	Dollar General 25338	Hazardous Waste, Minimal quantity generator	Active	218 Riverside Ave South
260793	Sartell Landfill	Industrial Stormwater	Active	4th Ave South
216381	Storage Sheds	Construction Stormwater	Active	301 4th Ave South
217667	SP 220-117-004	Construction Stormwater	Active	

b. Project related generation/storage of solid wastes - Describe solid wastes generated/stored during construction and/or operation of the Project. Indicate method of disposal. Discuss potential environmental effects from solid waste handling, storage and disposal. Identify measures to avoid, minimize or mitigate adverse effects from the generation/storage of solid waste including source reduction and recycling.

Construction waste would be primarily non-hazardous and would be managed as municipal solid waste (MSW) or construction/demolition debris. Hazardous wastes in the form of used oils/lubricants, waste paints, or other materials may be generated during construction. The contractor would be required to manage and dispose of all construction-generated waste in accordance with MPCA requirements and all other applicable regulatory requirements. Construction waste would either be recycled or stored in approved containers and disposed of in the proper facilities. Any excess soil material that is not suitable for use onsite would become the property of the contractor and would be disposed of properly.

Operational solid waste would consist of typical municipal solid waste and recyclable materials. The collection of solid waste would be managed by a licensed waste hauler. The Project would adhere to all MPCA requirements and other regulations pertaining to the use, handling, and disposal of solid waste. Recycling areas would be provided in compliance with the Minnesota State Building code.

c. Project related use/storage of hazardous materials - Describe chemicals/hazardous materials used/stored during construction and/or operation of the Project including method of storage. Indicate the number, location and size of any new above or below ground tanks to store petroleum or other materials. Indicate the number, location, size and age of existing tanks on the property that the Project will use. Discuss potential environmental effects from accidental spill or release of

hazardous materials. Identify measures to avoid, minimize or mitigate adverse effects from the use/storage of chemicals/hazardous materials including source reduction and recycling. Include development of a spill prevention plan.

Construction equipment may require the limited use of potentially hazardous materials, such as gasoline or diesel fuels, engine motor oils, hydraulic fluids, and other lubricants. Vehicles responsible for the transportation of hazardous materials would be equipped with spill kits for rapid response to any spills and refueling procedures would be implemented to eliminate leakage. Additionally, all fuels, oils, and lubricants would be stored in containment apparatuses while not in use. Construction staff would be trained to spot and appropriately respond to potential spills. In the event that a leak or spill incident occurs, the contractor would be required to respond in accordance with MPCA containment and remedial action procedures. A SPCC plan would be prepared by a Minnesota Professional Engineer pursuant to federal regulations.

Niron anticipates using materials like ammonia, hydrogen, methanol, and corrosive liquids in their manufacturing process. Facilities for storing and using these hazardous materials would be constructed and operated per building codes, fire codes, industry best practices, and federal Chemical Accident Prevention requirements of 40 CFR 68.[22] Niron anticipates chemical inventories will exceed EPA's Risk Management Program thresholds and Niron would create a Risk Management Program and submit a Risk Management Plan to EPA for review and approval.

Niron would register Aboveground Storage Tanks with MPCA after tank designs are completed. Niron would create a Spill Prevention Control and Countermeasure (SPCC) plan for oil storage. Niron would have HAZWOPER-trained employees and establish Memorandums of Understanding for supplementary 3rd party spill response support capabilities. Local- and State- Emergency Planning Committees would receive annual reports of hazardous chemical inventories, per Section 312 of the federal Emergency Planning and Community Right-to-Know Act (EPCRA).

The Project would not utilize underground storage tanks during construction or operations.

d. Project related generation/storage of hazardous wastes - Describe hazardous wastes generated/stored during construction and/or operation of the Project. Indicate method of disposal. Discuss potential environmental effects from hazardous waste handling, storage, and disposal. Identify measures to avoid, minimize or mitigate adverse effects from the generation/storage of hazardous waste including source reduction and recycling

Project construction-related hazardous wastes in the form of used oils/lubricants, waste paints, or other materials may be generated during construction. The contractor would be required to manage and dispose of all construction-generated waste in accordance with MPCA requirements and all other applicable regulatory requirements.

Niron anticipates the facility would operate under an MPCA Large Quantity Generator (LQG) license and would submit an appropriate license application through MPCA's e-Services website prior to waste generation. Niron would create a Resource Conservation Recovery Act (RCRA) Contingency Plan to manage risks related to hazardous waste incidents. All wastes would be shipped offsite for disposal. Niron intends to recycle and purify for reuse certain feedstocks. Byproducts, like still bottoms, would be created and managed as a hazardous waste. "Still bottoms" are residues that accumulate at the bottom of distillation units.

[22] Code of Federal Regulations. Date unknown. Title 40, Chapter I, Subchapter C, Part 68. Available here: https://www.ecfr.gov/current/title-40/chapter-I/subchapter-C/part-68?toc=1.

14. Fish, Wildlife, Plant Communities, and Sensitive Ecological Resources (Rare Features)

a. Describe fish and wildlife resources as well as habitats and vegetation on or in near the site.

The Project area is located in the Minnesota and Northeast Morainal Section (222M) and Eastern Broadleaf Forest Province (222) as defined by the Minnesota Department of Natural Resources (DNR) in the *Field Guide to the Native Plant Communities of Minnesota – The Eastern Broadleaf Forest Province*.[23] Pre-settlement vegetation consisted primarily of oak barrens, openings, brushland, upland prairie, and floodplain forest. Characteristic trees included burr oak (*Quercus macrocarpa*), jack pine (*Pinus banksiana*), and northern pin oak (*Quercus ellipsoidalis*), among other species. Current land use within this subsection consists of wetlands, woodland, cropland, and urban development.[24]

Land cover within the 63.02-acre Project area was reviewed and is described in EAW Item 8 (Cover Types). Most of the Project area (43.50 acres, 69%), consists of brush/grassland and recently fallowed cropland. Other cover types present within the Project area include forested areas (11.51 acres, 18%), wetlands (7.88 acres, 12.5%), and two small historic stormwater ponds (0.13 acres, 0.21%). Figure 4, Appendix A illustrates land cover types within the Project area based on geospatial analysis.

The presence of brush/grassland, forested areas, and wetlands are likely to provide nesting, foraging, or travel habitat to a variety of urban wildlife species, including squirrels, mice, rabbits, deer, coyotes, foxes, passerine birds, raptors, and other small mammals. Suitable roosting habitat for bats may be present within the forested areas. Wetlands may provide habitat for amphibian species such as turtles, frogs and toads, or minnows and other aquatic species depending on the hydrologic regime of the wetland.

b. Describe rare features state-listed (endangered, threatened or special concern) species, native plant communities, Minnesota Biological Survey Sites of Biodiversity Significance, and other sensitive ecological resources on or within close proximity to the site. Provide the license agreement number (LA-) and/or correspondence number (MCE) from which the data were obtained and attach the Natural Heritage Review letter from the DNR. Indicate if any additional habitat or species survey work has been conducted within the site and describe the results.

Native Plant Communities and Sites of Biodiversity Significance

Based on a review of the DNR Minnesota Conservation Explorer (MCE) portal, there are no DNR Native Plant Communities, Minnesota Biological Survey (MBS) Sites of Biodiversity Significance, DNR Old Growth Stands, Lakes of Biological Significance, or calcareous fens located within the Project area.[25]

State-Listed Species

Under Stantec's Limited License to Use Copyrighted Material (2024-057) related to Rare Features Data, the DNR Natural Heritage Information System (NHIS) was searched in March 2025 and updated in January 2026 to identify rare features records within the Project area and within a one-mile radius of the Project area. The NHIS search did not identify rare species records within the Project area, but records of three rare species were identified within the one-mile radius of the Project area:

- Butternut tree (*Juglans cinerea*) – Endangered
- Black sandshell mussel (*Ligumia recta*) – Special Concern
- Peregrine falcon (*Falco peregrinus*) - Special Concern

A formal NHIS review request was also submitted to the DNR through the MCE portal[26] for the Project area on March 24, 2025. A final response from the DNR was received on June 24, 2025 (MCE-2025-

[23] Aaseng, N. (2005). *Field Guide to the Native Plant Communities of Minnesota – The Eastern Broadleaf Forest Province*. St. Paul: DNR.
[24] MNDNR. undated(a). Ecological Classification System. Available at: https://www.dnr.state.mn.us/ecs/index.html. Accessed January 2026.
[25] MNDNR. undated(b). Minnesota Conservation Explorer. Available at: https://mce.dnr.state.mn.us/content/explore. Accessed January 2026.
[26] MNDNR (2)

00309). Individual state-listed species were not identified for the Project from this review, but the DNR recommends that tree removal be avoided during the bat pupping season (June 1 to August 15). Appendix D provides a copy of the DNR MCE response letter.

The state-listed species identified through this review are described below.

Butternut

The butternut is a tree species that occurs in mesic hardwood forest systems, often along river terraces in loamy, alluvial, or sandy soils.[27] No mesic hardwood forest systems were identified during the review of the DNR MCE portal. Therefore, impacts to the butternut as a result of the Project are not anticipated.

Black sandshell

The black sandshell mussel inhabits riffles and runs of medium to large rivers that have sand or gravel substrate.[28] No medium or large rivers are located within the Project area. The Mississippi River is located within 0.1 miles of the Project area, but direct impacts are not anticipated and mitigation strategies would limit the risk of indirect impacts to this resource. As such, impacts to the black sandshell as a result of the Project are not anticipated.

Peregrine falcon

The peregrine falcon nests along cliff ledges over rivers or lakes as well as on bridges and buildings in urban settings. Foraging habitat generally consists of open, non-forested areas for direct aerial pursuit of prey.[29] No cliff ledges or buildings or bridges suitable for peregrine falcon nesting are located within the Project area. Open, non-forested areas for hunting are located within the Project area, so the peregrine falcon may occur in this area. However, the lack of nesting habitat and the overall high mobility of the peregrine falcon make impacts unlikely to occur as a result of the Project. Once construction begins, this species is likely to be deterred from using the Project area.

Federally-Listed Species

A review of the United States Fish and Wildlife Service (USFWS) Information for Planning and Consultation (IPaC) tool[30] was conducted initially in March 2025 to identify federally listed species, those species proposed for federal listing, and candidates for federal listing with the potential to occur within the Project area. An updated official species list under the same Project Code (2025-0073129) was obtained on January 20, 2026. Six species were identified from this review:

- Northern long-eared bat (*Myotis septentrionalis*) – Endangered
- Tricolored bat (*Perimyotis subflavus*) – Proposed Endangered
- Suckley's cuckoo bumble bee (*Bombus suckleyi*) – Proposed Endangered
- Monarch butterfly (*Danaus plexippus*) – Proposed Threatened
- Western regal fritillary (*Argynnis idalia occidentalis*) – Proposed Threatened
- Whooping crane (*Grus americana*) – Non-essential experimental population

No proposed or designated critical habitats were identified from this review. Appendix E includes the species list generated through the USFWS IPaC tool.

[27] Smith, W. 2008. Rare Species Guide: Butternut (*Juglans cinerea*). Minnesota Department of Natural Resources. Updated 2018. Available at: https://www.dnr.state.mn.us/rsg/profile.html?action=elementDetail&selectedElement=PDJUG02030. Accessed January 2026.
[28] DNR. undated(c). Rare Species Guide: Black Sandshell (*Ligumia recta*). Available at: https://www.dnr.state.mn.us/rsg/profile.html?action=elementDetail&selectedElement=IMBIV26020. Accessed January 2026.
[29] Stucker, S.P. 2018. Rare Species Guide: Peregrine Falcon (*Falco peregrinus*). Minnesota Department of Natural Resources. Available at: https://www.dnr.state.mn.us/rsg/profile.html?action=elementDetail&selectedElement=ABNKD06070. Accessed January 2026.
[30] USFWS. 2025-2026. Information for Planning and Consultation. Available at: https://ipac.ecosphere.fws.gov/. Accessed March and June 2025 and January 2026.

These species and their habitat requirements are described below.

Northern long-eared bat

Suitable roosting, forage, and travel habitat for northern long-eared bat (NLEB) in the summer consists of a wide variety of contiguous forested and wooded habitats with varying tree density and amounts of canopy closure. While roosting, NLEB is generally found in deep crevices in areas such as forests and woodlots (i.e. live trees and/or snags greater than or equal to three inches in diameter at breast height that have exfoliating bark, cracks, crevices, and/or cavities) as well as linear features such as fence rows, riparian forests, and other wooded corridors. NLEB roosts in both live trees and snags.[31,32,33] Additional summer habitat for the NLEB consists of areas adjacent to wooded areas, namely emergent wetlands and edges of agricultural fields, old fields, and pastures. The NLEB has also been observed roosting in human-made structures, such as buildings, barns, bridges, and bat houses.[34] During winter months, NLEB hibernates in caves or abandoned mines.[35]

Suitable summer roosting habitat and foraging habitat for the NLEB is present within the Project area and the USFWS interactive map for modeled NLEB habitat indicates that there is potential NLEB habitat within and in the Project area.[36] Therefore, the NLEB may occur within the Project area.

According to the DNR NHIS review conducted in March 2025 and January 2026, no known records of NLEB were identified within the Project area or within one mile of the Project area. Additionally, according to the USFWS-issued Northern Long-eared Bat and Tricolored Bat Range-wide Determination Key, there are no known NLEB hibernacula within one-half mile of the Project area, no known NLEB-occupied culverts within one-quarter mile of the Project area, and no known NLEB roost sites within 150 feet of the Project area.

Review of the NLEB relies on the USFWS-issued Northern Long-eared Bat and Tricolored Bat Range-wide Determination Key within the IPaC system and a determination of “May Affect” was reached for this species (Appendix E). Approximately 3.25 acres of tree clearing is proposed for the Project, primarily concentrated in the southwest corner of the Project area (see draft civil design drawings in Appendix B). If tree clearing occurs during the bat active season (April 15 to October 31), then impacts to the NLEB may occur. If feasible, tree clearing during the bat inactive season (November 1 to April 14), which also avoids the June 1 to August 15 pupping season, is recommended to avoid impacts.

Tricolored bat

During the non-hibernating seasons, tricolored bats will roost primarily in leaf clusters of live or dead deciduous hardwood trees. Tricolored bats have also been observed roosting among pine needles and in human-made structures such as barns, bridges, roofs, and other concrete structures. Non-hibernating season roosting is rarely observed in caves. During the winter, tricolored bats hibernate in caves and mines.[37]

The tricolored bat may occur within the Project area. Tree canopy is present within the Project area that may provide suitable roosting habitat for the tricolored bat. The USFWS interactive map for

[31] Sasse, D.B., and Perkins P.J. 1996. Summer roosting ecology of northern long-eared bats (*Myotis septentrionalis*) in the White Mountain National Forest. Bats and forests symposium. British Columbia Ministry of Forests Working Paper 23: 91-101.
[32] Foster, R.W. and A. Kurta. 1999. Roosting ecology of the northern bat. (*Myotis septentrionalis*) and comparisons with the endangered Indiana bat (*Myotis sodalis*). Journal of Mammalogy 80:659-672.
[33] Owen, S.F.; Menzel, M.A.; Ford, M.W.; Chapman, B.R,; Miller, K.V.; Edwards, J.W.; and Wood, P.B. 2003. Homerange size and habitat use by the northern Myotis (*Myotis septentrionalis*). American Midland Naturalist 150: 352-359.
[34] USFWS. 2024a. Rangewide-Wide Indiana Bat & Northern Long-Eared Bat Survey Guidelines. Available at: https://www.fws.gov/sites/default/files/documents/2024-04/final_usfws_range-wide_ibat-nleb_survey_guidelines_508-compliant.pdf. Accessed December 2025.
[35] Owen et al (11)
[36] USFWS. undated(a). Northern Long-eared Bat (*Myotis septentrionalis*) Interactive Map. Available at: https://www.fws.gov/species/northern-long-eared-bat-myotis-septentrionalis/map. Accessed January 2026.
[37] USFWS. 2026. Tricolored Bat – Habitat. Available at: https://www.fws.gov/species/tricolored-bat-perimyotis-subflavus. Accessed January 2026.

modeled tricolored bat habitat indicates that there is potential habitat within and in the Project area.[38]

According to the DNR NHIS review conducted in March 2025 and January 2026, no known records of tricolored bats were identified within the Project area or within one mile of the Project area. Additionally, according to the USFWS-issued Northern Long-eared Bat and Tricolored Bat Range-wide Determination Key, there are no known tricolored bat hibernacula within one-half mile of the Project area and no known tricolored bat occupied culverts within one-quarter mile of the Project area.

Review of the tricolored bat relies on the USFWS-issued Northern Long-eared Bat and Tricolored Bat Range-wide Determination Key within the IPaC system and a determination of "May Affect" was reached for this species (Appendix E). Approximately 3.25 acres of tree clearing is proposed for the Project, primarily concentrated in the southwest corner of the Project area (see draft civil design drawings in Appendix B). If tree clearing occurs during the bat active season (April 15 to October 31), then impacts to the NLEB may occur. If feasible, tree clearing during the bat inactive season (November 1 to April 14), which also avoids the June 1 to August 15 pupping season, is recommended to avoid impacts.

Suckley's cuckoo bumble bee

The Suckley's cuckoo bumble bee (SCBB) is a parasitic species that relies exclusively on other bumble bees as hosts. The SCBB historically occurs across a wide variety of habitats, including woodlands, prairies, meadows, agricultural areas, and urban areas where host bumble bee nests are present. While this species has historically occurred in portions of western and northern Minnesota, no extant populations are known to occur in Minnesota at present. The last confirmed sighting in the United States was in 2016 in Oregon.[39]

It is anticipated that the Project would have no effect on the SCBB. The USFWS Minnesota-Wisconsin Determination Key and Technical Assistance letter (Appendix E) did not cover the SCBB under its "No Effect" determination. Woodlots within the Project area may provide suitable habitat for nesting bumble bee host species. However, the lack of extant populations of the SCBB within the state of Minnesota and the fact that the last SCBB was observed in Minnesota prior to 2000 make the likelihood of occurrence of this species in the Project area very low.

Monarch butterfly

The monarch butterfly is a migratory butterfly that exists in two main populations within the United States divided by the Rocky Mountains: the eastern population that overwinters in the mountains of Mexico, and the western population that overwinters along the southern pacific coast of California.[40] Monarch butterflies are a widespread species found in fields, prairies, savannahs, and most places where their host plant milkweed (*Asclepias* spp.) occurs throughout the United States and southern Canada. This species generally occurs in areas with high densities of native nectar sources. During late summer and migration, adults use nectar species such as black-eyed Susan (*Rudbeckia hirta*), narrow-leaved coneflower (*Echinacea angustifolia*), and rough blazing star (*Liatris aspera*).[41] However, the presence of milkweed is required as it is the only plant on which monarch caterpillars can feed.[42]

It is anticipated that the Project would have no adverse effect on the monarch butterfly. Grasslands within the Project area may provide milkweed and flowering resources to support the monarch butterfly. While ground and vegetation disturbance is proposed for the Project, impacts could be mitigated through the

[38] USFWS. undated(b). Tricolored Bat (*Perimyotis subflavus*) Interactive Map. Available at: https://www.fws.gov/species/tricolored-bat-perimyotis-subflavus/map. Accessed January 2026.

[39] USFWS. 2024b. Endangered Species Status for Suckley's Cuckoo Bumble Bee. Available at: https://www.fws.gov/species-publication-action/endangered-species-status-suckleys-cuckoo-bumble-bee. Accessed October 2025.
[40] United States Department of Agriculture [USDA] Forest Service. undated-a. Migration and Overwintering. Available at: https://www.fs.fed.us/wildflowers/pollinators/Monarch_Butterfly/migration/. Accessed November 2021.
[41] MNDNR. 2022. Butterfly Gardens. Available at: https://www.dnr.state.mn.us/gardens/butterfly/index.html. Accessed March 2022.
[42] National Wildlife Federation. undated. Monarch Butterfly. Available at: https://www.nwf.org/Educational-Resources/Wildlife-Guide/Invertebrates/Monarch-Butterfly. Accessed December 2021.

use of native seed in revegetation plans. The effect determination for this species relies on the USFWS Minnesota- Wisconsin Determination Key within the IPaC system and a determination of "No Effect" was made for the monarch butterfly. The Technical Assistance letter is provided in Appendix E.

Western regal fritillary

Western regal fritillary requires large, intact grasslands at a landscape scale, with violets for larvae; nectar sources for adults; and native warm-season bunch grasses for shelter at all life stages. The grasslands need to be large and contiguous, generally more than 3.86 square miles, and be maintained by periodic disturbances. Voilet species (*Viola* sp.) are required as the exclusive source of larval forage.[43]

It is anticipated that the Project would have no effect on the western regal fritillary. The USFWS Minnesota-Wisconsin Determination Key and Technical Assistance letter (Appendix E) did not cover the western regal fritillary under its "No Effect" determination. However, quality native prairie habitat is not known to be present within or near the Project area, nor was it identified during the review of the DNR MCE portal.

Whooping crane

The whooping crane is a migratory bird species that once nested in northern prairies but now breeds in remote northern forests in Canada as well as in an experimental population in Wisconsin, preferably within coniferous habitat containing swamps and nearby lakes or ponds. Winter habitat consists of coastal marshes (e.g., Texas, Louisiana, and Florida).[44]

It is anticipated that the Project would have no effect on the whooping crane. Suitable habitat for the whooping crane, prairies and coniferous habitat with nearby swamps, is not present within the Project area. Additionally, the Project is located within the Mississippi Flyway while the wild population of whooping crane uses the Central Flyway located further west in the Great Plains. Any occurrence of a whooping crane within the Project area would likely be from the experimental population based out of Wisconsin that is not federally regulated. The effect determination for this species relies on the USFWS Minnesota-Wisconsin Determination Key within the IPaC system and a determination of "No Effect" was made for the whooping crane. The Technical Assistance letter is provided in Appendix E.

Migratory Birds

The USFWS IPaC review also provides information on potential eagle species and Birds of Conservation Concern (BCC) that have the potential to occur within the Project area. One eagle species and five BCC species have the potential to occur within the Project area (Appendix E). These species and their habitat requirements are detailed in Table 14.

Table 14. Migratory Birds Listed as BCC with Potential to Occur within the Project Area

Common Name	Scientific Name	Nesting, Foraging, and/or Migration Stopover Habitat[45]
Bald eagle[1]	*Haliaeetus leucocephalus*	Forested areas (conifers and deciduous trees) near large bodies of open water. Open uplands near open water in winter.

[43] USFWS. 2024c. Endangered and Threatened Wildlife and Plants; Endangered Status for the Eastern Regal Fritillary, and Threatened Status With Section 4(d) Rule for the Western Regal Fritillary. 89 FR 63888. August 6, 2024.
[44] Audubon. undated. Whooping Crane. Available at: https://www.audubon.org/field-guide/bird/whooping-crane. Accessed December 2025.
[45] Cornell Lab of Ornithology. undated. All About Birds. Available at: https://www.birds.cornell.edu/home/. Accessed January 2026.

Common Name	Scientific Name	Nesting, Foraging, and/or Migration Stopover Habitat[45]
Canada warbler	*Cardellina canadensis*	Breeds in mixed conifer and deciduous forest with shrubby and mossy understory near water; forested wetlands. Found in parks, forest edges, and woodlots during migration.
Chimney swift	*Chaetura pelagica*	Breeds in rural and urban settings in chimneys, tree cavities, and caves. Forage over open habitats, forests, ponds, and residential areas.
Grasshopper sparrow	*Ammodramus savannarum perpallidus*	Grasslands, prairies, hayfields, and open pastures with little scrub and some bare ground.
Red-headed woodpecker	*Melanerpes erythrocephalus*	Breeds in mature deciduous woodlands that contain dead or dying trees that can act as nest cavities. Oak, oak-hickory, maple, ash, and beech are often used in the northern portion of their range.
Rusty blackbird	*Euphagus carolinus*	Breeds in wet forests with fens, bogs, muskeg, or beaver ponds and winters in swamps, wet woodlands, and pond edges.
[1]This species is not listed as BCC but warrants special attention under the Bald and Golden Eagle Protection Act (BGEPA).		

The bald eagle is the protected migratory species most likely to occur within or near the Project area. This species is not listed as BCC but warrants special attention under the Bald and Golden Eagle Protection Act (BGEPA). Forested areas within and in the vicinity of the Project area may provide suitable nesting sites for the bald eagle, especially given the proximity to the Mississippi River.

The forested areas, grasslands, and wetlands within the Project area may provide nesting, foraging, and/or migration stopover habitat for the Canada warbler, chimney swift, grasshopper sparrow, red-headed woodpecker, rusty blackbird and other non-BCC migratory bird species.

If vegetation clearing activities can occur outside the peak breeding window for these and other migratory birds in Minnesota (approximately May 15 to August 1), then impacts on these species are unlikely to occur. If this is not feasible, a pre-construction breeding bird survey would be recommended as described below in the mitigation strategies.

c. Discuss how the identified fish, wildlife, plant communities, rare features and ecosystems may be affected by the project including how current Minnesota climate trends and anticipated climate change in the general location of the project may influence the effects. Include a discussion on introduction and spread of invasive species from the project construction and operation. Separately discuss effects to known threatened and endangered species.

Impacts Analysis for Native Plant Communities and Sites of Biodiversity Significance

Based on a review of the DNR MCE portal, there are no DNR Native Plant Communities, MBS Sites of Biodiversity Significance, DNR Old Growth Stands, Lakes of Biological Significance, or calcareous fens located within the Project area. Therefore, there would be no impacts on these resources.

Impacts Analysis for State-Listed Species

Butternut

Impacts on the butternut are not anticipated given that suitable habitat, river terraces and mesic hardwood forest systems, are not present within the Project area. These habitats

With an increase in more intense storms in Minnesota as a result of climate change, flooding events have become more common. These conditions favor siltation and flood scouring, both of which are unfavorable for the butternut.[46] Given that the Project area does not provide suitable habitat, the Project would not exacerbate the impacts of climate change on this species.

Black sandshell

Impacts on the black sandshell are not anticipated given that suitable habitat, medium to large rivers, is not present within the Project area. While the Mississippi River is located near the Project, no direct or indirect impacts to this resource are anticipated. Appropriate erosion and sediment control devices would be used to avoid indirect impacts to wetlands and waterbodies.

Freshwater mussels, such as the black sandshell, rely on burrowing behavior to escape predation. However, United States Geological Survey (USGS) studies have shown that increasing water temperatures lead to increased stress and decreased burrowing activity, resulting in mussels being more exposed.[47] Given that the Project area does not provide suitable habitat, the Project would not exacerbate the impacts of climate change on this species.

Peregrine falcon

Impacts on the peregrine falcon are unlikely given the lack of nesting habitat, cliffs or tall buildings, within the Project area. Construction within the Project area would likely deter peregrine falcons from hunting in the immediate vicinity.

Given the warming climate trend in Minnesota, overall suitable habitat for the peregrine falcon is anticipated to increase, but this comes at the expense of a loss of wintering grounds for the species.[48]

Impacts Analysis for Federally-Listed Species

Northern long-eared bat

The Project may affect the NLEB due to proposed tree clearing within the Project area, which can cause direct mortalities as well as habitat loss for the species. The use of temporary and/or permanent lighting may also affect this species when directed at suitable bat habitat. Tree clearing during the bat inactive season (November 1 to April 14) is recommended to avoid adverse effects on the NLEB.

As discussed in EAW Item 7 (Climate Adaptation and Resilience), Minnesota's climate is trending warmer with more extreme precipitation events. Changes in temperature and precipitation may influence the NLEBs available suitable roosting and foraging habitat, as well as prey availability.[49] Although a less significant stressor compared to white-nose syndrome, climate change variables may negatively affect

[46] Smith (5)
[47] USGS. 2008. Modeling the Response of Freshwater Mussels to Changes in Water Temperature, Habitat, and Streamflow. Available at: https://www.usgs.gov/programs/climate-adaptation-science-centers/science/modeling-response-freshwater-mussels-changes. Accessed September 2024.
[48] Audubon. 2019. Climate Threatened – Peregrine Falcon. Available at: https://climate2014.audubon.org/birds/perfal/peregrine-falcon. Accessed January 2024.
[49] USFWS. 2023. Northern Long-eared Bat. Available at: https://www.fws.gov/species/northern-long-eared-bat-myotis-septentrionalis. Accessed June 2024.

the NLEB.[50]

Tricolored bat

The Project may affect the tricolored bat due to proposed tree clearing within the Project area, which can cause direct mortalities as well as habitat loss for the species. The use of temporary and/or permanent lighting may also affect this species when directed at suitable bat habitat. Tree clearing during the bat inactive season (November 1 to April 14) is recommended to avoid adverse effects on the tricolored bat.

The tricolored bat is susceptible to climate change. For instance, areas that are experiencing more intense rainfall, such as Minnesota, may also see decreased foraging behavior from the tricolored bat along with decreased insect availability.[51]

Suckley's cuckoo bumble bee

The Project is anticipated to have no effect on the SCBB. While suitable nesting habitat (woodlots) is present within the Project area that may support hosts of this species, no extant populations of SCBB are known in Minnesota at present.

Climate change is anticipated to impact the SCBB in a variety of ways. Drought events are anticipated to increase and bloom dates for floral resources are occurring earlier, resulting in frost damage and overall fewer nectar species for SCBB and the host species it depends on. According to various different climate scenarios, widespread declines in bumble bee species are also predicted.[52]

Monarch butterfly

Given the wide range of habitats the species occupies, the removal and damage of vegetation within the Project area could result in habitat loss for the monarch butterfly as well as potential individual fatalities. If a native seed mix is used to revegetate the site post-construction, then development within the Project area may be a net positive for the species.

Climate change is anticipated to result in increasing temperatures in Minnesota, which may increase the number of days and the area in which monarch butterfly populations would be exposed to unsuitably high temperatures. This can result in them using up fat stores too quickly and may result in them incorrectly judging when to enter and exit states of dormancy (diapause).[53]

Western regal fritillary

The Project is anticipated to have no effect on the western regal fritillary due to the lack of native prairie habitat within the Project area. Permanent conversion of brush/grassland is proposed, but this habitat would not support this species due to its limited size (<0.1 square miles) and lack of native forage.

The western regal fritillary relies on violets for their life cycle, and their abundance is closely linked to violet density.[54,55] With an increase in more intense storms and droughts in Minnesota, invasive species are likely to become more dominant and push violet numbers down, thus furthering the decline of western

[50] USFWS. 2022. Final Rule 87 FR 73488: Endangered and Threatened Wildlife and Plants; Endangered Species Status for Northern Long-Eared Bat. Available at: https://www.federalregister.gov/documents/2022/11/30/2022-25998/endangered-and-threatened-wildlife-and-plantsendangered-species-status-for-northern-long-eared-bat. Accessed June 2024.

[51] USFWS. 2021. Species Status Assessment Report for the Tricolored Bat (*Perimyotis subflavus*). Version 1.1. Page iii. USFWS Northeast Region. Hadley, MA. Available at: https://fws.gov/species/tricolored-bat-perimyotis-subflavus. Accessed February 2023.

[52] USFWS. 2024d. Endangered and Threatened Wildlife and Plants; Endangered Species Status for Suckley's Cuckoo Bumble Bee. 89 FR 102074. December 17, 2024.

[53] Kobilinksy, Dana. 2019. Watch: Temperature Drives Internal Clock for Monarchs. The Wildlife Society. Available at: https://wildlife.org/watch-temperature-drives-internal-clock-for-monarchs/. Accessed January 2024.

[54] Debinskl, D. M., & Kelly, L. 1998. Decline of Iowa populations of the regal fritillary (*Speyeria idalia*) Drury. *Journal of the Iowa Academy of Science: JIAS*, *105*(1), 16-22.

[55] Beilfuss, K. G., & Harrington, J. A. (2001). Distribution patterns of the Regal Fritillary butterfly (*Speyeria idalia* Drury) within a Wisconsin dry prairie remnant. In Proc N Am Prairie Conference (Vol. 17, pp. 191-196).

regal fritillary habitat.

Whooping crane

The Project is anticipated to have no effect on the whooping crane due to the lack of coniferous forest and swamp habitat within the Project area. Impacts to wetlands present within the Project area would be avoided. The Project area is also not within the range of the wild population of whooping cranes. Any unlikely occurrences of this species within the Project area would likely be from the unregulated experimental population based in Wisconsin.

Based on models that consider various climate factors, it has been predicted that climate change may impact the juvenile recruitment and population growth of the whooping crane. For instance, increased precipitation during fall migration and the breeding season indicated lower recruitment and increased atmospheric carbon dioxide indicated lower population growth rates and recruitment.[56]

Impacts Analysis for Migratory Birds

Construction activities and development within the Project area may cause impacts to migratory birds and/or their nests. Based on the IPaC species review results (Appendix E), the majority of the BCC species with the potential to occur in the Project area are most likely to be nesting in the Project area between May 1 and August 31. Some of these species, as well as other migratory birds, may use the wetlands within the Project area, but impacts to wetlands would be avoided. If construction activities occur within vegetated areas of the Project area, it may cause impacts to migratory birds, eggs, young, and/or active nests if conducted during the bird nesting timeframe in Minnesota.

Impacts Analysis for Urban Wildlife

Urban wildlife such as squirrels, mice, rabbits, raccoons, deer, coyotes, foxes, and other small mammals may be impacted by the development within the Project area, such as through the removal of grasslands, forest, and/or wetlands. Additionally, lighting may have the potential to negatively impact wildlife. These species are generally adaptable to change and would likely relocate to other undeveloped areas.

Invasive Species

Noxious weeds and invasive species in Minnesota are managed through the Minnesota Department of Agriculture (MDA) under Minnesota Statutes Section 18.78, the DNR, and local ordinances. Best management practices (BMPs) during construction activities and operation within the Project area should be implemented where practicable to minimize the introduction or spread of noxious weeds and invasive species. These practices include cleaning vehicles and equipment of mud and dirt from other construction areas, removing seeds that attach to clothing or equipment, minimizing soil disturbance, not moving potentially contaminated materials between sites, and staying on designated roads/trails.[57,58]

d. Identify measures that will be taken to avoid, minimize, or mitigate the adverse effects to fish, wildlife, plant communities, ecosystems, and sensitive ecological resources.

- Sightings of any rare species during future development within the Project area should be reported to the DNR Nongame Wildlife specialist as soon as possible and their guidance should be followed before proceeding with work. Do not attempt to handle or move the species or its nest unless the animal is at immediate risk of injury and the action is being done under agency approval.
- If a bald eagle or bald eagle nest are discovered, work near the nest tree(s) would immediately

[56] Butler, M. J., Metzger, K. L., & Harris, G. M. (2017). Are whooping cranes destined for extinction? Climate change imperils recruitment and population growth. *Ecology and Evolution*, *7*(8), 2821-2834.

[57] USDA National Invasives Species Information Center. undated. Best Management Practices. Available at: https://www.invasivespeciesinfo.gov/subject/best-management-practices. Accessed January 2023.

[58] DNR. 2023. Terrestrial Invasive Species. Available at: https://www.dnr.state.mn.us/invasives/terrestrial/index.html. Accessed January 2023.

cease and USFWS would be consulted.

- The DNR Project review is valid for one year. If Project details change or the Project has not occurred within one year, the Project should be resubmitted for review.
- Wildlife-friendly erosion control devices should be used both to protect wetlands and other habitats from sediment-laden stormwater runoff and to prevent injury to wildlife. Typical DNR recommendations include:

    - Biodegradable netting should be used, preferably natural materials with short degradation periods. Erosion control blankets should be limited to bio-netting or natural netting types due to the risk of entanglement of small animals.
    - Identify acceptable materials in MnDOT Category 3N or 4N mulches.
    - Do not use products that require UV-light to degrade (also called “photodegradable”), as they do not degrade properly when covered/shaded.
    - Do not use products containing plastic mesh netting or other plastic components.
    - Do not use mulch products that contain synthetic (plastic) fiber additives near waterbodies.
    - See https://files.dnr.state.mn.us/eco/nongame/wildlife-friendly-erosion-control.pdf for more information.

- Native seed would be used for revegetation within the Project area in order to provide suitable habitat for species like the monarch butterfly and to prevent the spread of invasive plants and noxious weeds.
- Although the DNR NHIS review did not identify records of the NLEB or tricolored bat within the Project area, tree clearing is recommended to occur during the bat inactive season (November 1 to April 14, inclusive) when possible. If this is not possible, tree clearing should be conducted to avoid the bat pupping season of June 1 to August 15 per DNR recommendations.
- Niron would follow the City of Sartell’s tree replacement rule (Sartell City Code Title 10, Chapter 12) which states that one tree is to be planted per 1,000 square feet of building floor square footage or per 100 feet of lot perimeter, whichever is greater. The number of new required trees can be reduced based on the number of existing mature trees not removed by the Project. Niron must submit a Landscaping Plan to the City for approval.
- The use of downward facing, full cut-off lens lights are recommended for any permanent lighting used on the Project. Any temporary lighting should also be directed away from suitable bat habitat during the bat active season (April 15 – October 31).
- When possible, removal of vegetation should occur outside of the bird nesting window to minimize potential impacts to migratory birds.

15. Historic Properties

Describe any historic structures, archeological sites, and/or traditional cultural properties on or in close proximity to the site. Include: 1) historic designations, 2) known artifact areas, and 3) architectural features. Attach letter received from the State Historic Preservation Office (SHPO). Discuss any anticipated effects to historic properties during Project construction and operation. Identify measures that will be taken to avoid, minimize, or mitigate adverse effects to historic properties.

Stantec reviewed the SHPO previous survey report data as well as the Office of the State Archaeologist (OSA) Portal and the Minnesota Statewide Historic Inventory Portal in January 2026[59,60]. The literature search focused on previously identified cultural resources (archaeological sites and above-ground historic resources) within and adjacent to the Project area. Traditional Cultural Properties within or adjacent to the Project area are unknown as a Tribal Cultural Property identification survey has not been conducted for this Project. In addition, Stantec reviewed archival resources including General Land Office (GLO) maps, county atlases, the University of Minnesota Borchert Map Library, Trygg maps, and historical aerial imagery to identify potential cultural features in the Project area.

No previously conducted archaeological surveys overlap with the Project area.

No previously recorded archaeological sites are located within the Project area. Seven previously recorded archaeological sites are documented within 1-mile of the Project area (Table 15). Of the seven archaeological sites, two are eligible for the National Register of Historic Places (NRHP), one site is not eligible and the remaining four sites are unevaluated. Additionally, two of the archaeological sites within 1-mile of the Project area are precontact burial mounds located on the opposite side of the Mississippi River. Burial sites in Minnesota are protected under Minnesota Statute 307.08.

Table 15. Previously Recorded Archaeological Sites within 1-Mile of the Project Area

Site Number	Site Name	Site Type	Cultural Affiliation	NRHP Status
21BN0001	-	Burial Mound	Precontact	Unevaluated
21BN0002	-	Burial Mound	Precontact	Eligible
21BN0006	East Terrace	Artifact Scatter	Precontact: Paleo Indian, Archaic, Woodland	Eligible
21BN0017	Municipal Park	Lithic Scatter	Precontact	Unevaluated
21BN0036	Sartell Paper Mill	Paper Mill	Historic	Not Eligible
21SNt	Sartell	Structural Ruin (Mill)	Historic	Unevaluated
21SNaq	-	Artifact Scatter		Unevaluated

The MnModel, available on the OSA online portal, shows that the Project is located almost entirely within an area of unknown archaeological site potential. The southeastern edge of the Project area is within an area of low archaeological site potential. The MnModel dataset classifies archaeological site potential based on the number and distribution of archaeological sites and surveys, the resolution of environmental data, and the degree to which the environmental data represents the historic and precontact landscape. According to the OSA Portal, during the precontact period the Project area was mostly wetland, with small pockets of permanently wet areas. Deciduous forest was present in the eastern portion of the Project area along the Mississippi River while the western portion was interspersed deciduous forest and savanna.

[59] Minnesota Office of the State Archaeologist (OSA). 2026. Office of the State Archaeologist Portal. Electronic database, https://osaportal.gisdata.mn.gov/, accessed January 20, 2026.
[60] Minnesota State Historic Preservation Office (SHPO). 2026. Minnesota Statewide Historic Inventory Portal. Electronic database, https://mnship.gisdata.mn.gov/, accessed January 20, 2026.

No previously identified burial sites/cemeteries are recorded in the Project area. Two previously identified historic cemeteries (Oak Hill Cemetery and St. Francis Xavier Cemetery) are located within 1-mile of the Project area. Both cemeteries are mapped at the 40-acre level on the OSA Portal and are unevaluated for the NRHP. The cemeteries are protected through Minnesota Statute 307.08.

No previously identified above-ground historic resources are recorded in the Project area. Six previously identified above-ground historic resources are documented within 0.25-mile of the Project area; of which four are not eligible for the NRHP and two are unevaluated (Table 16).

Table 16. Previously Identified Above-Ground Historic Resources within 0.25-Mile of the Project Area

Resource No.	Name	Resource Type	Address/Location	NRHP Status
BN-LAN-00006	Brainerd Branch: Sauk Rapids to Brainerd Railroad	Structure	-	Unevaluated
SN-STC-00005	Farmstead	Building	600 Riverside Ave.	Unevaluated
XX-ROD-00037	Trunk Highway 10: Anoka to Little Falls Segment	Structure	Trunk Highway 47 in Anoka to Hilton Rd in Little Falls	Not Eligible
XX-RRD-NPR022	St. Paul and Northern Pacific Railway Company/Northern Pacific Railway Company: Staples to St. Paul	Structure	Staples and its terminus at Union Depot, St Paul	Not Eligible
XX-RRD-NPR024	St. Paul and Northern Pacific Railway Company/Northern Pacific Railway Company: Brainerd to St. Paul	Structure	Brainerd and terminus at Union Depot St Paul	Not Eligible
XX-RRD-NPR025	Western Railroad Company of Minnesota/St. Paul and Northern Pacific Railway Company/Northern Pacific Railway Company	Structure	Brainerd and junction with St Paul and Pacific Sauk Rapids	Not Eligible

Historic Document Review

An unnamed road extends through the Project area on the original GLO survey map from 1858 running parallel to the Mississippi River. No structures are mapped within the Project area or the vicinity in 1858; however, fields are mapped to the south of the Project Area, and a sawmill is mapped to the north. A handwritten note across the township map describes the township as rolling swamp, with other areas containing prairie, Tamarack, Ash, Lynn, Aspen, and Timber Oak[61].

Stantec reviewed atlas maps from 1874, 1896, 1916, 1925, and 1947 [62,63,64,65,66]. Riverside Avenue, extending along the eastern boundary of the Project area, first appears in the current alignment in 1874. A mapped

[61] General Land Office (GLO). 1858. Original Survey, MN, 5th PM, T125N – R28W. U.S. Department of the Interior, Bureau of Land Management, https://glorecords.blm.gov/details/survey/default.aspx?dm_id=112554&sid=thxgs45y.gd2#surveyDetailsTabIndex=0, accessed January 21, 2026.

[62] A.T. Andreas. 1874. Minnesota State Atlas, https://historicmapworks.com/Atlas/US/8283/, accessed January 21, 2026.

[63] C. M. Foote & Co. 1896. Outline Map of Stearns County. John R. Borchert Map Library, https://www.lib.umn.edu/collections/borchert/digitized-plat-maps-and-atlases#s-45631, accessed January 21, 2026.

[64] State of Minnesota. 1916. State of Minnesota Plat Book. John R. Borchert Map Library, https://geo.lib.umn.edu/plat_books/stateofmn1916/counties/stearns.htm, accessed January 21, 2026.

[65] Thomas O. Nelson Co. 1947. Plat Book of Stearns County, Minnesota, https://historicmapworks.com/Atlas/US/33049/Stearns+County+1947/, accessed January 21, 2026.

[66] W.W. Hixson & Co. 1925. Minnesota State Atlas, https://historicmapworks.com/Atlas/US/32714/, accessed January 21, 2026.

structure identified on all reviewed atlas maps aligns with the location of a house immediately adjacent to the Project area. No structures or cultural features are depicted within the Project area on any reviewed atlas maps. Development to the north of the Project area along the Watab River in Section 21 is first identified in 1896 when numerous labeled structures are first depicted on atlas maps. By 1916 the area is labeled as "Sartell" and by 1947 the NE1/4 NE1/4 of Section 28 and most of Section 27, overlapping with the Project area, are within the limits of Sartell.

Stantec reviewed United States Geological Survey (USGS) topographic maps from 1952, 1966, 1973, 1976, and 1993[67]. The above-mentioned structure mapped immediately adjacent to the Project area and Riverside Avenue also appeared on all reviewed USGS maps. A trailer park immediately north of the Project area and sewage disposal ponds south of the Project area first appear in 1976. Additional structures to the north of the Project area, as well as Heritage Drive/4th Ave South, extending along the western boundary of the Project area, first appear in 1993. No structures are depicted within the Project area on any reviewed USGS map.

The earliest aerial imagery of the Project area from 1938 shows a farmstead with numerous outbuildings at the location of the above-mentioned structure identified on atlas and topographic maps. Sparse trees surround the farmstead and extend to the north, within the northeastern portion of the Project area. The remainder of the Project area appears as grassland and cultivated land. A water-filled depression and a cattle trail are located within the grassland portion of the Project area. A structure associated with a house directly north of the Project area lies along the northern boundary of the Project area in 1938 and is absent by 1965. In 1965 a water-filled depression appears in the southwestern portion of the Project area. The Project area appears relatively unchanged as cultivated land and grassland in aerial imagery from 1938 to 1973[68,69].

In 1985, the western portion of the Project area transitions to grassland and a gravel road following the current alignment of Heritage Drive/4th Ave South first appears on aerial imagery. A disturbed area is noted in the northwest corner of the Project area, across the street from a house that first appears in aerial imagery in 1973. The disturbed area is visible in aerial imagery from 1985 to the present and appears largely as a rock and hay bale pile in recent aerial imagery. Between 1985 and 1991 a channel was constructed between the water-filled depression in the southwestern corner of the Project area and the agricultural field and is visible on all aerial imagery from 1991 to the present day as a cut on the landscape. Additional ground disturbance, evidenced by two circular newly disturbed areas, along the western border of the Project Area is first seen in 2021, continues to present day[70]. Based on historic aerial imagery, primary land use within the Project area consists of cultivated land and grassland since 1938.

Stantec understands that ground disturbing work, including grading and introduction of fill, has occurred within the western portion of the Project area. Available aerial imagery does not extend to dates that would illustrate the disturbance.

Despite previous disturbance, the Project area yields a moderate potential for intact cultural resources along the eastern half due to the proximity to the Mississippi River, as well as the presence of moderately well-drained soils within the Project Area.

Conclusions

Archaeology

- As construction and ground disturbance has already begun, and the Project area has not been previously surveyed, Stantec cannot recommend a determination of effect. A Phase I archaeological reconnaissance investigation is recommended if a thorough determine of the potential for the Project to impact historic properties is deemed necessary.

[67] United States Geological Survey. 2026. Historical Topo Map Explorer, https://livingatlas.arcgis.com/topomapexplorer/#maps=&loc=-94.20,45.60&LoD=13.66, accessed January 21, 2026.
[68] University of Minnesota. 2015. Minnesota Historical Aerial Photographs Online, https://apps.lib.umn.edu/mhapo/, accessed January 21, 2026.
[69] Nationwide Environmental Title Research, LLC. 2026. Historic Aerials by Netronline, https://www.historicaerials.com/viewer, accessed January 21, 2026.
[70] Google Earth. 2026. Historical Imagery, https://earth.google.com/web/@45.61027602,-94.20621329,318.47313108a,1107.79292329d,35y,0h,0t,0r/data=ChYqEAgBEgoyMDI1LTAzLTA5GAFCAggBMikKJwolCiExUGs1ZVBHSGEwT0VVZkNkbVBZMG5WUEY3d1NYU0N0SEMgAToDCgEwQgIIAEoICL2V8-IBEAE, accessed January 21, 2026.

- Should the Project require significant federal funding or permitting, a Section 106 review would be required along with consultation with the SHPO.

Architectural

- No previously identified above-ground historic resources documented within 0.25-mile of the Project area are listed on or eligible for the NRHP based on the desktop review.
- Based on the preliminary desktop review, a historic architectural property survey is not recommended at this time. Should the Project require significant federal funding or permitting, a Section 106 review would be required along with consultation with the SHPO.

16. Visual

Describe any scenic views or vistas on or near the Project site. Describe any Project related visual effects such as vapor plumes or glare from intense lights. Discuss the potential visual effects from the Project. Identify any measures to avoid, minimize, or mitigate visual effects.

Project area primarily consists of grassland, recently fallowed cropland, wetlands, and several groves of trees. No designated scenic views or vistas are present in the vicinity of the Project. The Project area is easily visible along its 4th Avenue frontage. The landscape immediately surrounding the site consists of single-family residential neighborhoods to the north and east, light industrial and vacant land to the west, and a landfill to the south.

The facility would operate 24 hours a day and would be illumated at night using downward-facing lights. Brightness would be the minmimum needed for safety and security. The cooling tower may create a downwind cloud-like water vapor plume, visible during the day from the river or adjacent neighborhoods. The size and density of the plume would vary with weather conditons.

The proposed Project would significantly alter the appearance of the site. The primary public vantage points are from 4th Avenue and from the adjacent residential neighborhood to the north, though mature trees provide partial screening along the north side of the Project area. The building façades from the street view would be designed to meet City requirements. The facility buildings would be painted white with green and black accents. Most structures would be less than 50 feet tall though several elements would be taller, including the Nitriding Structure (105 feet) and the Flare Structure (82 feet). Table 1 under EAW Item #6 lists the proposed heights of the facility's structures. The taller structures would be located in the rear of the facility and largely obscured from public view. Below is a rendering of the proposed facility at full build-out, looking from 4th Avenue. Also see draft civil design drawings in Appendix B.



17. Air

a. Stationary source emissions - Describe the type, sources, quantities and compositions of any emissions from stationary sources such as boilers or exhaust stacks. Include any hazardous air pollutants, criteria pollutants. Discuss effects to air quality including any sensitive receptors, human health or applicable regulatory criteria. Include a discussion of any methods used assess the Project's effect on air quality and the results of that assessment. Identify pollution control equipment and other measures that will be taken to avoid, minimize, or mitigate adverse effects from stationary source emissions.

The Facility is permitted under an Option D Registration Permit, number 14500196-101, issued by MPCA on August 28, 2025.

Construction of the Project would be expected to be completed in two phases over four years. Emission units included in Phase 1 of construction were included in the Option D Registration Permit application. The emission units include: a spray dryer, spray booths with spray painting guns, methanol solvent reclaim, ammonia gas reclaim, two natural gas-fired emergency generators, and a hot oil process heater. Insignificant activities under Minn. R. 7007.1300 Subp. 3(F) include: process bins with fabric filters, dry milling machines with HEPA filters, and natural gas heating units. Although Insignificant Activities are not required to be included in an Option D air permit application, they are included in the calculations for reference in relation to the EAW.

Table 17 describes all air emissions sources that were included in the Option D Registration Permit application.

Table 17. Data From Option D Registration Permit application

Emission Unit Description	Pollutants Generated	Pollutant Control Equipment (if applicable)
Spray Dryer	PM, PM_{10}, $PM_{2.5}$, SO_2, NO_x, VOC, CO, CO_2e, Lead, HAPs	Fabric Filter for PM/PM_{10}/$PM_{2.5}$ control
Solvent Reclaim	VOC, HAPs	None
Paint Booth Spray Gun (2)	PM, PM_{10}, $PM_{2.5}$, VOC	Wall Filter for PM/PM_{10}/$PM_{2.5}$ control
Ammonia Gas Reclaim	PM, PM_{10}, $PM_{2.5}$	Spray Tower for Ammonia control
Hot Oil Heater	PM, PM_{10}, $PM_{2.5}$, SO_2, NO_x, VOC, CO, CO_2e, Lead, HAPs	None
Emergency Generator (2)	PM, PM_{10}, $PM_{2.5}$, SO_2, NO_x, VOC, CO, CO_2e, HAPs	None
Bins and Hoppers (4)	PM, PM_{10}, $PM_{2.5}$	Fabric Filters for PM/PM_{10}/$PM_{2.5}$ control
Dry Milling (2)	PM, PM_{10}, $PM_{2.5}$	HEPA Filters for PM/PM_{10}/$PM_{2.5}$ control
Natural Gas Heating Units (5)	PM, PM_{10}, $PM_{2.5}$, SO_2, NO_x, VOC, CO, CO_2e, Lead, HAPs	None

The facility's actual air emissions for equipment included in the Option D Registration Permit application are provided in Table 18 below.

Table 18. Emissions Summary from Option D Registration Permit Application

Pollutant	Existing Facility Actual Emissions (tpy)	Option D Permit Threshold (tpy)
PM	1.82	50
PM_{10}	1.82	50
$PM_{2.5}$	1.82	NA
SO_2	0.080	50
NO_x	13.67	50
VOC	25.10	50

Pollutant	Existing Facility Actual Emissions (tpy)	Option D Permit Threshold (tpy)
CO	11.99	50
CO_2e	15,825	50,000
Lead	6.61E-05	0.5
Single HAP (Methanol)	1.30	5
Total HAPs	3.46	12.5

Niron has updated plans for the Phase 1 facility to include several design improvements. These design improvements are expected to reduce emissions from some sources in the originally proposed facility design and include an emergency flare and a hot oil burner optimized for ammonia combustion, which will replace the wet scrubber originally scoped for Phase 1. Niron would add additional air emission equipment to the facility in Phase 2 of construction. Additional equipment anticipated to be added to the facility in Phase 2 includes three nickel plating lines. Facility production is anticipated to increase with the implementation of Phase 2, which would increase air emissions from emissions equipment included in the Option D Registration Permit application.

Table 19 describes all air emissions sources that are proposed second phase of the Project.

Table 19. Phase 2 Emission Sources, Pollutants, and Pollution Control Equipment

Emission Unit Description	Pollutants Generated	Pollutant Control Equipment (if applicable)	Equipment Status
Ammonia Gas Reclaim	PM, PM_{10}, $PM_{2.5}$	Spray Tower for Ammonia control	Spray Tower not needed.
Hot Oil Heater	NO_x, PM, PM_{10}, $PM_{2.5}$, CO, VOC	Burner optimized for Ammonia combustion	Addition
Nickel Plating Lines (3)	PM, PM_{10}, $PM_{2.5}$, HAPs	Controls per NESHAP WWWWWW	Addition

Niron anticipates the Facility will still qualify for its Option D Registration Permit after the completion of Phase 2 of the Project. Process equipment design and associated air emissions are still under Facility review and expected air emissions will be updated as information becomes available. The Registration Permit Option D thresholds are lower than thresholds for MPCA's state permit, Part 70 permit, or Prevention of Significant Deterioration permit types. Given the relatively low levels of expected actual emissions through both phases of the Project, the potential for significant environmental effects from Facility air emissions is low. MPCA's air modeling guidance does not require modeling for Registration Permit facilities.

The following is included to describe ongoing air-related compliance requirements. Two natural gas-fired emergency generators were originally scoped but were replaced with a single natural gas-fired emergency generator. The natural gas-fired emergency generator will be subject to 40 CFR 60 Subpart JJJJ: Standards of Performance for Stationary Spark Ignition Internal Combustion Engines (NSPS JJJJ). NSPS JJJJ applies to all spark ignition internal combustion engines used for emergency purposes with a maximum engine power greater than 25 hp manufactured on or after January 1, 2009. In addition, the emergency generator engine will be subject to NESHAP ZZZZ. However, since the new unit is subject to NSPS JJJJ and located at an area source of HAPs, there are no applicable requirements under NESHAP ZZZZ. A subsequent review identified the hot oil heater may be subject to NSPS Dc, to which Niron would update any application materials as appropriate. The powder metallurgy technology used in the Niron process may be subject to 40 CFR 63 NESHAP XXXXXX. If so, application materials would be updated.

The nickel plating line would be subject 40 CFR 63 Subpart WWWWWW: National Emissions Standards for Hazardous Air Pollutants: Area Source standards for Plating and Polishing Operations (NESHAP WWWWWW). NESHAP WWWWWW applies to plating facilities that emit one or more plating and polishing metal HAP, including cadmium, chromium, lead, manganese, or nickel. The nickel plating line will have emissions of nickel. Therefore, NESHAP WWWWWW applies to the line.

The facility is not subject to any other NSPS or Area-Source NESHAPs, as summarized below:

- All tanks that will be used to store volatile organic liquids (VOL) will have capacities of less than 20,000 gallons; therefore, NSPS Kc does not apply.
- All natural gas heaters will have individual capacities of less than 10 MMBtu/hr; therefore, NSPS Dc does not apply to the natural gas heaters.
- The hot oil heater and natural gas heaters are not Industrial, Commercial, or Institutional Boilers; therefore, NESHAP JJJJJJ does not apply.
- The hot oil heater does not combust liquid wastes, solid wastes or containerized gases, therefore NSPS CCCC does not apply.

The facility is not subject to any other NSPS or Area-Source NESHAPs. The facility is also not one of the 28 listed source categories.

The facility would be subject to and would manage the facility to comply with Chemical Accident Prevention regulations (aka, Risk Management Program) in both 40 CFR 68 and 29 CFR 1910 (Process Safety Management).

b. Vehicle emissions - Describe the effect of the Project's traffic generation on air emissions. Discuss the Project's vehicle-related emissions effect on air quality. Identify measures (e.g. traffic operational improvements, diesel idling minimization plan) that will be taken to minimize or mitigate vehicle-related emissions.

The Project is not located within a CO or PM maintenance or non-attainment area. Traffic at the proposed Facility will be minimal and will consist of approximately 70 employee vehicles and up to 15 delivery trucks per day. Relative to existing traffic patterns in Sartell and the surrounding area, the minor increases in operational traffic would not result in significant vehicle-related emissions, nor would they result in significant vehicle-related impacts. The project is expected to generate minimal increases in temporary vehicle emissions during the approximately 30- to 36-month construction period. Niron will encourage the use of ultra-low-sulfur diesel fuel for construction equipment. Equipment idling will be minimized, and equipment will be shut off when not in use.

c. Dust and odors - Describe sources, characteristics, duration, quantities, and intensity of dust and odors generated during Project construction and operation. (Fugitive dust may be discussed under item 17a). Discuss the effect of dust and odors in the vicinity of the Project including nearby sensitive receptors and quality of life. Identify measures that will be taken to minimize or mitigate the effects of dust and odors.

Temporary dust and odors may be generated during construction of the Project. Project construction is anticipated to occur for approximately 30 to 36 months. Potential odors would likely be associated with exhaust from diesel engines and fuel storage, but anticipated odors from construction are not expected to be substantial. Dust will be mitigated with good dust management practices during the construction phase.

No significant sources of dust are associated with the Project. Dust from facility operations will be negligible because all facility parking lots and roads will be paved. All facility operations will occur indoors; therefore, no operational increases in levels of dust would occur. Ammonia emissions from industrial processes will be routed to the Hot Oil Heater for heat recovery. With these ammonia mitigation

strategies, odor emissions generated from operation are expected to be minimal.

Ammonia would be handled in fully enclosed systems. The basis of design of the facility would be to ensure that during operation there would be no impact (nuisance or otherwise) to the surrounding areas. Emergency systems would be designed to mitigate offsite impacts. See EAW Question 13 for discussion of hazardous materials storage and handling.

18. Greenhouse Gas (GHG) Emissions/Carbon Footprint

a. GHG Quantification: For all proposed Projects, provide quantification and discussion of Project GHG emissions. Include additional rows in the tables as necessary to provide Project-specific emission sources. Describe the methods used to quantify emissions. If calculation methods are not readily available to quantify GHG emissions for a source, describe the process used to come to that conclusion and any GHG emission sources not included in the total calculation.

GHG emissions would be generated during construction and operation of the Project and are summarized below in Table 20. Scope 1 emissions are those emitted as a direct result of the Project's operations, including construction operations. Scope 2 emissions are those emitted from the off-site production of electricity for the Facility. Scope 3 emissions are those emitted from the off-site treatment of waste generated at the Facility.

Table 20. Emission Categories for Carbon Footprint

Category	Scope	Project Phase	Type of Emissions
Direct Emissions	Scope 1	Construction	Combustion (On-Road Mobile Sources)
	Scope 1	Construction	Combustion (Off-Road Mobile Sources)
	Scope 1	Construction	Building Materials
	Scope 1	Construction	Land Use Change
	Scope 1	Operations	Combustion (Mobile Sources)
	Scope 1	Operations	Combustion (Stationary Sources)
	Scope 1	Operations	HFC Leakage
Indirect Emissions	Scope 2	Operations	Purchased Electricity
	Scope 3	Operations	Off-site Waste Management

Table 21 presents estimated annual emissions associated with the construction and operation of the Project. Emissions have been calculated using the Environmental Quality Board (EQB) Minnesota Climate Calculator with supplementary calculations prepared for truck deliveries during construction. Additional calculation details are provided below the table.

Table 21. GHG Emissions Summary (CO2e in short tons per year)

Scope	Source	Project Emissions (tons)
Direct Emissions		
Scope 1	Construction – On-Road Mobile Sources[1]	61
Scope 1	Construction – Off-Road Mobile Sources[1]	28
Scope 1	Construction – Building Materials	117
Scope 1	Construction – Land Use Change	0.12
Scope 1	Operations – Stationary Combustion	30,822
Scope 1	Operations – Mobile Sources	373
Scope 1	Operations – HFC Leakage	25

Scope	Source	Project Emissions (tons)
Indirect Emissions		
Scope 2	Operations – Purchased Electricity	212
Scope 3	Operations – Off-Site Waste Management	61
Total		**31,700**

[1]*Note that construction emissions are annualized over the life of the project, estimated to be 50 years.*

Construction Emissions

On-road mobile source combustion emissions include diesel construction and delivery vehicles for building materials and construction laborers' vehicle emissions. The EQB Minnesota Climate Calculator defaults were used for the average employee one-way commute length and transportation mode breakout. It was assumed that an average of 300 employees would be needed for all stages of construction except for demolition, which is not required for the project as it is being constructed on a greenfield site. GHG emissions for the transportation of materials were calculated with the Minnesota Climate Calculator using the number of tons of material expected to be used for the construction. The Minnesota Climate Calculator is unable to account for emissions from the delivery of fill and miscellaneous materials used for site grading and construction. Supplementary calculations were prepared for on-road emissions from the delivery trucks. Diesel fuel usage per mile was taken from the U.S. Department of Transportation, Federal Highway Administration, Highway Statistics 2024, Table VM-1. Greenhouse gas emission factors were taken from EPA's Emission Factors Hub.

Off-road mobile source combustion emissions were calculated using the default number of hours per day by construction stage from the Minnesota Climate Calculator for all phases of construction except for demolition, which is not required for the Project.

GHG emissions from building materials were calculated with the Minnesota Climate Calculator using the estimated quantities of building materials needed for construction of the Project. All materials were assumed to be sourced domestically. Default values for construction waste from the Minnesota Climate Calculator were used to calculate waste emissions. Emissions from the disposal of construction waste are included in the emissions from building materials.

GHG emissions from land use conversion were also considered for the Project using the estimated number of acres of each land use type prior to and after construction.

Operational Emissions

Operational stationary combustion sources include natural gas-fired heaters, industrial equipment, and emergency generators. It was assumed that natural gas-fired heaters and industrial equipment will operate 8,760 hours per year. The emergency generators were assumed to operate up to 500 hours per year as the units are subject to the EPA September 6, 1995, "Calculating Potential to Emit (PTE) for Emergency Generators" memorandum from John Seitz to the Directors of EPA Regions I-X. This is an overestimation of the actual facilities emissions as heaters will not operate at full capacity in warm months, and emergency generators will only be operated for maintenance and emergencies.

Operational mobile combustion sources include employee vehicle traffic and delivery truck traffic. Emission calculations assumed a daily average of 70 employee vehicles per day and 15 delivery trucks per week traveling up to 50 miles per day. Vehicles were assumed to travel at the fleet average speed provided in the Minnesota Climate Calculator.

Emissions may also be generated from hydrofluorocarbons (HFCs) that are used in air conditioning and refrigeration equipment. Leakage of HFCs happens during equipment installation, operation, servicing, and disposal. Calculations for HFC leakage assume that 100% of the Facility utilizes air conditioning or refrigeration equipment.

Operational emissions also include emissions from purchased electricity and off-site waste management. Emission calculations for purchased electricity are based on the square footage of the proposed Facility. Emission calculations for off-site waste treatment assume an average of 70 employees at the Facility each day for industrial activities with the default waste treatment practices from the Minnesota Climate Calculator.

b. GHG Assessment

i. Describe any mitigation considered to reduce the Project's GHG emissions.

To reduce GHG emissions from construction, equipment would idle as little as possible in an efficient manner. Travel distances may be shorter than estimated.

To mitigate GHG emissions from operation, Niron would only use electricity and natural gas for equipment and building power, and no diesel-fired or oil-fueled equipment would be used on site.

ii. Describe and quantify reductions from selected mitigation, if proposed to reduce the Project's GHG emissions. Explain why the selected mitigation was preferred.

On-road construction emissions would be reduced proportionally to the reduced travel distance compared to the assumed 26.4 miles. Calculations used the Minnesota Climate Calculator default travel distance of 13.2 miles each direction. Actual travel distances may be shorter, and on-road construction emissions would be reduced proportionally to the shorter travel distance.

In the Minnesota Climate Calculator, electricity has a CO_2e emission factor of 29.83 kg/MMBtu, and natural gas has a CO_2e emission factor of 65.15 kg/MMBtu. Diesel has a CO_2e emission factor of 90.31 kg/MMBtu. On a per MMBtu basis, combusting diesel produces three times more CO_2e emissions than electricity and 1.4 times more CO_2e emissions than natural gas. Therefore, the use of electric and natural gas-fired equipment results in a reduction of CO_2e emissions for the Project.

iii. Quantify the proposed Projects predicted net lifetime GHG emissions (total tons/# of years) and how those predicted emissions may affect achievement of the Minnesota Next Generation Energy Act goals and/or other more stringent state or local GHG reduction goals.

Construction would last approximately 30-36 months. The lifetime GHG emissions from construction are 10,942 tons. Assuming a 50-year lifetime, GHG emissions from operation are 1,669,157 tons CO_2e. Total Project lifetime GHG emissions are 1,680,098 tons.

Minnesota's Climate Action Framework aims to reduce emissions by 50% by 2030 and achieve net-zero emissions by 2050. The Project is not anticipated to significantly negatively affect Minnesota's GHG reduction goals.

19. Noise

Describe sources, characteristics, duration, quantities, and intensity of noise generated during Project construction and operation. Discuss the effect of noise in the vicinity of the Project including 1) existing noise levels/sources in the area, 2) nearby sensitive receptors, 3) conformance to state noise standards, and 4) quality of life. Identify measures that will be taken to minimize or mitigate the effects of noise.

Existing noise sources near the Project area include moderate traffic noise along 4th Avenue and existing commercial and industrial uses adjacent to 4th Avenue. There are no major noise emitters in the immediate area. Nearby sensitive receptors include residents of the nearby residential neighborhoods to the north, west, and east of the Project area.

The City of Sartell's noise regulations prohibit loud construction activities between 9:00 p.m. and 6:00 a.m. and generally prohibit construction activities on Sundays. The City's General Industrial District Ordinance requires that facility noise needs to be "muffled so as not to become objectionable due to intermittence, beat frequency, shrillness or intensity. The sound pressure level of noise in an octave band frequency radiated continuously from a facility shall not exceed the noise area classification established by the MPCA".[71]

During construction, noise levels would temporarily increase and vary in intensity based on the types of construction equipment being used and distance from the noise source. See Table 22 below. To minimize the effects of this noise, construction would be limited to daytime hours consistent with the City's construction and noise ordinances. In addition, construction equipment would be fitted with mufflers that would be maintained throughout the construction process.

Table 22. Estimated Noise for Typical Construction Equipment

Equipment	Impact Device (Yes/No)	Lmax Sound dBA*
Backhoe	No	78
Front loader	No	79
Dozer	No	82
Dump truck	No	76
Excavator	No	81
Grader	No	85
Scraper	No	84
Impact pile driver	Yes	101

**Noise levels listed represent the A-weighted maximum sound level (Lmax), measured at a distance of 50 feet from the construction equipment.*

Source: FHWA. Roadway Construction Noise Model (RCNM) Version 1 User Guide. Table 1. CA/T equipment noise emissions and acoustical usage factors database. January 2006. https://www.fhwa.dot.gov/environment/noise/construction_noise/rcnm/rcnm.pdf

[71] Sartell City Code, Title 10, Chapter 7. General Industrial District Ordinance: https://cms5.revize.com/revize/sartell/Title%2010%20Zoning%20Regulations%20RV%202025%20KH%20Edits.pdf?t=202511251020390&t=202511251020390.

The State of Minnesota's noise rules (Minn. Rules Ch. 7030) establish noise limits by noise area classifications (NACs) based on land use at the location of the person that hears noise. Table 23 below identifies state noise standards for each NAC. The MPCA enforces noise standards at industrial facilities for which it has issued an air permit. It is not anticipated that the Project would generate operational noise that would exceed state and local noise standards.

During operations, the facility would generate noise from compressors and other facility processes as well as daily vehicle traffic. Large truck traffic and compressors would likely be the loudest noise generators during operations. The facility would utilize soundproofing materials in their structures where feasible. Niron is currently developing a noise study to estimate operational facility peak noise levels at the property boundary.

The quality of life for nearby sensitive receptors would not be affected by the Project. The facility's vehicle traffic would enter and exit via 4th Avenue. Three or fewer delivery or shipping trucks would visit the facility on an average day. The nearest homes to the vehicle entrances are over 800 feet away and screened by mature trees. The compressors would be partially muffled by adjacent structures and sound mitigating materials. The nearest homes to the compressors would be approximately 850 feet away and partially screened my mature trees. The noise from the facility and truck traffic should not be audible to most nearby residences and would not exceed the limits below for any nearby sensitive receptor.

Table 23. Noise Area Classifications

NAC	Common land use associated with the Noise Area Classification	Daytime (dBA)		Nighttime (dBA)	
		L_{10}	L_{50}	L_{10}	L_{50}
1	Residential housing, religious activities, camping and picnicking areas, health services, hotels, educational services	65	60	55	50
2	Retail, business and government services, recreational activities, transit passenger terminals	70	65	70	65
3	Manufacturing, fairgrounds and amusement parks, agricultural and forestry activities	80	75	80	75

20. Transportation

a. Describe traffic-related aspects of Project construction and operation. Include: 1) existing and proposed additional parking spaces, 2) estimated total average daily traffic generated, 3) estimated maximum peak hour traffic generated and time of occurrence, 4) indicate source of trip generation rates used in the estimates, and 5) availability of transit and/or other alternative transportation modes.

The Project area is currently undeveloped and receives no traffic. The Project would create 120 parking spaces for staff and visitors and four loading docks for deliveries and shipping. Niron estimates up to 15 delivery and shipping truck trips per week during operations and up to 25 delivery trips per week during construction. The facility would have up to 175 total full-time employees spread across three shifts. Peak traffic times would be centered around shift changes at 7:00 AM, 3:00 PM, and 11:00 PM. Some staff may be able to carpool together. Estimated daily trips are summarized below.

- 175 employees x 2 trips per day = 350 daily trips.
- 15 truck operations deliveries/week x 2 trips / 7 = 4.29 daily trips.
- Total estimated daily trips during operations: 354.29.

Construction traffic would consist primarily of daily trips by construction staff as well as delivery of equipment and materials. Up to 300 workers may be on site during peak construction activity and most would likely drive alone (as opposed to carpooling or other transit modes). Most construction workers would arrive between 6:00 and 8:00 am and depart in the early evening. Equipment and materials delivery traffic would vary considerably based on a given day's planned construction activities. The highest rates of daily delivery traffic would include dump trucks bringing fill soil for grading and trucks delivering concrete during construction of building slabs. Much of the fill soil delivery has already been completed.

The site is accessible by bicycle and pedestrian traffic, though public transit is not available.

b. Discuss the effect on traffic congestion on affected roads and describe any traffic improvements necessary. The analysis must discuss the Project's impact on the regional transportation system. If the peak hour traffic generated exceeds 250 vehicles or the total daily trips exceeds 2,500, a traffic impact study must be prepared as part of the EAW. Use the format and procedures described in the Minnesota Department of Transportation's Access Management Manual, Chapter 5 (available at: http://www.dot.state.mn.us/accessmanagement/resources.html) or a similar local guidance.

All traffic would enter the facility via one of two driveways off 4th Avenue, a two-lane local thoroughfare with a center turn lane. The road was designed to accommodate development between 3rd Street South and Heritage Drive and connects to 2nd Street to the north and Heritage Drive to the south. Heritage Drive and 2nd Street provide access to regional transportation corridors including Highway 10, Highway 15, and Highway 120 It is anticipated that most truck traffic would approach the facility from the south via Highway 15 and Heritage Drive.

Anticipated traffic volumes are well below the threshold for a mandatory traffic impact study, which is required if peak hour traffic exceeds 250 vehicles or the total daily trips exceeds 2,500. Approximately 355 total daily trips are anticipated, including both employee trips and deliveries. Employee trips would be concentrated around shift changes and deliveries would generally occur during daytime hours. The peak shift change traffic at 7:00 AM, 3:00 PM, and 11:00 PM would create approximately 117 trips (58 or 59 employees coming and going).

c. Identify measures that will be taken to minimize or mitigate Project related transportation effects.

No specific mitigation or minimization is planned by Niron. The City of Sartell has targeted 4th Avenue for

a major reconstruction project to include utility maintenance, full road reconstruction, and new turn lanes to improve traffic flow and safety. Planning for the 4th Avenue project began before Niron obtained the Project property and the reconstruction project would proceed irrespective of the proposed Niron project.

21. Cumulative Potential Effects

*(**Preparers can leave this item blank if cumulative potential effects are addressed under the applicable EAW Items)***

a. Describe the geographic scales and timeframes of the Project related environmental effects that could combine with other environmental effects resulting in cumulative potential effects.

The Project would permanently disturb approximately 25.8 acres over a four-year construction timeframe. The primary ongoing environmental effects of the Project are related to facility air emissions. Air emissions for this facility type are closely regulated by MPCA and the Project would adhere to permit requirements. No cumulative effects are anticipated.

b. Describe any reasonably foreseeable future Projects (for which a basis of expectation has been laid) that may interact with environmental effects of the proposed Project within the geographic scales and timeframes identified above.

Niron and the City of Sartell are not aware of any reasonably foreseeable development projects nearby that could interact with the proposed Project's effects. Nearby land uses are expected to remain as they are now for the foreseeable future.

c. Discuss the nature of the cumulative potential effects and summarize any other available information relevant to determining whether there is potential for significant environmental effects due to these cumulative effects.

Not applicable.

22. Other Potential Environmental Effects

If the Project may cause any additional environmental effects not addressed by items 1 to 19, describe the effects here, discuss the how the environment will be affected, and identify measures that will be taken to minimize and mitigate these effects.

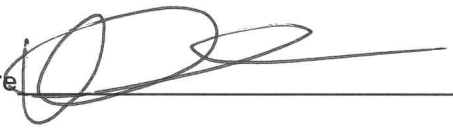
No other potential environmental effects are anticipated that are not addressed by Items 1 through 21.

RGU CERTIFICATION

*(The Environmental Quality Board will only accept **SIGNED** EnvironmentalAssessment Worksheets for public notice in the EQB Monitor.)*

I hereby certify that:

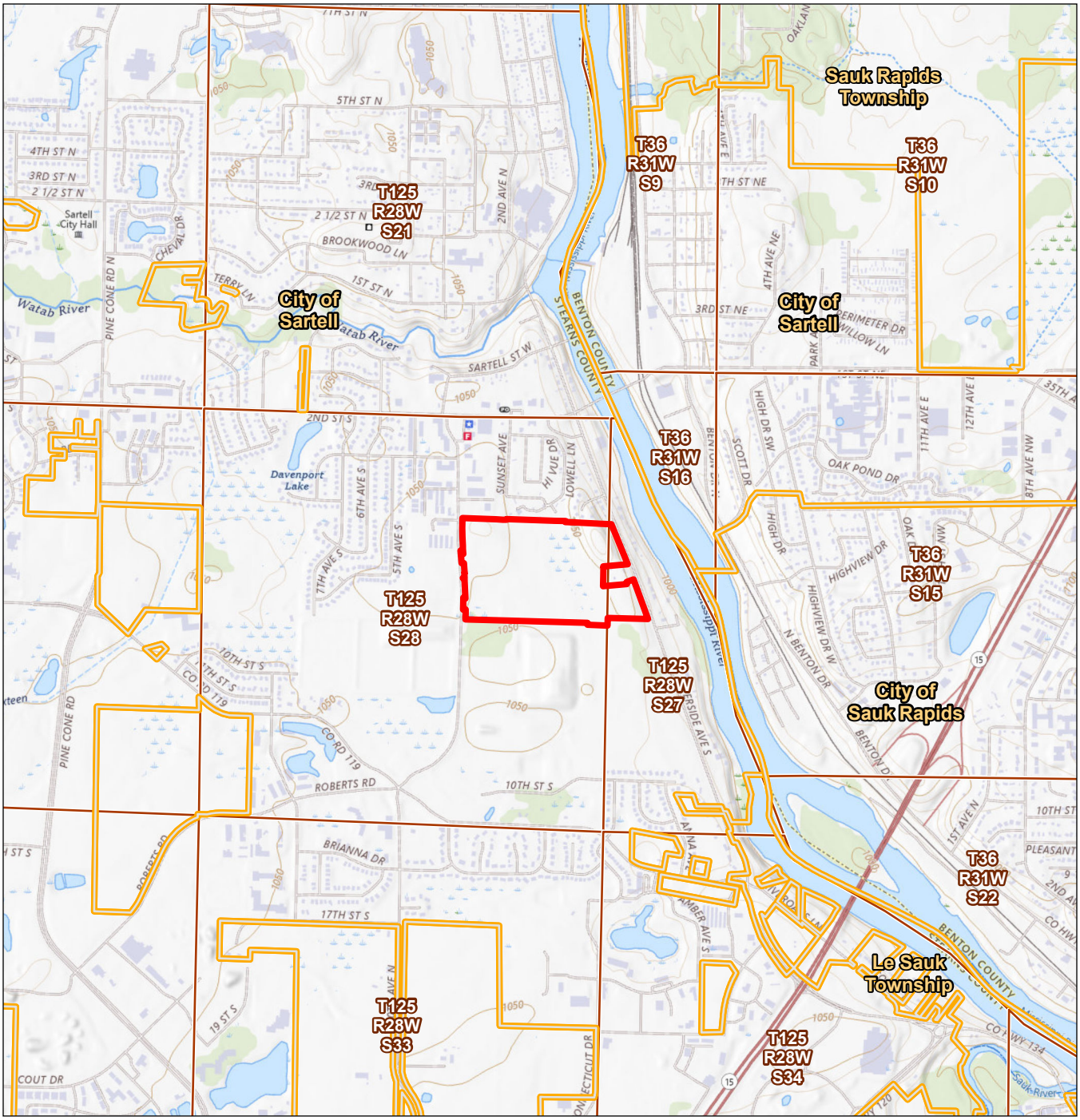
- The information contained in this document is accurate and complete to the best of myknowledge.
- The EAW describes the complete Project; there are no other Projects, stages or components other than those described in this document, which are related to the Project as connected actions or phased actions, as defined at Minnesota Rules, parts 4410.0200, subparts 9c and 60,respectively.
- Copies of this EAW are being sent to the entire EQB distribution list.

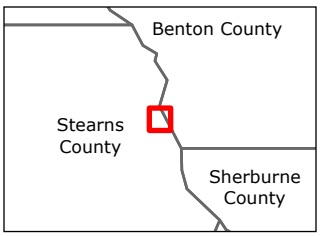
Signature  Date 02/24/2026

Title Community & Economic Development Director

Appendix A
Figures

Figure 1: Project Location USGS Topo
Figure 2: Project Location Aerial Map
Figure 3: Project Disturbance
Figure 4: Cover Types
Figure 5: Recreational Features
Figure 6: Proposed Land Use
Figure 7: City Zoning
Figure 8: Surficial Geology
Figure 9: Soil Survey
Figure 10: Water Resources
Figure 11: Delineated Wetlands and Water Features
Figure 12: Minnesota Well Index
Figure 13: MPCA Potentially Contaminated Sites





Legend

- Project Area
- Municipal Boundary
- Township, Range & Section Boundary

0 1,000 2,000 Feet

(At original document size of 8.5x11)
1:24,000

N

Stantec

Notes

1. Coordinate System: NAD 1983 UTM Zone 15N
2. Data Sources: USGS
3. Background: USGS 7.5 Minute Quadrangle

Project Location
T125N, R28W, S27 & S28
Sartell, Stearns Co., MN

Prepared by LAH on 2026-01-29

Client/Project
Niron Magnetics
Sartell
EAW

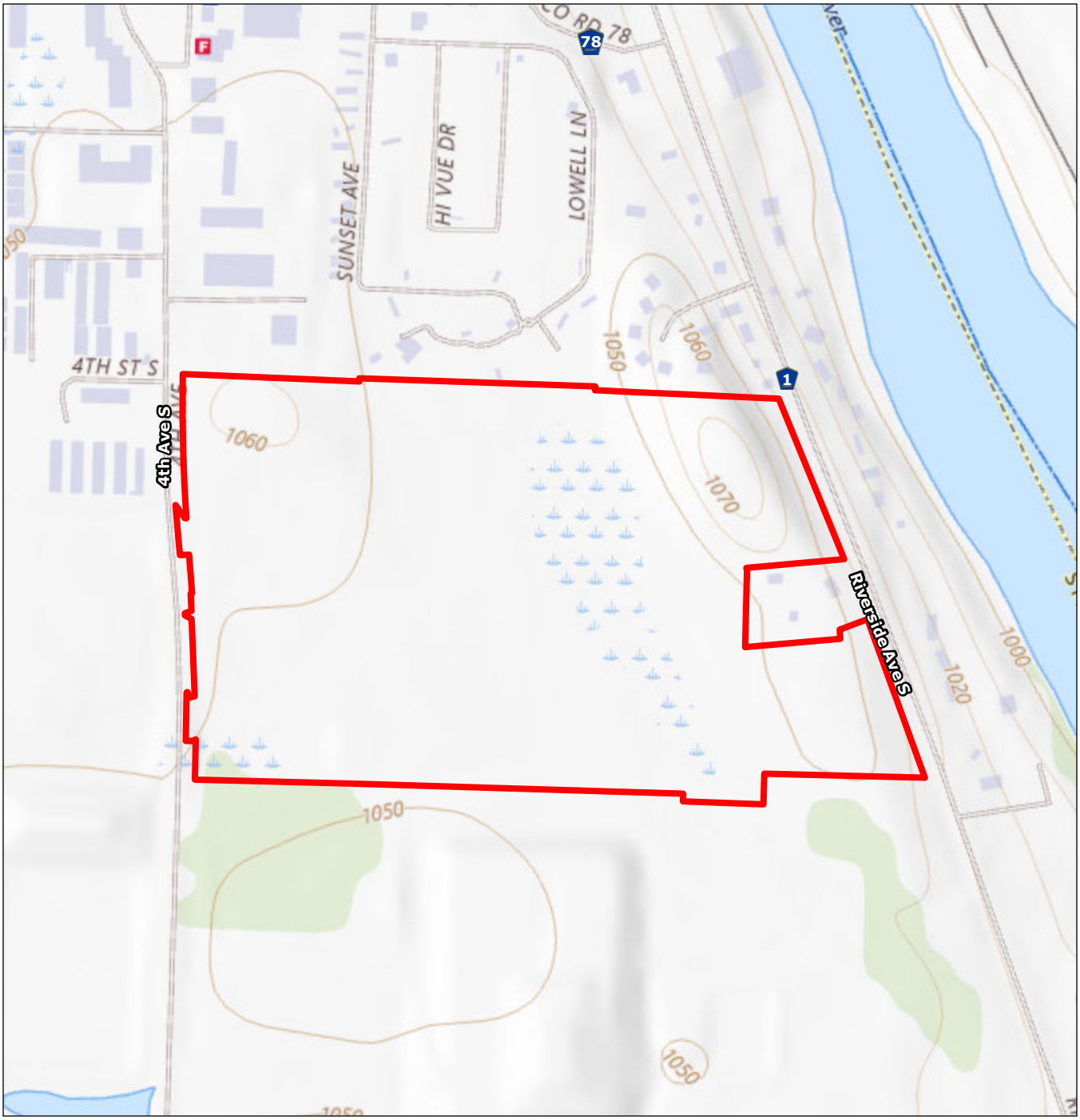
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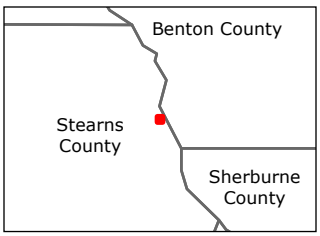
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1

Title
Project Location USGS Topo

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Legend

Project Area

0 250 500 Feet

(At original document size of 8.5x11)
1:6,000

N

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Project Location
T125N, R28W, S27 & S28
Sartell, Stearns Co., MN

Prepared by LAH on 2026-01-29

Client/Project
Niron Magnetics
Sartell
EAW

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Figure No.
2

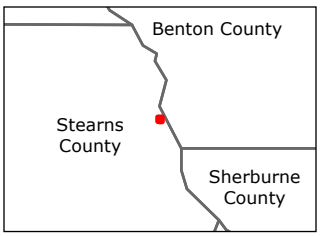
Title
Project Location Aerial

Notes
1. Coordinate System: NAD 1983 UTM Zone 15N
2. Data Sources: Stearns County
3. Background: Stearns Aerial 2024

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Legend

- Project Area
- Stearns County Parcels
- Permanent Ground Disturbance Area
- Temporary Ground Disturbance Area

0 200 400 Feet

(At original document size of 8.5x11)
1:4,800

N

Stantec

Notes

1. Coordinate System: NAD 1983 HARN Adj MN Stearns Feet
2. Data Sources: Stearns County
3. Background: Stearns Aerial 2024

Project Location
T125N, R28W, S27 & S28
Sartell, Stearns Co., MN

Prepared by LAH on 2026-01-29

Client/Project
Niron Magnetics
Sartell
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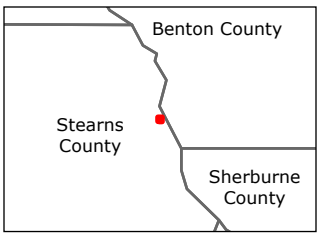
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Title
Project Disturbance

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Legend

- Project Area
- Brush/Grassland
- Fallowed Cropland
- Deciduous Forest
- Wetlands
- Historic Stormwater Ponds

0 200 400 Feet

(At original document size of 8.5x11)
1:4,800

N

Notes

1. Coordinate System: NAD 1983 HARN Adj MN Stearns Feet
2. Data Sources: Stantec, SEH
3. Background: Stearns Aerial 2024

Stantec

Project Location
T125N, R28W, S27 & S28
Sartell, Stearns Co., MN

Prepared by LAH on 2026-02-11

Client/Project
Niron Magnetics
Sartell
EAW

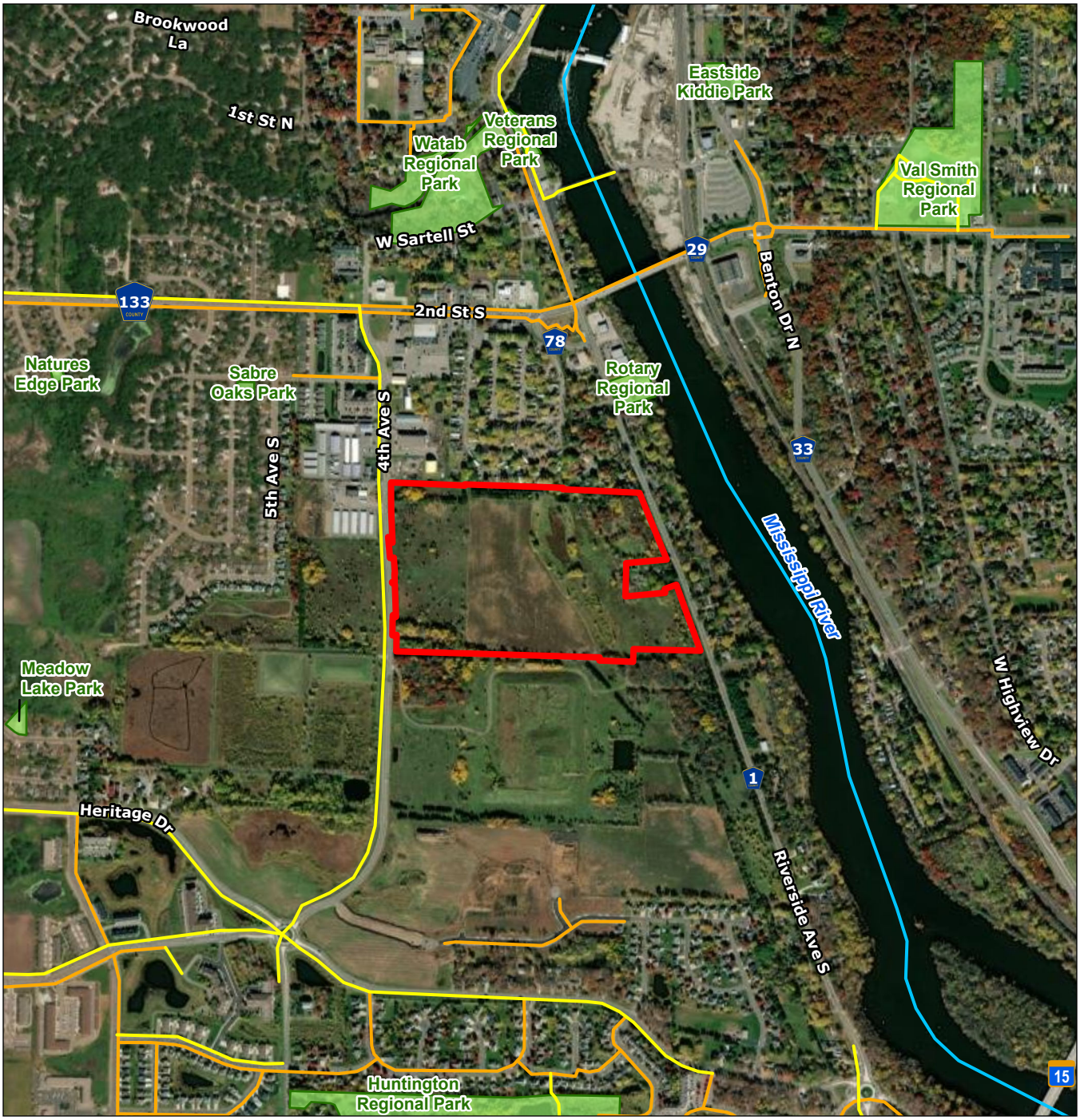
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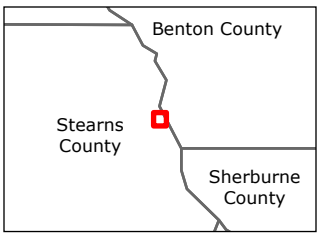
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Title
Cover Types

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Legend

- Project Area
- City of Sartell Parks
- City of Sartell Sidewalks
- City of Sartell Trails and Paths
- Minnesota Water Trails

0 600 1,200 Feet

(At original document size of 8.5x11)
1:14,400

N

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Project Location
T125N, R28W, S27 & S28
Sartell, Stearns Co., MN

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Niron Magnetics
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EAW

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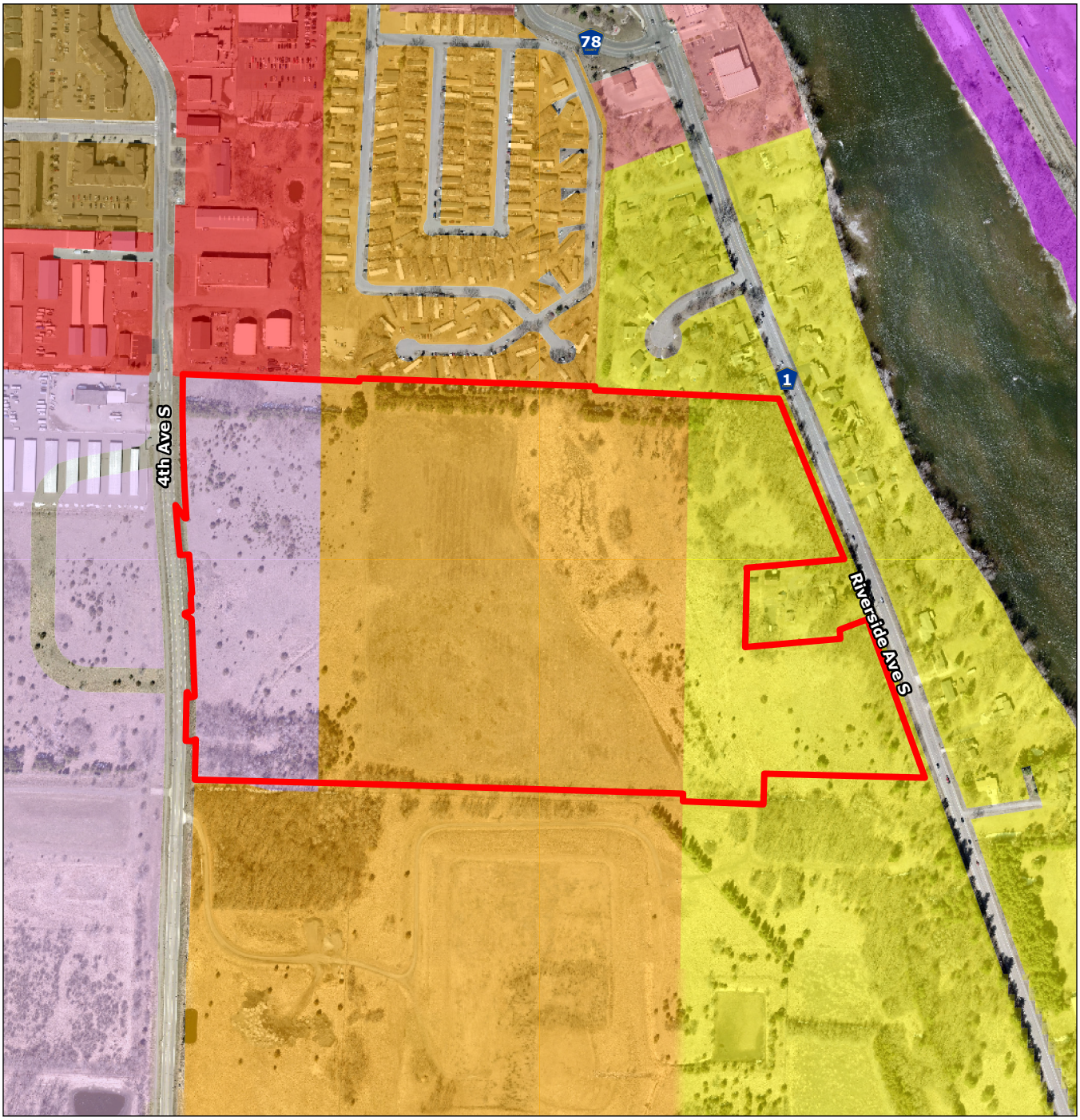
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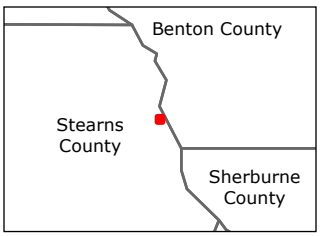
Title
Recreational Features

Notes
1. Coordinate System: NAD 1983 UTM Zone 15N
2. Data Sources: City of Sartell, MNDNR
3. Background: ESRI World Imagery (Vivid, 2020)

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Notes
1. Coordinate System: NAD 1983 UTM Zone 15N
2. Data Sources: City of Sartell
3. Background: Stearns County Aerial 2024

Legend
- Project Area
- Very Low Density Residential (VLDR)
- Low Density Residential (LDR)
- Medium Density Residential (MDR)
- High Density Residential (HDR)
- Limited Business (LB)
- General Business (GB)
- Town Square (TS)
- Medical Professional Mix (HP)
- Office_Warehouse (OI)
- Industrial (I)
- Park
- Public (PUB)

0 250 500 Feet
(At original document size of 8.5x11)
1:6,000

N

Stantec

Project Location
T125N, R28W, S27 & S28
Sartell, Stearns Co., MN

Prepared by LAH on 2026-01-29

Client/Project
Niron Magnetics
Sartell
EAW

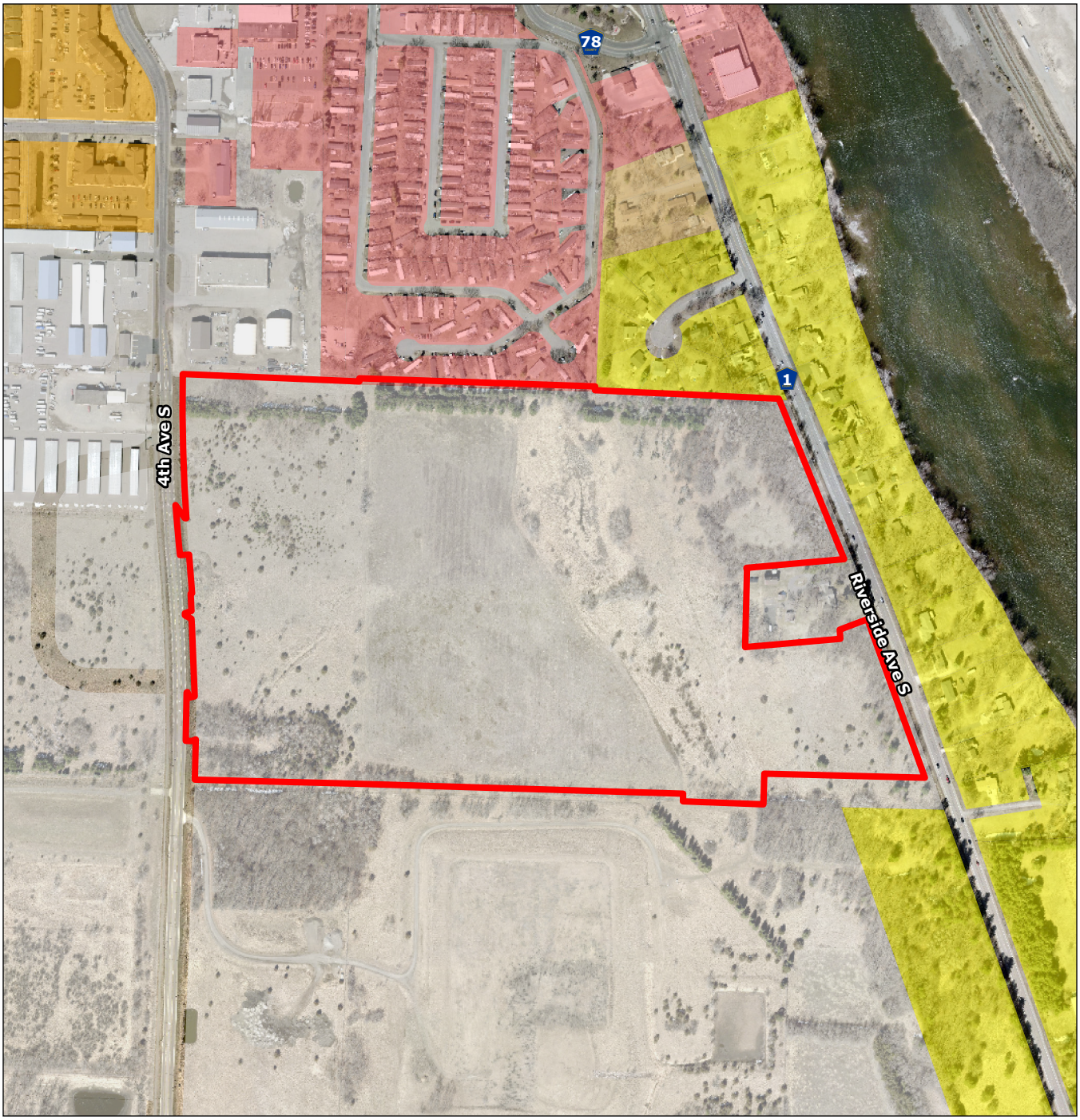
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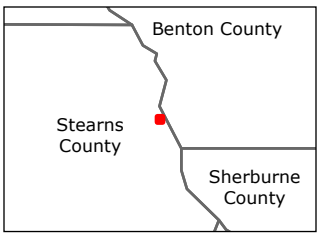
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Title
Proposed Land Use

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Notes
1. Coordinate System: NAD 1983 UTM Zone 15N
2. Data Sources: City of Sartell
3. Background: Stearns County Aerial 2024

Legend

Project Area

Zoning

- General Business
- Light Industrial
- Heavy Industrial
- Single Family Residence
- Single Two Family Residence
- Multiple Family Residence

0 250 500 Feet

(At original document size of 8.5x11)
1:6,000

N

Stantec

Project Location
T125N, R28W, S27 & S28
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Prepared by LAH on 2026-01-29

Client/Project
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Sartell
EAW

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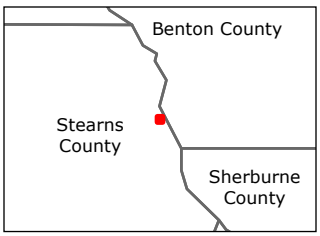
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Title
City Zoning

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Legend

- Project Area

Surficial Geology

- Qwr - Richfield terrace
- Al - Alluvium
- Do - Outwash depostis
- St - Till

0 250 500 Feet

(At original document size of 8.5x11)
1:6,000

N

Stantec

Notes

1. Coordinate System: NAD 1983 UTM Zone 15N
2. Data Sources: UMN MGS
3. Background: Stearns County Aerial 2024

Project Location
T125N, R28W, S27 & S28
Sartell, Stearns Co., MN

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Sartell
EAW

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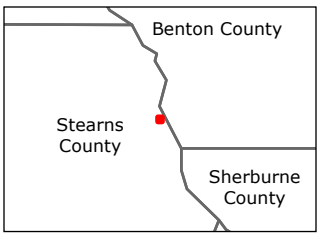
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Title
Surficial Geology

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Legend
- Project Area
- Soil Map Units

0 200 400 Feet
(At original document size of 8.5x11)
1:4,800

N

Stantec

Project Location
T125N, R28W, S27 & S28
Sartell, Stearns Co., MN

Prepared by LAH on 2026-02-06

Client/Project
227708731
Niron Magnetics
Sartell
EAW

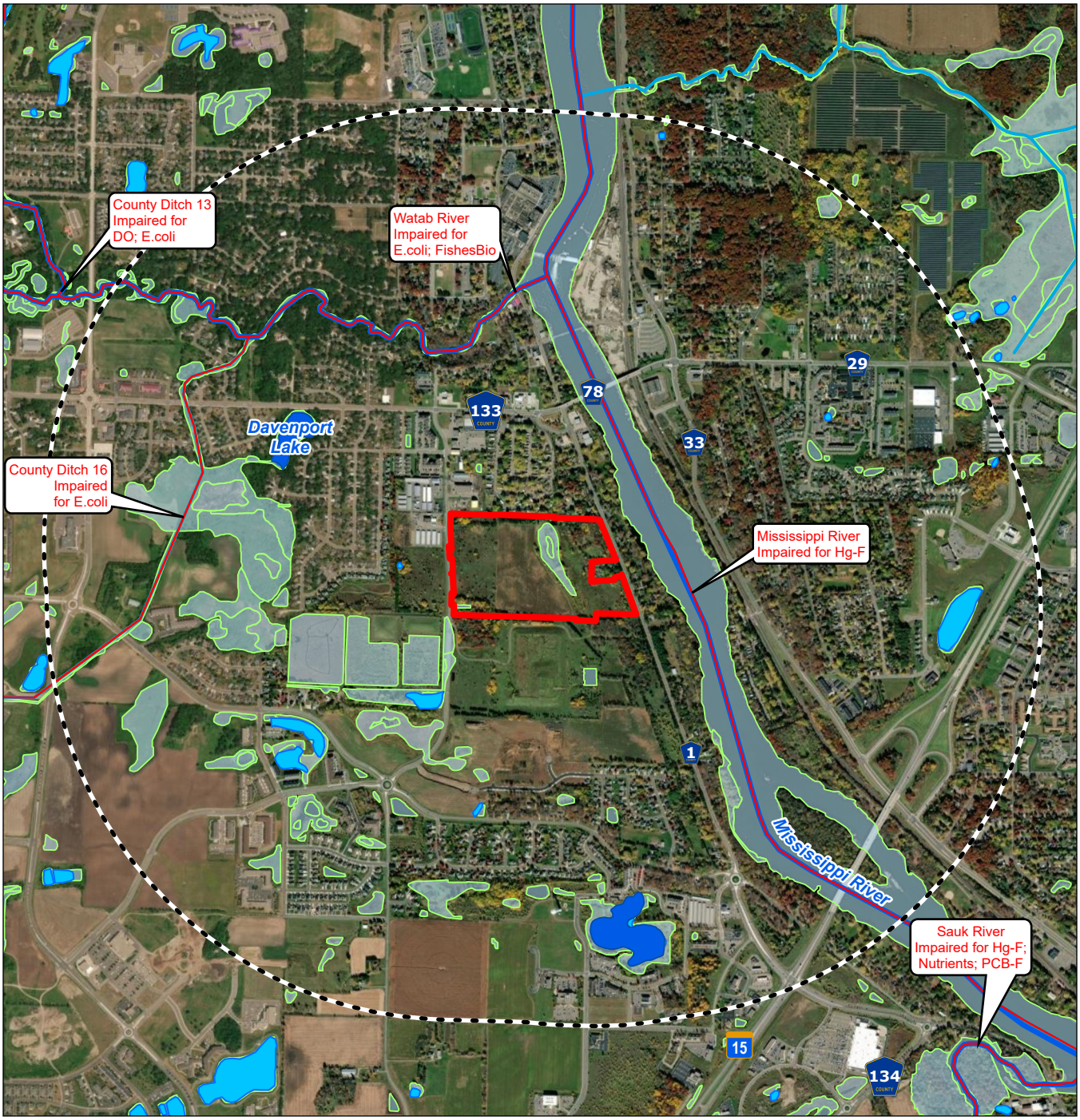
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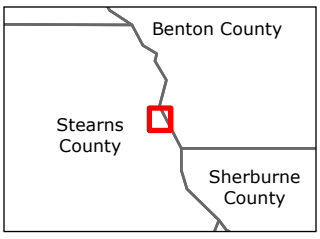
Title
Soil Survey

Notes
1. Coordinate System: NAD 1983 UTM Zone 15N
2. Data Sources: USGS NRCS
3. Background: Stearns County Aerial 2024

U:\227\227708731\03_data\gis_cad\gis\ArcPro\EAW\EAW.aprx Revised: 2026-02-06 By: lhershley

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Notes
1. Coordinate System: NAD 1983 UTM Zone 15N
2. Data Sources: USGS NWI, USGS NHD, MDNR PWI, MPCA Impaired Waters
3. Background: ESRI World Imagery (Vivid, 2020)

Legend
- Project Area
- One Mile Radius
- National Wetland Inventory
- Public Waters Basin
- Public Watercourse
- NHD Waterbody
- NHD Stream
- 2024 Impaired Streams

0 1,000 2,000 Feet
(At original document size of 8.5x11)
1:24,000

N

Stantec

Project Location
T125N, R28W, S27 & S28
Sartell, Stearns Co., MN

Prepared by LAH on 2026-02-06

Client/Project
Niron Magnetics
Sartell
EAW

227708731

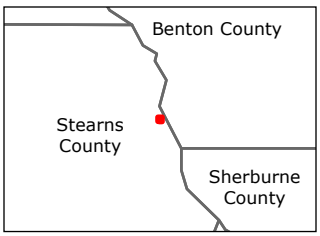
Figure No.
10

Title
Water Resources

U:\227\227708731\03_data\gis_cad\gis\ArcPro\EAW\EAW.aprx Revised: 2026-02-06 By: lhershley

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Legend

- Project Area
- Delineated Wetland
- Delineated Stormwater Feature
- Delineated Dry Ditch

0 200 400 Feet

(At original document size of 8.5x11)
1:4,800

N

Notes

1. Coordinate System: NAD 1983 HARN Adj MN Stearns Feet
2. Data Sources: USGS NWI, USGS NHD, MDNR PWI, MPCA Impaired Waters
3. Background: ESRI World Imagery (Vivid, 2020)

Stantec

Project Location
T125N, R28W, S27 & S28
Sartell, Stearns Co., MN

Prepared by LAH on 2026-02-06

Client/Project
227708731
Niron Magnetics
Sartell
EAW

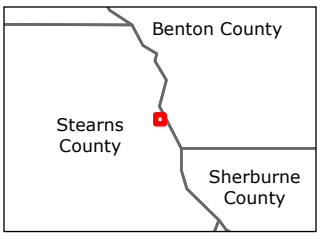
Figure No.
11

Title
Delineated Wetlands and Water Features

U:\227\227708731\03_data\gis_cad\gis\ArcPro\EAW\EAW.aprx Revised: 2026-02-06 By: lhershley

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Notes
1. Coordinate System: NAD 1983 UTM Zone 15N
2. Data Sources: MDH
3. Background: ESRI World Imagery (Vivid, 2020)

Legend
- Project Area
- 1/4 Mile Radius
- Wellhead Protection Area

Drinking Water Supply Management Area
- High Vulnerability

Minnesota Well Index
- Domestic Well
- Monitoring Well

0 400 800 Feet
(At original document size of 8.5x11)
1:9,600

N

Stantec

Project Location
T125N, R28W, S27 & S28
Sartell, Stearns Co., MN

Prepared by LAH on 2026-02-06

Client/Project
Niron Magnetics
Sartell
EAW

227708731

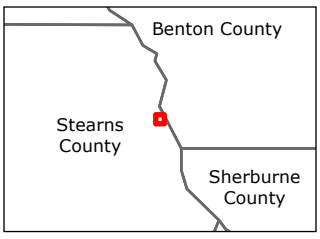
Figure No.
12

Title
Minnesota Well Index

U:\227\227708731\03_data\gis_cad\gis\ArcPro\EAW\EAW.aprx Revised: 2026-02-06 By: lhershley

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Notes
1. Coordinate System: NAD 1983 UTM Zone 15N
2. Data Sources: MPCA
3. Background: ESRI World Imagery (Vivid, 2020)

Legend
- Project Area
- 1/4 Mile Radius

MPCA Potentially Contaminated Sites
- Multiple Programs
- Hazardous Waste
- Investigation and Cleanup
- Stormwater
- Water Quality

0 400 800 Feet
(At original document size of 8.5x11)
1:9,600

N

Stantec

Project Location
T125N, R28W, S27 & S28
Sartell, Stearns Co., MN

Prepared by LAH on 2026-02-06

Client/Project
Niron Magnetics
Sartell
EAW

227708731

Figure No.
13

Title
MPCA Potentially Contaminated Sites

U:\227\227708731\03_data\gis_cad\gis\ArcPro\EAW\EAW.aprx Revised: 2026-02-06 By: lhershley

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Appendix B
Site Plans

PROJECT

801 4th AVE, Sartell, MN 56377

DRAWING INDEX

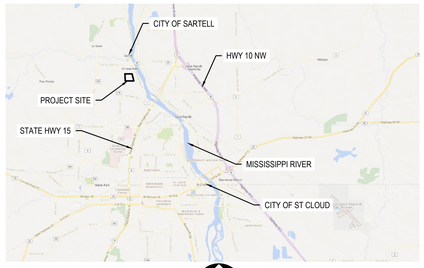
DRAWING NUMBER	DESCRIPTION
267354-0000-CIV-DWG-0001	COVER SHEET, GENERAL NOTES, LEGEND, AND ABBREVIATIONS
267354-0000-CIV-DWG-0010	EXISTING CONDITIONS AND DEMOLION PLAN
267354-0000-CIV-DWG-0020	SITE PLAN
267354-0000-CIV-DWG-0030	GRADING AND DRAINAGE PLAN
267354-0000-CIV-DWG-0040	UNDERGROUND UTILITIES PLAN
267354-0000-CIV-DWG-0050	STORMWATER POND PLAN

OWNER: CONFIDENTIAL

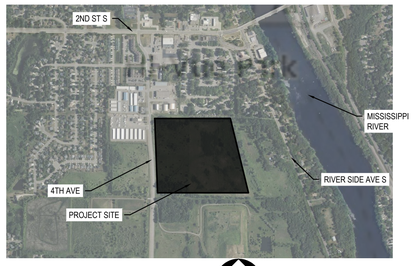
CIVIL ENGINEER: WOOD.
Ken Vogel
30 PATEWOOD DR #200
GREENVILLE, SC 29615
(864) 458-3600
Ken.Vogel@woodplc.com

GEOTECHNICAL: AMERICAN ENGINEERING TESTING
Robin L. Flickinger
550 CLEVELAND AVENUE NORTH
SAINT PAUL, MN 55114
(651) 659-1301
rflickinger@teamAET.com

SURVEYOR: WESTWOOD PROFESSIONAL SERVICES, INC
Mathew J Welinski
1900 MEDICAL ARTS AVE SOUTH, SUITE 100
SARTELL, MN 56377
(320) 253-9495



VICINITY MAP
APPROX 1" = 2 MILE



LOCUS MAP
APPROX 1" = 1000'

GENERAL NOTES
1. GENERAL NOTES APPLICABLE TO ALL DRAWINGS.
2. THE HORIZONTAL COORDINATE SYSTEM USED ON THESE DRAWINGS IS THE PLANT GRID COORDINATE SYSTEM AND NAVD88 VERTICAL DATUM.TRANSLATION FROM NAD83 MINNESOTA DOT STEARNS COUNTY COORDINATE SYSTEM TO PLANT COORDINATE SYSTEM SHALL BE SHIFT FROM BASE POINT N 219998.789, E 740933.980 TO BASE POINT N 2000.000, E 2000.000, NO ROTATION. SURVEY CONTROL MONUMENT DATA TO BE PROVIDED BY OWNER FOR SURVEYOR'S/SUE CONSULTANT'S USE AND VERIFICATION AND/OR ADJUSTMENT OF THE RECORD HORIZONTAL COORDINATE AND ELEVATION DATA.
3. ALL WORK TO BE PERFORMED SHALL CONFORM TO ALL APPLICABLE CODES AND ORDINANCES OF AUTHORITIES HAVING JURISDICTION OVER THE PROJECT.
4. PROJECT SITE LIES IN THE AREA OF MINIMAL FLOOD HAZARD ZONE OF ZONE X - OUTSIDE THE 0.2% ANNUAL FLOOD CHANCE FLOOD PLAIN, PER THE FLOOD INSURANCE RATE MAP OF STEARNS COUNTY, MINNESOTA, MAP NUMBER 27145C0627E, EFFECTIVE DATE FEBRUARY 16, 2012.
5. CONTRACTOR SHALL BE RESPONSIBLE FOR MAINTAINING CONTINUOUS PUBLIC ACCESS DURING CONSTRUCTION ACTIVITIES.

UTILITY NOTES
1. CONTRACTOR SHALL BE RESPONSIBLE FOR LOCATING AND PROTECTING ALL UTILITIES WHICH ARE TO REMAIN IN USE WHETHER OR NOT UTILITIES ARE SHOWN ON THE DRAWINGS. CONTRACTOR OR UTILITY COMPANY SHALL EXCAVATE TO EXPOSE UNDERGROUND UTILITIES WHERE NEEDED FOR VERIFICATION AT CRITICAL LOCATIONS AND/OR CROSSINGS. THE CONTRACTOR SHALL NOTIFY ALL PUBLIC UTILITY COMPANIES AND OWNERS OF PRIVATE UTILITIES WITHIN THE CONSTRUCTION AREA 3 BUSINESS DAYS PRIOR TO THE START OF CONSTRUCTION.
2. IT SHALL BE THE CONTRACTOR'S RESPONSIBILITY TO CONTACT THE OWNER'S REPRESENTATIVE AND MINNESOTA 811 THREE (3) FULL BUSINESS DAYS BEFORE ANY EXCAVATIONS OF ANY KIND TAKE PLACE TO LOCATE EXISTING UNDERGROUND UTILITIES. THE LOCATION, SIZE, AND OTHER DESCRIPTIONS OF EXISTING UTILITIES INDICATED ON THESE DRAWINGS ARE BASED UPON INFORMATION AVAILABLE AT THE TIME OF DRAWING PREPARATION. NO GUARANTEE IS MADE OR INTENDED AS TO THE ACCURACY OR COMPLETENESS OF THIS INFORMATION.
3. SEE ELECTRICAL DRAWINGS FOR UNDERGROUND ELECTRICAL DUCT BANK DESIGN AND LOCATIONS.

EARTHWORK & DRAINAGE NOTES
1. CONTRACTOR SHALL BE RESPONSIBLE FOR LOCATING, PROTECTING, AND RELOCATING ALL UNDERGROUND UTILITIES AND STORM WATER SYSTEMS WHICH ARE TO REMAIN IN PLACE WHETHER OR NOT SAID UTILITIES ARE SHOWN ON THE DRAWINGS. CONTRACTOR OR UTILITY COMPANY SHALL LOCATE TO EXPOSE THE UNDERGROUND SYSTEM TO DETERMINE THE PHYSICAL SIZE(S), HORIZONTAL LOCATION(S) AND VERTICAL ELEVATION(S) AT CRITICAL LOCATIONS AND/OR CROSSINGS. THE CONTRACTOR SHALL NOTIFY THE OWNER'S REPRESENTATIVE AND AFFECTED UTILITY OWNERS A MINIMUM OF THREE FULL BUSINESS DAYS BEFORE ANY EXCAVATIONS TAKE PLACE TO LOCATE THE PHYSICAL LOCATIONS.
2. SPOT ELEVATIONS AND CONTOURS SHOWN ON THESE DRAWINGS ARE TOP OF FINISHED GRADE. CONTRACTOR SHALL SUBTRACT FINISH SURFACING MATERIAL THICKNESS(ES) TO OBTAIN TOP OF SUBGRADE. GRADE SHALL SLOPE UNIFORMLY TO DRAIN BETWEEN CONTOURS AND SPOT ELEVATIONS SHOWN ON THE PLANS.
3. THE CONTRACTOR SHALL INSTALL AND MAINTAIN ALL OF THE PERIMETER EROSION AND SEDIMENTATION CONTROL MEASURES INDICATED AS AN INITIAL STEP IN THE CONSTRUCTION PROCESS BEFORE ANY OTHER LAND DISTURBING ACTIVITIES COMMENCE. THE CONTRACTOR SHALL BE RESPONSIBLE TO MONITOR AND REMOVE ACCUMULATED SEDIMENT FROM ALL EROSION AND SEDIMENTATION CONTROL BMP'S WHEN THE MAXIMUM ALLOWABLE LEVELS ARE REACHED. THE CONTRACTOR SHALL STABILIZE REMOVED SEDIMENT ON THE PROJECT SITE AT LOCATION(S) APPROVED BY THE OWNER'S REPRESENTATIVE AND GEOTECHNICAL ENGINEER OR OTHERWISE THE CONTRACTOR SHALL LEGALLY DISPOSE OF THE SEDIMENT OFF-SITE.
4. MAXIMUM TEMPORARY CONSTRUCTION SLOPE ON SITE SHALL BE 3 FEET HORIZONTAL TO 1 FOOT VERTICAL, UNLESS NOTED ON THE PLANS OR OTHERWISE MANDATED BY OSHA.

EROSION AND SEDIMENTATION CONTROL NOTES
1. CONTRACTOR SHALL COMPLY WITH ALL EROSION AND SEDIMENT CONTROL MEASURES DESCRIBED AND DETAILED IN THE DRAWINGS, PROJECT SPECIFIC SWPPP, AND ALL REQUIREMENTS OF MPCA GENERAL STORM WATER PERMIT FOR CONSTRUCTION ACTIVITY MNR100001.
2. EROSION AND SEDIMENT CONTROL MEASURES SHALL BE IMPLEMENTED PRIOR TO, AND MAINTAINED DURING, CONSTRUCTION UNTIL FINAL STABILIZATION.
3. ALL TEMPORARY STOCKPILES SHALL BE PROTECTED BY INSTALLING AND MAINTAINING TEMPORARY STABILIZATION MEASURES AND SEDIMENTATION BARRIERS AROUND THE PERIMETER. SLOPES SHALL NOT EXCEED 3:1. ALL STOCKPILES SHALL BE SURFACE ROUGHENED AND STABILIZED OR OTHERWISE COVERED WITHIN THE REQUIRED TIME FRAMES.
4. ALL ENTRANCES INTO PROJECT SHALL HAVE A STABILIZED CONSTRUCTION ENTRANCE / EXIT.
5. ADDITIONAL BMP'S MAY BE REQUIRED DURING CONSTRUCTION TO CONTROL EROSION AND SEDIMENTATION CAUSED BY CONSTRUCTION ACTIVITIES. CONTRACTOR SHALL BE RESPONSIBLE TO INSTALL AND MAINTAIN ALL BMPS NECESSARY TO ACHIEVE THIS OBJECTIVE.
6. UPON FINAL STABILIZATION OF THE SITE, ALL TEMPORARY EROSION AND SEDIMENT CONTROL BMP'S SHALL BE REMOVED AND THE ASSOCIATED REMOVAL AREAS SHALL BE STABILIZED.

EROSION & SEDIMENT CONTROL

DESCRIPTION	KEY	SYMBOL
CONSTRUCTION ENTRANCE	CE	
STORM DRAIN INLET PROTECTION	IP	
TEMPORARY SEEDING	TS	
SILT FENCE	SF	
DUST CONTROL	DC	
EROSION CONTROL BLANKET	ECB	
CHECK DAM	CD	
MULCHING	M	

ABBREVIATIONS AND ACRONYMS

AGG	AGGREGATE
ASPH	ASPHALT
BLDG	BUILDING
BM	BENCHMARK
BMP	BEST MANAGEMENT PRACTICE
CB	CATCH BASIN (DROP INLET)
CI	CURB INLET
CJ	CONTROL JOINT (CONCRETE PAVEMENT)
℄	CENTERLINE
CS	CARBON STEEL
DEMO	DEMOLISH
DIA	DIAMETER
DI	DROP INLET
DOM	DOMESTIC
EA	EACH
EG	EXISTING GRADE
EL	ELEVATION
EU	ELECTRICAL UNDERGROUND
EX. (E)	EXISTING
FFE	FINISHED FLOOR ELEVATION
FG	FINISHED GRADE
HDPE	HIGH DENSITY POLYETHYLENE
HP	HIGH POINT
HORZ	HORIZONTAL
IE	INVERT ELEVATION
IPS	IRON PIPE SIZING
INV	INVERT
JB	JUNCTION BOX
LP	LOW POINT
MnDOT	MINNESOTA DEPARTMENT OF TRANSPORTATION
MPCA	MINNESOTA POLLUTION CONTROL AGENCY
MH	MANHOLE
MAX	MAXIMUM
MEE	MATCH EXISTING ELEVATION
MIN	MINIMUM
NO.	NUMBER
NPDES	NATIONAL POLLUTANT DISCHARGE ELIMINATION SYSTEM
NTS	NOT TO SCALE
OC	ON CENTER
O/H	OVERHEAD
PE	POLYETHYLENE
PL	PROPERTY LINE
PVC	POLYVINYL CHLORIDE (FOR PIPE)
R	RADIUS
RCP	REINFORCED CONCRETE PIPE
RECP	ROLLED EROSION CONTROL PRODUCT
R/W	RIGHT-OF-WAY
SCH	SCHEDULE
SS	SANITARY SEWER (GRAVITY)
SSFM	SANITARY SEWER FORCE MAIN
STA	STATION
STM	STORM SEWER
SWPPP	STORMWATER POLLUTION PREVENTION PLAN
SQ	SQUARE
T/P	TOP OF PAVEMENT
TOC	TOP OF CONCRETE
TYP	TYPICAL
UG	UNDERGROUND
UNO	UNLESS NOTED OTHERWISE
VERT	VERTICAL
W/	WITH
W	WATER LINE
WT	WATER TIGHT
WTR	WATER LINE

LEGEND	NEW	EXISTING
CHAIN LINK FENCE	X	X
CONCRETE PAVEMENT		
GRAVEL SURFACING		
ASPHALT PAVEMENT		
PROPERTY LINE	PL	
LIMITS OF DISTURBANCE	LOD	
SPOT ELEVATION	11.00	11.00
MAJOR CONTOURS	10	10
MINOR CONTOURS	11	11
MINOR HALF CONTOURS	10.5	10.5
SLOPE ARROW	S	
STORM SEWER		STO
SANITARY SEWER	SS	SAN
PROCESS SEWER	P	
POTABLE WATER	W	WAT
COOLING WATER	CW	
UNDERGROUND ELECTRIC	E	PUG
OVERHEAD ELECTRIC	E	E_X
FIREWATER	F	F F
ELECTRIC POLE		
HYDRANT		
BOLLARD		
CATCH BASIN, JUNCTION BOX	D OR	

811
SAFETY IS IN YOUR HANDS.
EVERY DIG. EVERY TIME.

WORK SAFELY

REF	NUMBER	TITLE
REFERENCES		

REV	DDMMMYY	DESCRIPTION	DRN	CHK	APP	APP
A	19DEC25	ISSUED FOR ESTIMATE	JZ	KAV	JCS	ZT

REVISION HISTORY

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NOT FOR CONSTRUCTION

APPROVED FOR ESTIMATE

DN	JCS	JS
CLIENT PROJECT MGR	DEPARTMENT MGR	PROJECT MGR

PROJECT PHASE: POLARIS - PHASE I

PROJECT NO.: 267354

SCALE: AS NOTED

	BY	DDMMMYY
DES	JZ	04DEC25
DRN	JZ	04DEC25
CHK	KAV	15DEC25
APP	KAV	19DEC25

CONFIDENTIAL CLIENT

SUBJECT: CIVIL
COVER SHEET, GENERAL NOTES, LEGEND, AND ABBREVIATIONS

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wood.

30 PATEWOOD DR, SUITE 200, GREENVILLE, SC 29615 (864) 458-3600
CORPORATE OFFICE: 17325 PARK ROW, SUITE 500, HOUSTON, TX 77084

AREA: 0000

CLIENT DWG NO.:

DRAWING NO.: 267354-0000-CIV-DWG-0001

REV: A

SAVED: 18-Dec-25 9:29 AM PLOTTED: 05-Nov-25 9:22 AM USER: ZHANG, JUN (ENGINEERING AND PROJECT MANAGEMENT)

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ARCH FES 30x42



(TRUE NORTH)

0 10' 25' 50' 100'

1"=50'-0"

WORK SAFELY

REF	NUMBER	TITLE
		REFERENCES

REV	DDMMMYY	DESCRIPTION	DRN	CHK	APP	APP
		REVISION HISTORY				

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APPROVED FOR INFORMATION

DN	JCS	JS
CLIENT PROJECT MGR	DEPARTMENT MGR	PROJECT MGR

PROJECT PHASE: POLARIS - PHASE I

PROJECT NO.: 267354

SCALE: 1" = 50'

	BY	DDMMMYY
DES		
DRN		
CHK		
APP		

SUBJECT: CIVIL PLAN SITE

Niron Magnetics

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wood.

30 PATEWOOD DR, SUITE 200, GREENVILLE, SC 29615 (864) 458-3600
CORPORATE OFFICE: 17325 PARK ROW, SUITE 500, HOUSTON, TX 77084

AREA: 0000

CLIENT DWG NO.:

DRAWING NO.: REV A

DATA FILE: C:\USERS\KEN.VOGEL\DOCDOCS\WORK FILES\POLARIS\PROJECT FILES\DESIGN\CAD\XLSX\PRESIZED\DP-267354-000-CIV-DWG-AXV.DWG

SAVED: 29-Jan-26 5:10 PM PLOTTED: 13-Oct-25 4:30 PM USER: VOGEL, KEN

ARCH REF: D-SHT

NOTES:

1. FOR GENERAL NOTES, LEGEND, AND ABBREVIATIONS SEE DWG 267354-0000-CIV-DWG-0001

811 SAFETY IS IN YOUR HANDS. EVERY DIG. EVERY TIME.

WORK SAFELY

(TRUE NORTH)

0 10' 20' 40' 80'
1"=40'-0"

REF	NUMBER	TITLE
		REFERENCES

REV	DDMMMYY	DESCRIPTION	DRN	CHK	APP	APP
B	28JAN26	ISSUED FOR ESTIMATE	JZ	KAV	JCS	ZT
A	19DEC25	ISSUED FOR ESTIMATE	JZ	KAV	JCS	ZT
		REVISION HISTORY				

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NOT FOR CONSTRUCTION

APPROVED FOR ESTIMATE		
DN	JCS	JS
CLIENT PROJECT MGR	DEPARTMENT MGR	PROJECT MGR

PROJECT PHASE: POLARIS - PHASE I

PROJECT NO.

SCALE

	BY	DDMMMYY
DES	JZ	04DEC25
DRN	JZ	04DEC25
CHK	KAV	15DEC25
APP	KAV	15DEC25

CONFIDENTIAL CLIENT

SUBJECT: CIVIL PLAN SITE

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wood.
30 PATEWOOD DR, SUITE 200, GREENVILLE, SC 29615 (864) 458-3600
CORPORATE OFFICE: 17325 PARK ROW, SUITE 500, HOUSTON, TX 77084

AREA 0000

CLIENT DWG NO.

DRAWING NO. 267354-0000-CIV-DWG-0020

REV B

SAVED: 27-Jan-26 11:48 AM PLOTTED: 05-Nov-25 9:22 AM USER: ZHANG, JUN (ENGINEERING AND PROJECT MANAGEMENT)
DATA FILE: C:\USERS\JUN.ZHANG\DOCUMENTS\WOOD\PLOTFLAN\SRPROJECT FILES\267354\0000\CIV\DWG\0020.DWG

ARCH FB1 (SHx2)

NOTES:

1. FOR GENERAL NOTES, LEGEND, AND ABBREVIATIONS SEE DWG 267354-0000-CIV-DWG-0001

RIM=1055.07
INV(N,E)=1041.42
INV(S)=1041.32

7011
MF IP W/ CAP 46562
1052.11

ASPHALT PAVEMENT, TYP

100' ROW

L=110.00
CHB=N 86°07'04" E
A=1°07'04"

RIM=1051.96
INV(N,W,SE)
=1048.81

EASEMENT PER CITY OF SARTELL ROW PLAT NO. 4

7012
MF IP W/ CAP 46562
1051.44

RIM=1051.97
INV(E)=1049.07

INV=1048.62

INV=1046.18
24" RCP

POND

RIM=1050.75
INV(W)=1046.77, 24" RCP
INV(SE)=1048.51, 24" RCP

INV=1045.62
28" RCP

RIM=1051.44
INV(E,W)=1048.74

INV=1048.23
28" RCP

RIM=1051.50
INV(E)=1048.80

POND

INV=1045.61
28" RCP

INV=1048.63

RIM=1052.06
INV(N)=1037.71
INV(S)=1037.61

RIM=1051.71
INV(E)=1048.91

RIM=1051.70
INV(NE,W,S)=1048.70

UNDERGROUND POWER LINE

RIM=1052.02
INV(E)=1049.22

RIM=1052.13
INV(N,S,W)=1049.03

CONC CURB, TYP

EX SANITARY SEWER (TYP)

EX CITY WATER (TYP)

HYDRANT (TYP)

L=731.29
CHB=N 12°39'35" W
A=10°07'33"
CH=730.83

RIM=1053.26
INV(N,E,W)=1036.46
INV(S)=1036.36

8" WM STUB
TOP PIPE ELEV
=1045.00 PER PLAN

8" PVC STUB
INV=1036.74
PER PLAN

EDGE OF ASPHALT SIDE WALK

RIM=1052.29
INV(N,S,W)=1048.29

RIM=1052.16
INV(E)=1048.86

LIGHTING POLE, TYP

DRAINAGE EASEMENT PER CHAMPION PLAT 2

100' ROW

EX STORM WATER PIPE (TYP)

UNKNOWN TERMINUS

INV=1043.90
30" RCP

RIM=1051.40
INV(N,S,W)=1047.60

DRAINAGE AND UTILITY EASEMENT PER CHAMPION PLAT 2

DRAINAGE EASEMENT PER CHAMPION PLAT 2

RIM=1051.45
INV(E)=1048.55

7018
MF IP W/ CAP 46562
1047.74

S89°58'58"W 320.56

7019
MF IP NO CAP
1048.08

10" PVC

RIM=1051.87
INV(N,E,W)=1035.12
INV(S)=1035.02

RIM=1050.87
INV(N,S,W)=1047.57

BOUNDARY (TYP)

7013
MF IP W/ CAP 46562
1050.02

N89°05'22"W 1313.07

LIMITS OF DEVELOPMENT (TYP)

EDGE OF VEGETATION, TO BE CLEARED WITHIN THE LOD, TYP

DITCH, TO BE CLEARED AND FILLED

TREE, TO BE CLEARED WITHIN THE LOD, TYP

7017
MF IP W/ CAP 46562
1047.92

RIM=1048.70
INV(W)=1034.00
INV(E)=1033.90

RIM=1046.84
INV(W)=1033.94
INV(E)=1033.84

RIM=1046.91
INV(W)=1033.01
INV(E)=1032.91

N89°47'34"W 1072.23

RIM=1045.39
INV(W)=1032.04
INV(E)=1031.94

7992
MF LATH 150FT OS POL
1040.04

SURVEYED WATER EDEG

7016
MF IP W/ CAP 46562
1042.61

S80°50'21"E
525.05

DRAINAGE EASEMENT PER CHAMPION PLAT 2

DELINEATED WETLAND APPROVED ON 10/06/23

LIMITS OF DEVELOPMENT (TYP)

DRAINAGE AND UTILITY EASEMENT PER CHAMPION PLAT 2

N00°15'43"E
27.61

RIM=1043.38
INV(W)=1030.88
INV(E)=1030.78

811
SAFETY IS IN YOUR HANDS.
EVERY DIG. EVERY TIME.

WORK SAFELY

(TRUE NORTH)

0 10' 25' 50' 100'
1"=50'-0"

REF	NUMBER	TITLE
REFERENCES		

REV	DDMMMYY	DESCRIPTION	DRN	CHK	APP	APP
A	19DEC25	ISSUED FOR ESTIMATE	JZ	KAV	JCS	ZT
REVISION HISTORY						

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DN	JCS	JS
CLIENT PROJECT MGR	DEPARTMENT MGR	PROJECT MGR

PROJECT PHASE: POLARIS - PHASE I

PROJECT NO.: 267354

SCALE: AS NOTED

	BY	DDMMMYY
DES	JZ	04DEC25
DRN	JZ	04DEC25
CHK	KAV	15DEC25
APP	KAV	15DEC25

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wood.
30 PATEWOOD DR, SUITE 200, GREENVILLE, SC 29615 (864) 458-3600
CORPORATE OFFICE: 17325 PARK ROW, SUITE 500, HOUSTON, TX 77084

SUBJECT: CIVIL PLAN EXISTING CONTITIONS AND DEMOLITION

AREA: 0000

CLIENT DWG NO.:

DRAWING NO.: 267354-0000-CIV-DWG-0010

REV: A

CAD FILE: C:\USERS\JHUANG\DOCUMENTS\WOOD FLOR\JHUANG\PROJECT FILES\267354-0000-CIV-DWG-0010.DWG

SAVED: 18-Dec-25 8:55 AM PLOTTED: 05-Nov-25 9:22 AM USER: ZHANG, JUN (ENGINEERING AND PROJECT MANAGEMENT)

ARCH FES (24x36)

NOTES:

1. FOR GENERAL NOTES, LEGEND, AND ABBREVIATIONS SEE DWG 267354-0000-CIV-DWG-0001
2. WATER SERVICE LINE AND FIRE WATER LINE SHALL BE INSTALLED MINIMUM 8.5 FEET BELOW THE FINISHED GRADE.
3. SANITARY SEWER LINE SHALL BE PVC SDR 26 MINIMUM.
4. HDPE FIRE LINE IS PROPOSED TO BE HDPE IPS SDR 9 PE4710.

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WORK SAFELY

(TRUE NORTH)

0 10' 20' 40' 80'
1"=40'-0"

REF	NUMBER	TITLE
REFERENCES		

REV	DDMMMYY	DESCRIPTION	DRN	CHK	APP	APP
B	28JAN25	ISSUED FOR ESTIMATE	JZ	KAV	JCS	ZT
A	19DEC25	ISSUED FOR ESTIMATE	JZ	KAV	JCS	ZT

REVISION HISTORY

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APPROVED FOR ESTIMATE

DN	JCS	JS
CLIENT PROJECT MGR	DEPARTMENT MGR	PROJECT MGR

PROJECT PHASE: POLARIS - PHASE I

PROJECT NO.: 267354

SCALE: AS NOTED

CONFIDENTIAL CLIENT

	BY	DDMMMYY
DES	JZ	04DEC25
DRN	JZ	04DEC25
CHK	KAV	15DEC25
APP	KAV	15DEC25

SUBJECT: CIVIL PLAN UNDERGROUND UTILITIES

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CORPORATE OFFICE: 17325 PARK ROW, SUITE 500, HOUSTON, TX 77084

AREA: 0000

CLIENT DWG NO.:

DRAWING NO.: 267354-0000-CIV-DWG-0040

REV: B

SAVED: 27-Jan-26 11:12 AM PLOTTED: 05-Nov-26 9:22 AM USER: ZHANG, JUN (ENGINEERING AND PROJECT MANAGEMENT)
C:\USERS\JUN.ZHANG3\DOCUMENTS\WORKSHARING\267354-0000-CIV-DWG-0040.DWG

ARCH-FED-SHAD

NOTES:

1. FOR GENERAL NOTES, LEGEND, AND ABBREVIATIONS SEE DWG 267354-0000-CIV-DWG-0001

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WORK SAFELY

(TRUE NORTH)

0 10' 20' 40' 80'
1"=40'-0"

REF	NUMBER	TITLE
REFERENCES		

REV	DDMMMYY	DESCRIPTION	DRN	CHK	APP	APP
B	28JAN26	ISSUED FOR ESTIMATE	JZ	KAV	JCS	ZT
A	19DEC25	ISSUED FOR ESTIMATE	JZ	KAV	JCS	ZT
REVISION HISTORY						

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DN	JCS	JS
CLIENT PROJECT MGR	DEPARTMENT MGR	PROJECT MGR

PROJECT PHASE: POLARIS - PHASE I

PROJECT NO.: 267354

SCALE: AS NOTED

	BY	DDMMMYY
DES	JZ	04DEC25
DRN	JZ	04DEC25
CHK	KAV	15DEC25
APP	KAV	15DEC25

CONFIDENTIAL CLIENT

SUBJECT: CIVIL PLAN GRADING AND DRAINAGE

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CORPORATE OFFICE: 17325 PARK ROW, SUITE 500, HOUSTON, TX 77084

AREA: 0000

CLIENT DWG NO.:

DRAWING NO.: 267354-0000-CIV-DWG-0030

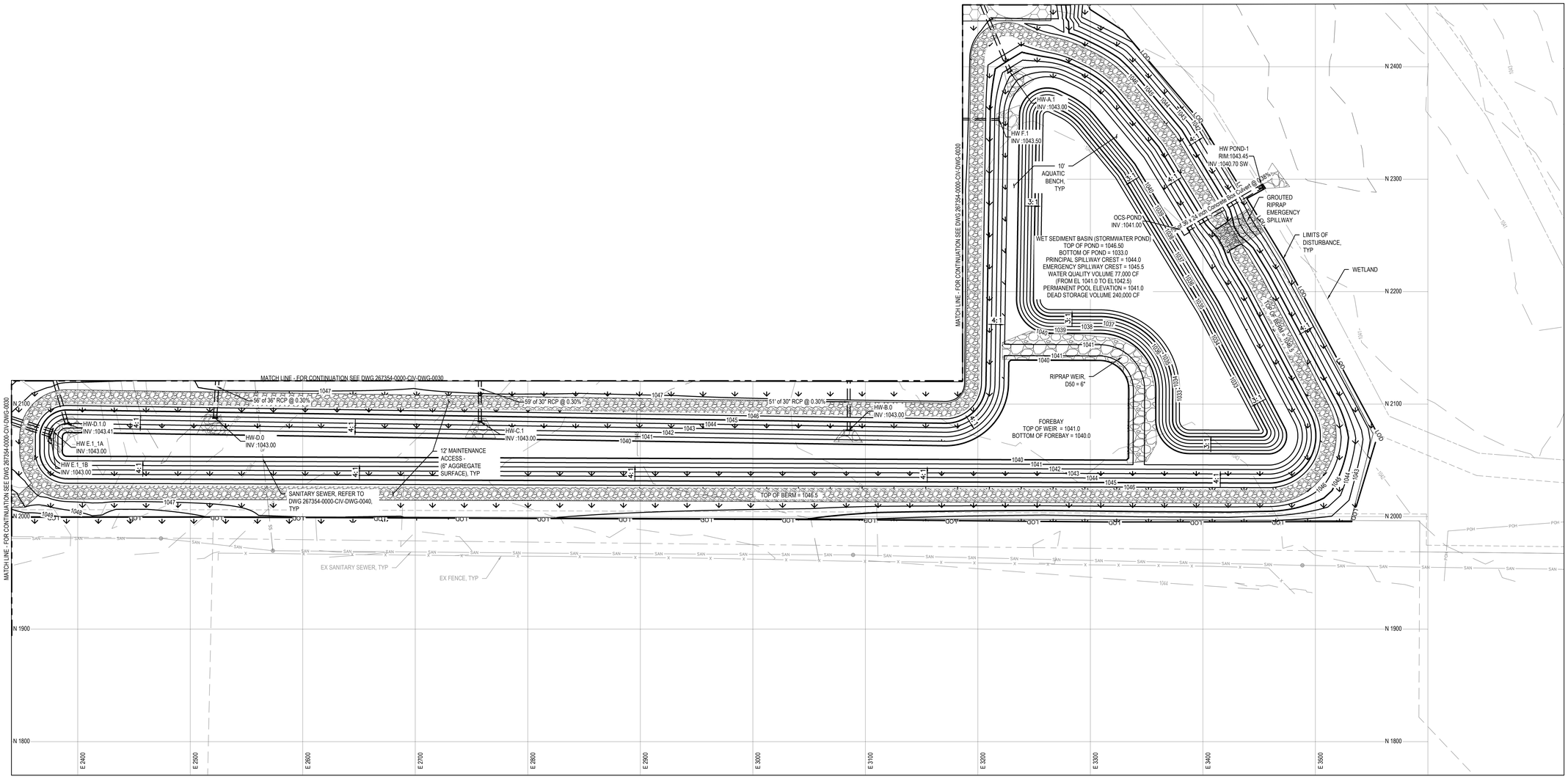
REV: B

SAVED: 27-Jan-26 10:19 AM PLOTTED: 05-Nov-25 9:22 AM USER: ZHANG, JUN (ENGINEERING AND PROJECT MANAGEMENT)
CAD FILE: C:\USERS\JUN.ZHANG\DOCUMENTS\ACCDOCS\WOOD PLC\POLARIS PROJECT FILES\000000\CAD\CIVIL\267354-0000-CIV-DWG-0030.DWG

ARCH FILE: A3.dwt

NOTES:

1. FOR GENERAL NOTES, LEGEND, AND ABBREVIATIONS SEE DWG 267354-0000-CIV-DWG-0001



SAFETY IS IN YOUR HANDS.
EVERY DIG. EVERY TIME.

(TRUE NORTH)

0 10' 20' 40' 80'
1"=40'-0"

WORK SAFELY

REF	NUMBER	TITLE
		REFERENCES

REV	DDMMMYY	DESCRIPTION	DRN	CHK	APP	APP
B	28JAN26	ISSUED FOR ESTIMATE	JZ	KAV	JCS	ZT
A	19DEC25	ISSUED FOR ESTIMATE	JZ	KAV	JCS	ZT
		REVISION HISTORY				

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APPROVED FOR ESTIMATE

DN	JCS	JS
CLIENT PROJECT MGR	DEPARTMENT MGR	PROJECT MGR

PROJECT PHASE: POLARIS - PHASE I

PROJECT NO.: 267354

SCALE: AS NOTED

	BY	DDMMMYY
DES	JZ	04DEC25
DRN	JZ	04DEC25
CHK	KAV	15DEC25
APP	KAV	15DEC25

CONFIDENTIAL CLIENT

SUBJECT: CIVIL PLAN STORMWATER POND

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CORPORATE OFFICE: 17325 PARK ROW, SUITE 500, HOUSTON, TX 77084

AREA: 0000

CLIENT DWG NO.:

DRAWING NO.: 267354-0000-CIV-DWG-0050

REV: B

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DATA FILE: C:\USERS\JUN.ZHANG3\DOCACCOUNT\WOOD\DATA\267354-0000-CIV-DWG-0050.DWG

ARCH 1 (ED) - 30.0x42

Appendix C
Well Logs

Minnesota Unique Well Number

135955

County Stearns
Quad St Cloud
Quad ID 156C

MINNESOTA DEPARTMENT OF HEALTH

WELL AND BORING REPORT

Minnesota Statutes Chapter 1031

Entry Date 04/17/1988
Update Date 06/02/2014
Received Date

Well Name	Township	Range	Dir	Section	Subsection
NEUMANN, DR.	125	28	W	27	BCBCCD

Elevation 1054 **Elev. Method** 7.5 minute topographic map (+/- 5 feet)

Address

C/W RIVER RD N ST CLOUD MN

Stratigraphy Information

Geological Material	From	To (ft.)	Color	Hardness
SAND	0	8	YELLOW	SOFT
HARDPAN	8	62	YELLOW	HARD
GRAVEL & WATER	62	76		

Remarks

Well Depth 76 ft. **Depth Completed** 76 ft. **Date Well Completed** 05/25/1977

Drill Method Air Rotary **Drill Fluid**

Use domestic **Status** Active

Well Hydrofractured? Yes ☐ No ☐ **From** **To**

Casing Type Single casing **Joint** Welded

Drive Shoe? Yes ☒ No ☐ **Above/Below** 1 ft.

Casing Diameter	Weight	Hole Diameter
6 in. To 76 ft.	lbs./ft.	6 in. To 76 ft.

Open Hole From 62 ft. To 76 ft.

Screen? ☐ **Type** **Make**

Static Water Level

Pumping Level (below land surface)

Wellhead Completion

Pitless adapter manufacturer Model

☐ Casing Protection ☒ 12 in. above grade

☐ At-grade (Environmental Wells and Borings ONLY)

Grouting Information Well Grouted? ☐ Yes ☒ No ☐ Not Specified

Nearest Known Source of Contamination

feet Direction Type

Well disinfected upon completion? ☐ Yes ☐ No

Pump ☐ Not Installed Date Installed 00/00/1977

Manufacturer's name GOULD

Model Number 25EL15412 HP 0.5 Volt

Length of drop pipe 13 ft Capacity g.p. Typ Submersible

Abandoned

Does property have any not in use and not sealed well(s)? ☐ Yes ☐ No

Variance

Was a variance granted from the MDH for this well? ☐ Yes ☐ No

Miscellaneous

First Bedrock Aquifer Quaternary

Last Strat gravel (+larger) Depth to Bedrock ft

Located by Minnesota Geological Survey

Locate Method Digitized - scale 1:24,000 or larger (Digitizing Table)

System UTM - NAD83, Zone 15, Meters X 406359 Y 5051384

Unique Number Verification Information from Input Date 01/01/1990

Angled Drill Hole

Well Contractor

Licensee Business	Lic. or Reg. No.	Name of Driller
Donabauer Well Co.	73061	DONABAUER, G.

Minnesota Unique Well Number

472168

County Stearns
Quad St Cloud
Quad ID 156C

MINNESOTA DEPARTMENT OF HEALTH
WELL AND BORING REPORT
Minnesota Statutes Chapter 1031

Entry Date 11/05/1992
Update Date 03/03/2017
Received Date

Well Name	Township	Range	Dir	Section	Subsection
CITY OF	125	28	W	28	DBBBAB

Elevation 1050 **Elev. Method** 7.5 minute topographic map (+/- 5 feet)

Address

Contact 310 2ND #140 ST S SARTELL MN 56377

Stratigraphy Information

Geological Material	From	To (ft.)	Color	Hardness
SAND & GRAVEL	0	5	BROWN	
MED SAND	5	10	BROWN	
SILTY CLAY	10	14	BROWN	

Remarks

1A
END OF 4TH AVE. S.
SEALED 03-25-2010 BY 1685.

Well Depth 14 ft. **Depth Completed** 14 ft. **Date Well Completed** 03/01/1991

Drill Method Power Auger **Drill Fluid**

Use monitor well **Status** Sealed

Well Hydrofractured? Yes ☐ No ☐ **From** **To**

Casing Type Single casing **Joint** Threaded
Drive Shoe? Yes ☐ No ☒ **Above/Below** 1 ft.

Casing Diameter		Weight			Hole Diameter			
2	in. To 4	ft.	3.68	lbs./ft.	8	in. To 14	ft.	

Open Hole From ft. To ft.

Screen? ☒ **Type** stainless **Make** JOHNSON

Diameter	Slot/Gauze	Length		Set			
in.	10	10	ft.	4	ft.	14	ft.

Static Water Level
7 ft. land surface Measure 03/00/1991

Pumping Level (below land surface)

Wellhead Completion
Pitless adapter manufacturer Model
☐ Casing Protection ☒ 12 in. above grade
☐ At-grade (Environmental Wells and Borings ONLY)

Grouting Information Well Grouted? ☒ Yes ☐ No ☐ Not Specified

Material	Amount	From		To	
neat cement		1	ft.	3	ft.
bentonite		3	ft.	4	ft.

Nearest Known Source of Contamination
feet Direction Type
Well disinfected upon completion? ☐ Yes ☒ No

Pump ☐ Not Installed Date Installed
Manufacturer's name
Model Number HP Volt
Length of drop pipe ft Capacity g.p. Typ

Abandoned
Does property have any not in use and not sealed well(s)? ☐ Yes ☒ No

Variance
Was a variance granted from the MDH for this well? ☐ Yes ☐ No

Miscellaneous
First Bedrock Aquifer
Last Strat Depth to Bedrock ft
Located by Minnesota Geological Survey
Locate Method Digitization (Screen) - Map (1:24,000) (15 meters or
System UTM - NAD83, Zone 15, Meters X 405568 Y 5051204
Unique Number Verification Info/GPS from data Input Date 12/14/2012

Angled Drill Hole

Well Contractor
Barott Drilling 02303 BAROTT,B.
Licensee Business Lic. or Reg. No. Name of Driller

Minnesota Unique Well Number

472169

County Stearns
Quad St Cloud
Quad ID 156C

MINNESOTA DEPARTMENT OF HEALTH
WELL AND BORING REPORT
Minnesota Statutes Chapter 1031

Entry Date 11/05/1992
Update Date 03/03/2017
Received Date

Well Name	Township	Range	Dir	Section	Subsection
CITY OF	125	28	W	28	DBBBAB

Elevation 1050 **Elev. Method** 7.5 minute topographic map (+/- 5 feet)

Address

Contact 310 2ND #140 ST S SARTELL MN 56377

Stratigraphy Information

Geological Material	From	To (ft.)	Color	Hardness
CLAY	0	15	BROWN	
CLAY	15	50	BLUE	
SAND	50	60	GRAY	

Remarks

1B
END OF 4TH AVE. S.
SEALED 03-25-2010 BY 1685.

Well Depth 62 ft. **Depth Completed** 62 ft. **Date Well Completed** 03/01/1991

Drill Method Non-specified Rotary **Drill Fluid** Revert

Use monitor well **Status** Sealed

Well Hydrofractured? Yes ☐ No ☐ **From** **To**

Casing Type Single casing **Joint** Threaded
Drive Shoe? Yes ☐ No ☐ **Above/Below** 3 ft.

Casing Diameter		Weight			Hole Diameter		
2 in. To	52 ft.	3.68 lbs./ft.			7 in. To	62 ft.	

Open Hole From ft. To ft.

Screen? ☒ **Type** stainless **Make** JOHNSON

Diameter	Slot/Gauze	Length		Set			
2 in.	12	10	ft.	52	ft.	62	ft.

Static Water Level

22 ft. land surface Measure 03/01/1991

Pumping Level (below land surface)

Wellhead Completion

Pitless adapter manufacturer Model

☐ Casing Protection ☒ 12 in. above grade
☐ At-grade (Environmental Wells and Borings ONLY)

Grouting Information Well Grouted? ☒ Yes ☐ No ☐ Not Specified

Material	Amount	From		To	
neat cement		3	ft.	48	ft.
bentonite		48	ft.	50	ft.

Nearest Known Source of Contamination

feet Direction Type

Well disinfected upon completion? ☐ Yes ☒ No

Pump ☒ Not Installed Date Installed

Manufacturer's name

Model Number HP Volt

Length of drop pipe ft Capacity g.p. Typ

Abandoned

Does property have any not in use and not sealed well(s)? ☐ Yes ☒ No

Variance

Was a variance granted from the MDH for this well? ☐ Yes ☐ No

Miscellaneous

First Bedrock Aquifer
Last Strat Depth to Bedrock ft
Located by Minnesota Geological Survey
Locate Method Digitization (Screen) - Map (1:24,000) (15 meters or
System UTM - NAD83, Zone 15, Meters X 405568 Y 5051204
Unique Number Verification Info/GPS from data Input Date 12/14/2012

Angled Drill Hole

Well Contractor

Barott Drilling 02303 BAROTT,B.
Licensee Business Lic. or Reg. No. Name of Driller

Minnesota Unique Well Number

594766

County Stearns
Quad St Cloud
Quad ID 156C

MINNESOTA DEPARTMENT OF HEALTH

WELL AND BORING REPORT

Minnesota Statutes Chapter 1031

Entry Date 01/11/2013
Update Date 09/11/2014
Received Date 06/14/2010

Well Name	Township	Range	Dir	Section	Subsection
ME-5A	125	28	W	28	DBBADA

Elevation 1045 **Elev. Method** 7.5 minute topographic map (+/- 5 feet)

Address

Well 4TH AV S MN

Stratigraphy Information

Geological Material	From	To (ft.)	Color	Hardness
SAND-FILL	0	14	BROWN	SOFT
SILTY CLAY	14	30	BROWN	MEDIUM

Remarks

CONTAMINATION - METALS

Well Depth 30 ft. **Depth Completed** 27 ft. **Date Well Completed** 06/10/2010

Drill Method Auger (non-specified) **Drill Fluid**

Use monitor well **Status** Active

Well Hydrofractured? Yes ☐ No ☐ **From** **To**

Casing Type Single casing **Joint** Threaded

Drive Shoe? Yes ☐ No ☒ **Above/Below**

Casing Diameter	Weight	Hole Diameter
2 in. To 17 ft.	4 lbs./ft.	8 in. To 30 ft.

Open Hole From ft. To ft.

Screen? ☒ **Type** stainless **Make** JOHNSON

Diameter	Slot/Gauze	Length	Set	
2 in.	10	10 ft.	17 ft.	27 ft.

Static Water Level

20 ft. land surface Measure 06/10/2010

Pumping Level (below land surface)

27 ft. 1 hrs. Pumping at 0.1 g.p.m.

Wellhead Completion

Pitless adapter manufacturer Model

☐ Casing Protection ☐ 12 in. above grade
☐ At-grade (Environmental Wells and Borings ONLY)

Grouting Information Well Grouted? ☒ Yes ☐ No ☐ Not Specified

Material	Amount	From	To
high solids bentonite	3 Sacks	ft.	15 ft.

Nearest Known Source of Contamination

50 feet West Direction Other Type

Well disinfected upon completion? ☐ Yes ☒ No

Pump ☒ Not Installed Date Installed

Manufacturer's name

Model Number HP Volt

Length of drop pipe ft Capacity g.p. Typ

Abandoned

Does property have any not in use and not sealed well(s)? ☐ Yes ☒ No

Variance

Was a variance granted from the MDH for this well? ☐ Yes ☒ No

Miscellaneous

First Bedrock Aquifer

Last Strat Depth to Bedrock ft

Located by Minnesota Geological Survey

Locate Method Digitization (Screen) - Map (1:24,000) (15 meters or

System UTM - NAD83, Zone 15, Meters X 405698 Y 5051132

Unique Number Verification Info/GPS from data Input Date 01/11/2013

Angled Drill Hole

Well Contractor

Earth Science Associates, 1685 ALDRICH,T.

Licensee Business Lic. or Reg. No. Name of Driller

Minnesota Unique Well Number

594767

County Stearns
Quad St Cloud
Quad ID 156C

MINNESOTA DEPARTMENT OF HEALTH

WELL AND BORING REPORT

Minnesota Statutes Chapter 1031

Entry Date 01/11/2013
Update Date 09/11/2014
Received Date

Well Name	Township	Range	Dir	Section	Subsection
	125	28	W	28	DBBADA

Elevation 1045 **Elev. Method** 7.5 minute topographic map (+/- 5 feet)

Address

Well 4TH AV S MN

Contact 5200 FOUNDRY CI ST CLOUD MN 56303

Stratigraphy Information

Geological Material	From	To (ft.)	Color	Hardness
SAND - FILL	0	14	BROWN	SOFT
SILTY CLAY	14	36	BROWN	MEDIUM
SILTY CLAY	36	60	DK. GRY	HARD

Remarks

Well Depth 60 ft. **Depth Completed** 57.8 ft. **Date Well Completed** 06/10/2010

Drill Method Auger (non-specified) **Drill Fluid**

Use monitor well **Status** Active

Well Hydrofractured? **Yes** ☐ **No** ☐ **From** **To**

Casing Type Single casing **Joint** Threaded

Drive Shoe? **Yes** ☐ **No** ☒ **Above/Below**

Casing Diameter		Weight		Hole Diameter	
2 in. To	48 ft.	4 lbs./ft.		8 in. To	60 ft.

Open Hole From ft. To ft.

Screen? ☒ **Type** stainless **Make** JOHNSON

Diameter	Slot/Gauze	Length	Set	
2 in.	10	10 ft.	48 ft.	57.8 ft.

Static Water Level

26.8 ft. land surface Measure 06/10/2010

Pumping Level (below land surface)

35 ft. 1 hrs. Pumping at 0.2 g.p.m.

Wellhead Completion

Pitless adapter manufacturer Model

☐ Casing Protection ☐ 12 in. above grade
☐ At-grade (Environmental Wells and Borings ONLY)

Grouting Information Well Grouted? ☒ Yes ☐ No ☐ Not Specified

Material	Amount	From	To
high solids bentonite	5 Sacks	ft.	45 ft.

Nearest Known Source of Contamination

50 feet West Direction Other Type

Well disinfected upon completion? ☐ Yes ☒ No

Pump ☒ Not Installed Date Installed

Manufacturer's name

Model Number HP Volt

Length of drop pipe ft Capacity g.p. Typ

Abandoned

Does property have any not in use and not sealed well(s)? ☐ Yes ☒ No

Variance

Was a variance granted from the MDH for this well? ☐ Yes ☒ No

Miscellaneous

First Bedrock Aquifer

Last Strat Depth to Bedrock ft

Located by Minnesota Geological Survey

Locate Method Digitization (Screen) - Map (1:24,000) (15 meters or

System UTM - NAD83, Zone 15, Meters X 405696 Y 5051139

Unique Number Verification Info/GPS from data Input Date 01/11/2013

Angled Drill Hole

Well Contractor

Earth Science Associates, 1685 ALDRICH,T.

Licensee Business Lic. or Reg. No. Name of Driller

Minnesota Unique Well Number

680557

County Stearns
Quad St Cloud
Quad ID 156C

MINNESOTA DEPARTMENT OF HEALTH

WELL AND BORING REPORT

Minnesota Statutes Chapter 1031

Entry Date 11/01/2002
Update Date 03/26/2013
Received Date

Well Name	Township	Range	Dir	Section	Subsection
INTERNATIONAL	125	28	W	28	DBDBBA

Elevation 1045 **Elev. Method** 7.5 minute topographic map (+/- 5 feet)

Address

Well 100 SARTELL ST E SARTELL MN 56377

Stratigraphy Information

Geological Material	From	To (ft.)	Color	Hardness
SILTY SAND	0	22	BROWN	SOFT

Remarks

WELL LOCATION INFO: 1/2 MI. S OF 2ND ST. S & 4TH AVE. S, SARTELL, MN 56377

Well Depth	Depth Completed	Date Well Completed
22 ft.	20 ft.	08/20/2002

Drill Method Auger (non-specified) **Drill Fluid**

Use monitor well **Status** Active

Well Hydrofractured? Yes ☐ No ☒ **From** **To**

Casing Type Single casing **Joint** Unknown
Drive Shoe? Yes ☐ No ☒ **Above/Below**

Casing Diameter	Weight	Hole Diameter
2 in. To 10 ft.	lbs./ft.	9 in. To 20 ft.
		2 in. To 22 ft.

Open Hole From ft. To ft.

Screen? ☒ **Type** plastic **Make** LAIBE

Diameter	Slot/Gauze	Length	Set
2 in.	10	10 ft.	10 ft. 20 ft.

Static Water Level

16 ft. land surface Measure 08/20/2002

Pumping Level (below land surface)

Wellhead Completion

Pitless adapter manufacturer Model

☒ Casing Protection ☐ 12 in. above grade
☐ At-grade (Environmental Wells and Borings ONLY)

Grouting Information Well Grouted? ☒ Yes ☐ No ☐ Not Specified

Material	Amount	From	To
neat cement	2 Sacks	0 ft.	4 ft.
bentonite	2 Sacks	4 ft.	8 ft.

Nearest Known Source of Contamination

feet Direction Type

Well disinfected upon completion? ☐ Yes ☒ No

Pump ☒ Not Installed Date Installed

Manufacturer's name

Model Number HP Volt

Length of drop pipe ft Capacity g.p. Typ

Abandoned

Does property have any not in use and not sealed well(s)? ☐ Yes ☒ No

Variance

Was a variance granted from the MDH for this well? ☐ Yes ☒ No

Miscellaneous

First Bedrock Aquifer
Last Strat Depth to Bedrock ft
Located by Minnesota Geological Survey
Locate Method Digitization (Screen) - Map (1:24,000) (15 meters or
System UTM - NAD83, Zone 15, Meters X 405743 Y 5050981
Unique Number Verification Info/GPS from data Input Date 03/26/2013

Angled Drill Hole

Well Contractor

Traut M.J. Well Co. 71536 FEELY, B.
Licensee Business Lic. or Reg. No. Name of Driller

Appendix D
DNR NHIS Consultation

Formal Natural Heritage Review - Cover Page

See next page for results of review. A draft watermark means the project details have not been finalized and the results are not official.

Project Name: Niron Sartell Project

Project Proposer: Niron Magnetics

Project Type: Other

Project Type Activities: Wetland impacts (e.g., dewatering, tiling, drainage, discharge, excavation, fill, runoff, sedimentation, changes in hydrology);Waterbody or watercourse impacts (e.g., dewatering, discharge, excavation, fill, runoff, sedimentation, changes in hydrology));Groundwater Impacts (e.g., contamination, dewatering, change in hydrology, potential for aquifer breach);Tree Removal;Grading

TRS: T125 R28 S27, T125 R28 S28

County(s): Stearns

DNR Admin Region(s): Central

Reason Requested: Other

Project Description: Niron Magnetics proposes to construct a facility that produces industrial magnets. The process converts iron oxide into a magnetic material, iron nitride. ...

Existing Land Uses: The proposed Project area is largely undeveloped, consisting of woodlots, scattered trees and shrubs, grasslands, and wetlands. A residential property, ...

Landcover / Habitat Impacted: Land cover within the Project area consists of woodlots, trees/shrubs, grasslands, and wetlands. Tree/shrub clearing and grubbing is anticipated to occur ...

Waterbodies Affected: No rivers, lakes, or streams are located within the Project area. Wetlands are located within the Project area and the Mississippi River is located less ...

Groundwater Resources Affected: The Project area falls within the Minneapolis, St. Paul, and St. Cloud Priority A Drinking Water Supply Management Area (DWSMA). Impacts to groundwater ...

Previous Natural Heritage Review: No

Previous Habitat Assessments / Surveys: No

SUMMARY OF AUTOMATED RESULTS

Category	Results	Response By Category
Project Details	Comments	Tree Removal - Recommendations
Ecologically Significant Area	No Comments	No Further Review Required
State-Listed Endangered or Threatened Species	Needs Further Review	State-protected Species - Needs Further Review
State-Listed Species of Special Concern	Comments	Recommendations

Category	Results	Response By Category
Federally Listed Species	No Records	Visit IPaC For Federal Review

March 24, 2025

Project Name: Niron Sartell Project
Project Proposer: Niron Magnetics
Project Type: Other
Project ID: MCE #2025-00309

AUTOMATED RESULTS: FURTHER REVIEW IS NEEDED
As requested, the above project has undergone an automated review for potential impacts to rare features. Based on this review, one or more rare features may be impacted by the proposed project and further review by the Natural Heritage Review Team is needed. You will receive a separate notification email when the review process is complete and the Natural Heritage Review letter has been posted.

Please refer to the table on the cover page of this report for a summary of potential impacts to rare features. For additional information or planning purposes, use the Explore Page in Minnesota Conservation Explorer to view the potentially impacted rare features or to create a Conservation Planning Report for the proposed project.

If you have additional information to help resolve the potential impacts listed in the summary results, please attach related project documentation in the Edit Details tab of the Project page. Relevant information includes, but is not limited to, additional project details, completed habitat assessments, or survey results. This additional information will be considered during the project review.

Niron Sartell Project

Aerial Imagery With Locator Map



N
W E
S

0 0.130.25 0.5 0.75 1 Miles

Project Boundary

Project Type: Other

Project Size (acres): 61.06

County(s): Stearns

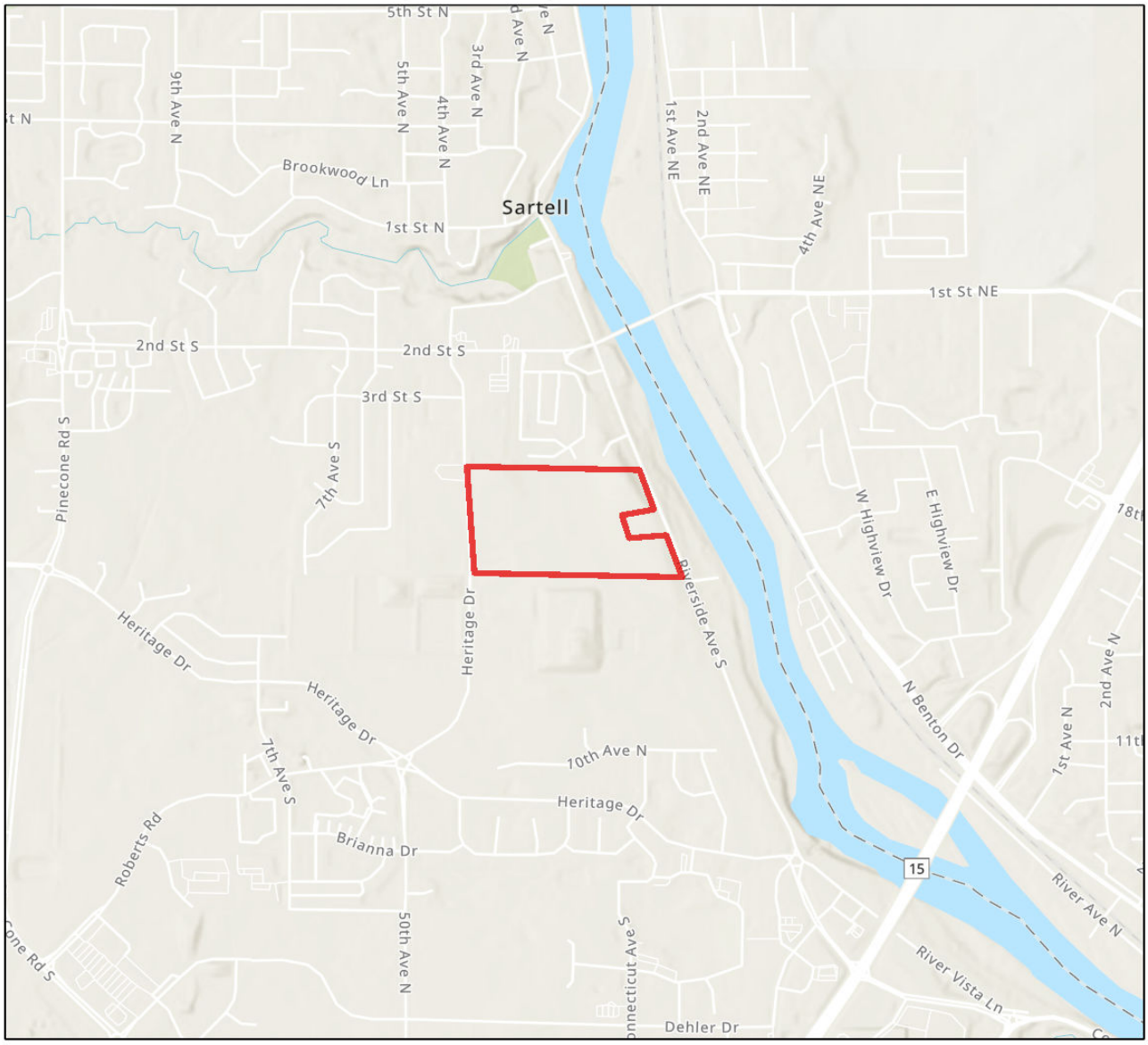
TRS: T125 R28 S27, T125 R28 S28



Esri, TomTom, Garmin, FAO, NOAA, USGS, EPA, USFWS
Maxar
Esri, TomTom, Garmin, SafeGraph, GeoTechnologies, Inc, METI/NASA, USGS,

Niron Sartell Project

USA Topo Basemap With Locator Map



N
W E
S

0 0.130.25 0.5 0.75 1 Miles

Project Boundary



Project Type: Other

Project Size (acres): 61.06

County(s): Stearns

TRS: T125 R28 S27, T125 R28 S28

Esri, TomTom, Garmin, FAO, NOAA, USGS, EPA, USFWS
Esri, NASA, NGA, USGS, FEMA
Esri, TomTom, Garmin, SafeGraph, GeoTechnologies, Inc, METI/NASA, USGS,

DEPARTMENT OF NATURAL RESOURCES

Minnesota Department of Natural Resources
Division of Ecological & Water Resources
500 Lafayette Road, Box 25
St. Paul, MN 55155-4025

June 24, 2025

Mia Bauer
Stantec

RE: Natural Heritage Review of the proposed **Niron Sartell Project**,
T125N R28W Sections 27 and 28; Stearns County

Dear Mia Bauer,

For all correspondence regarding the Natural Heritage Review of this project please include the project ID **MCE-2025-00309** in the email subject line.

As requested, the Minnesota Natural Heritage Information System has been reviewed to determine if the proposed project has the potential to impact any rare species or other significant natural features. Based on the project details provided with the request, the following rare features may be impacted by the proposed project:

State-listed Species

- The Natural Heritage Information System (NHIS) tracks bat roost trees and hibernacula plus some acoustic data, but this information is not exhaustive. Even if there are no bat records listed nearby, all of Minnesota's bats, including the federally endangered northern long-eared bat (*Myotis septentrionalis*), can be found throughout Minnesota. During the active season (approximately April-November) bats roost underneath bark, in cavities, or in crevices of both live and dead trees. Tree removal can negatively impact bats by destroying roosting habitat, especially during the pup rearing season when females are forming maternity roosting colonies and the pups cannot yet fly. To minimize these impacts, **the DNR recommends that tree removal be avoided from June 1 through August 15.**

- Please visit the DNR Rare Species Guide for more information on the habitat use of these species and recommended measures to avoid or minimize impacts.

- Please report incidental sightings of state-listed species via the DNR Plant and Animal Observation Form.

Federally Protected Species

- To ensure compliance with federal law, conduct a federal regulatory review using the U.S. Fish and Wildlife Service's (USFWS) online Information for Planning and Consultation (IPaC) tool.

Environmental Review and Permitting

- Please include a copy of this letter and the MCE-generated Final Project Report in any state or local license or permit application. Please note that measures to avoid or minimize disturbance to the above rare features may be included as restrictions or conditions in any required permits or licenses.

The Natural Heritage Information System (NHIS), a collection of databases that contains information about Minnesota's rare natural features, is maintained by the Division of Ecological and Water Resources, Department of Natural Resources. The NHIS is continually updated as new information becomes available and is the most complete source of data on Minnesota's native plant communities, rare species, and other rare features. However, the NHIS is not an exhaustive inventory and does not contain the locations of all rare features in the state. Therefore, ecologically significant features for which we have no records may exist within the project area. If additional information becomes available regarding rare features in the vicinity of the project, further review may be necessary.

For environmental review purposes, the results of this Natural Heritage Review are valid for one year; the results are only valid for the project location and project description provided with the request. **If project details change or the project has not occurred within one year, please resubmit the project for review within one year of initiating project activities.** Resubmit by selecting *Clone Project as Draft* on the project page in MCE.

The Natural Heritage Review does not constitute project approval by the Department of Natural Resources. Instead, it identifies issues regarding known occurrences of rare features and potential impacts to these rare features. Visit Natural Heritage Review for additional information regarding this process, survey guidance, and other related information. For information on the environmental review process or other natural resource concerns, please contact your DNR Regional Environmental Assessment Ecologist.

Thank you for consulting us on this matter and for your interest in preserving Minnesota's rare natural resources.

Sincerely,
Molly Barrett
Digitally signed by Molly Barrett
Date: 2025.06.24 17:17:46 -05'00'

Natural Heritage Review Specialist
molly.barrett@state.mn.us

Cc: Melissa Collins, Regional Environmental Assessment Ecologist, Central (Region 3)

Appendix E
USFWS Consultation

United States Department of the Interior

FISH AND WILDLIFE SERVICE
Minnesota-Wisconsin Ecological Services Field Office
3815 American Blvd East
Bloomington, MN 55425-1659
Phone: (952) 858-0793

In Reply Refer To: 01/30/2026 20:53:08 UTC
Project Code: 2025-0073129
Project Name: Niron Sartell Project

Subject: List of threatened and endangered species that may occur in your proposed project location or may be affected by your proposed project

To Whom It May Concern:

This response has been generated by the Information, Planning, and Conservation (IPaC) system to provide information on natural resources that could be affected by your project. The U.S. Fish and Wildlife Service (Service) provides this response under the authority of the Endangered Species Act of 1973 (16 U.S.C. 1531-1543), the Bald and Golden Eagle Protection Act (16 U.S.C. 668-668d), the Migratory Bird Treaty Act (16 U.S.C. 703-712), and the Fish and Wildlife Coordination Act (16 U.S.C. 661 *et seq.*).

Threatened and Endangered Species
The enclosed species list identifies threatened, endangered, proposed and candidate species, as well as proposed and final designated critical habitat, that may occur within the boundary of your proposed project and may be affected by your proposed project. The species list fulfills the requirement for obtaining a Technical Assistance Letter from the U.S. Fish and Wildlife Service under section 7(c) of the Endangered Species Act (Act) of 1973, as amended (16 U.S.C. 1531 *et seq.*).

New information based on updated surveys, changes in the abundance and distribution of species, changed habitat conditions, or other factors could change this list. Note that under 50 CFR 402.12(e) of the regulations implementing section 7 of the Act, the accuracy of this species list should be verified after 90 days. The Service recommends that verification be completed by visiting the IPaC website at regular intervals during project planning and implementation for updates to species lists and information. An updated list may be requested through the IPaC system by completing the same process used to receive the enclosed list.

Consultation Technical Assistance
Please refer to refer to our Section 7 website for guidance and technical assistance, including step-by-step instructions for making effects determinations for each species that might be present and for specific guidance on the following types of projects: projects in developed areas, HUD, CDBG, EDA, USDA Rural Development projects, pipelines, buried utilities, telecommunications, and requests for a Conditional Letter of Map Revision (CLOMR) from FEMA.

We recommend running the project (if it qualifies) through our **Minnesota-Wisconsin Federal Endangered Species Determination Key (Minnesota-Wisconsin ("D-key"))**. A demonstration video showing how-to access and use the determination key is available. Please note that the Minnesota-Wisconsin D-key is the third option of 3 available d-keys. D-keys are tools to help Federal agencies and other project proponents determine if their proposed action has the potential to adversely affect federally listed species and designated critical habitat. The Minnesota-Wisconsin D-key includes a structured set of questions that assists a project proponent in determining whether a proposed project qualifies for a certain predetermined consultation outcome for all federally listed species found in Minnesota and Wisconsin (except for the northern long-eared bat- see below), which includes determinations of “no effect” or “may affect, not likely to adversely affect." In each case, the Service has compiled and analyzed the best available information on the species’ biology and the impacts of certain activities to support these determinations.

If your completed d-key output letter shows a "No Effect" (NE) determination for all listed species, print your IPaC output letter for your files to document your compliance with the Endangered Species Act.

For Federal projects with a “Not Likely to Adversely Affect” (NLAA) determination, our concurrence becomes valid if you do not hear otherwise from us after a 30-day review period, as indicated in your letter.

If your d-key output letter indicates additional coordination with the Minnesota-Wisconsin Ecological Services Field Office is necessary (i.e., you get a “May Affect” determination), you will be provided additional guidance on contacting the Service to continue ESA coordination outside of the key; ESA compliance cannot be concluded using the key for “May Affect” determinations unless otherwise indicated in your output letter.

Note: Once you obtain your official species list, you are not required to continue in IPaC with d-keys, although in most cases these tools should expedite your review. If you choose to make an effects determination on your own, you may do so. If the project is a Federal Action, you may want to review our section 7 step-by-step instructions before making your determinations.

Using the IPaC Official Species List to Make No Effect and May Affect Determinations for Listed Species

1. If IPaC returns a result of “There are no listed species found within the vicinity of the project,” then project proponents can conclude the proposed activities will have **no effect** on any federally listed species under Service jurisdiction. Concurrence from the Service is not required for **no effect** determinations. No further consultation or coordination is required. Attach this letter to the dated IPaC species list report for your records.
2. If IPaC returns one or more federally listed, proposed, or candidate species as potentially present in the action area of the proposed project – other than bats (see below) – then project proponents must determine if proposed activities will have **no effect** on or **may affect** those species. For assistance in determining if suitable habitat for listed, candidate, or proposed species occurs within your project area or if species may be affected by project activities, you can obtain Life History Information for Listed and Candidate Species on our office website. If no impacts will occur to a species on the IPaC species list (e.g., there is no habitat present in the project area), the appropriate determination is **no effect**. No further consultation or coordination is required. Attach this letter to the dated IPaC species list report for your records.

3. Should you determine that project activities **may affect** any federally listed, please contact our office for further coordination. Letters with requests for consultation or correspondence about your project should include the Consultation Tracking Number in the header. Electronic submission is preferred.

Northern Long-Eared Bats
Northern long-eared bats occur throughout Minnesota and Wisconsin and the information below may help in determining if your project may affect these species.

Suitable summer habitat for northern long-eared bats consists of a wide variety of forested/wooded habitats where they roost, forage, and travel and may also include some adjacent and interspersed non-forested habitats such as emergent wetlands and adjacent edges of agricultural fields, old fields and pastures. This includes forests and woodlots containing potential roosts (i.e., live trees and/or snags ≥3 inches dbh for northern long-eared bat that have exfoliating bark, cracks, crevices, and/or hollows), as well as linear features such as fencerows, riparian forests, and other wooded corridors. These wooded areas may be dense or loose aggregates of trees with variable amounts of canopy closure. Individual trees may be considered suitable habitat when they exhibit the characteristics of a potential roost tree and are located within 1,000 feet (305 meters) of forested/wooded habitat. Northern long-eared bats have also been observed roosting in human-made structures, such as buildings, barns, bridges, and bat houses; therefore, these structures should also be considered potential summer habitat and evaluated for use by bats. If your project will impact caves or mines or will involve clearing forest or woodland habitat containing suitable roosting habitat, northern long-eared bats could be affected. For bat activity dates, please review Appendix L in the Range-wide Indiana Bat and Northern Long-Eared Bat Survey Guidelines.

Examples of unsuitable habitat include:
- Individual trees that are greater than 1,000 feet from forested or wooded areas,
- Trees found in highly developed urban areas (e.g., street trees, downtown areas),
- A pure stand of less than 3-inch dbh trees that are not mixed with larger trees, and
- A monoculture stand of shrubby vegetation with no potential roost trees.

If IPaC returns a result that northern long-eared bats are potentially present in the action area of the proposed project, project proponents can conclude the proposed activities **may affect** this species **IF** one or more of the following activities are proposed:
- Clearing or disturbing suitable roosting habitat, as defined above, at any time of year,
- Any activity in or near the entrance to a cave or mine,
- Mining, deep excavation, or underground work within 0.25 miles of a cave or mine,
- Construction of one or more wind turbines, or
- Demolition or reconstruction of human-made structures that are known to be used by bats based on observations of roosting bats, bats emerging at dusk, or guano deposits or stains.

If none of the above activities are proposed, project proponents can conclude the proposed activities will have **no effect** on the northern long-eared bat. Concurrence from the Service is not required for **No Effect** determinations. No further consultation or coordination is required. Attach this letter to the dated IPaC

species list report for your records.

If any of the above activities are proposed, and the northern long-eared bat appears on the user's species list, the federal project user will be directed to either the northern long-eared bat and tricolored bat range-wide D-key or the Federal Highways Administration, Federal Railways Administration, and Federal Transit Administration Indiana bat/Northern long-eared bat D-key, depending on the type of project and federal agency involvement. Similar to the Minnesota-Wisconsin D-key, these d-keys helps to determine if prohibited take might occur and, if not, will generate an automated verification letter. Additional information about available tools can be found on the Service's northern long-eared bat website.

Whooping Crane
Whooping crane is designated as a non-essential experimental population in Wisconsin and consultation under Section 7(a)(2) of the Endangered Species Act is only required if project activities will occur within a National Wildlife Refuge or National Park. If project activities are proposed on lands outside of a National Wildlife Refuge or National Park, then you are not required to consult. For additional information on this designation and consultation requirements, please review "Establishment of a Nonessential Experimental Population of Whooping Cranes in the Eastern United States."

Other Trust Resources and Activities
Bald and Golden Eagles - Although the bald eagle has been removed from the endangered species list, this species and the golden eagle are protected by the Bald and Golden Eagle Act and the Migratory Bird Treaty Act. It is the responsibility of the project proponent to survey the area for any migratory bird nests. If there is an eagle nest on-site while work is on-going, eagles may be disturbed. We recommend avoiding and minimizing disturbance to eagles whenever practicable. If you cannot avoid eagle disturbance, you may seek a permit. A nest take permit is always required for removal, relocation, or obstruction of an eagle nest. For communication and wind energy projects, please refer to additional guidelines below.

Migratory Birds - The Migratory Bird Treaty Act (MBTA) prohibits the taking, killing, possession, transportation, and importation of migratory birds, their eggs, parts, and nests, except when specifically authorized by the Service. The Service has the responsibility under the MBTA to proactively prevent the mortality of migratory birds whenever possible and we encourage implementation of recommendations that minimize potential impacts to migratory birds. Such measures include clearing forested habitat outside the nesting season (generally March 1 to August 31) or conducting nest surveys prior to clearing to avoid injury to eggs or nestlings.

Communication Towers - Construction of new communications towers (including radio, television, cellular, and microwave) creates a potentially significant impact on migratory birds, especially some 350 species of night-migrating birds. However, the Service has developed voluntary guidelines for minimizing impacts.

Transmission Lines - Migratory birds, especially large species with long wingspans, heavy bodies, and poor maneuverability can also collide with power lines. In addition, mortality can occur when birds, particularly hawks, eagles, kites, falcons, and owls, attempt to perch on uninsulated or unguarded power poles. To minimize these risks, please refer to guidelines developed by the Avian Power Line Interaction Committee and the Service. Implementation of these measures is especially important along sections of lines adjacent to wetlands or other areas that support large numbers of raptors and migratory birds.

Wind Energy - To minimize impacts to migratory birds and bats, wind energy projects should follow the Service's Wind Energy Guidelines. In addition, please refer to the Service's Eagle Conservation Plan Guidance, which provides guidance for conserving bald and golden eagles in the course of siting, constructing, and operating wind energy facilities.

State Department of Natural Resources Coordination
While it is not required for your Federal section 7 consultation, please note that additional state endangered or threatened species may also have the potential to be impacted. **Please contact the Minnesota or Wisconsin Department of Natural Resources for information on state listed species that may be present in your proposed project area.**

Minnesota
Minnesota Department of Natural Resources - Endangered Resources Review Homepage
Email: Review.NHIS@state.mn.us

Wisconsin
Wisconsin Department of Natural Resources - Endangered Resources Review Homepage
Email: DNRERReview@wi.gov

We appreciate your concern for threatened and endangered species. Please feel free to contact our office with questions or for additional information.

Attachment(s):

- Official Species List
- USFWS National Wildlife Refuges and Fish Hatcheries
- Bald & Golden Eagles
- Migratory Birds
- Wetlands

OFFICIAL SPECIES LIST

This list is provided pursuant to Section 7 of the Endangered Species Act, and fulfills the requirement for Federal agencies to "request of the Secretary of the Interior information whether any species which is listed or proposed to be listed may be present in the area of a proposed action".

This species list is provided by:

Minnesota-Wisconsin Ecological Services Field Office
3815 American Blvd East
Bloomington, MN 55425-1659
(952) 858-0793

PROJECT SUMMARY

Project Code: 2025-0073129
Project Name: Niron Sartell Project
Project Type: Mixed-Use Construction
Project Description: Niron Magnetics (Niron) proposes to construct a manufacturing facility that produces industrial magnets on an undeveloped site located on 4th Avenue South between Heritage Drive and 3rd Street South in Sartell, Minnesota. The process converts iron oxide into a magnetic material, iron nitride. The iron nitride is processed further and then pressed and formed into magnets of various shapes. The finished magnets are given a protective coating before shipping to customers. The processes may use gases or chemicals, and the specific processes and chemicals are still under development. The processes are enclosed and feedstocks are planned to be reused to the extent possible.

Additional outdoor structures like tanks or reactor columns will be installed. Controls like secondary containment, stormwater ponds, and waste management will be employed in the operation of the facility. Site construction is anticipated to take up to four years and would be completed over two phases.

A design change was implemented in January 2026 that increased the gross square footage above 200,000 square feet. The increase in proposed gross square footage was the result of adding a second floor to some buildings and did not expand the originally proposed and permitted overall ground disturbance footprint. The primary activities already completed are limited to preliminary grading and stockpiling of imported fill soil.

Project Location:

The approximate location of the project can be viewed in Google Maps: https://www.google.com/maps/@45.609588349999996,-94.20530387930691,14z



Counties: Stearns County, Minnesota

ENDANGERED SPECIES ACT SPECIES

There is a total of 6 threatened, endangered, or candidate species on this species list.

Species on this list should be considered in an effects analysis for your project and could include species that exist in another geographic area. For example, certain fish may appear on the species list because a project could affect downstream species.

IPaC does not display listed species or critical habitats under the sole jurisdiction of NOAA Fisheries[1], as USFWS does not have the authority to speak on behalf of NOAA and the Department of Commerce.

See the "Critical habitats" section below for those critical habitats that lie wholly or partially within your project area under this office's jurisdiction. Please contact the designated FWS office if you have questions.

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1. NOAA Fisheries, also known as the National Marine Fisheries Service (NMFS), is an office of the National Oceanic and Atmospheric Administration within the Department of Commerce.

MAMMALS

NAME	STATUS
Northern Long-eared Bat *Myotis septentrionalis* No critical habitat has been designated for this species. Species profile: https://ecos.fws.gov/ecp/species/9045	Endangered
Tricolored Bat *Perimyotis subflavus* No critical habitat has been designated for this species. Species profile: https://ecos.fws.gov/ecp/species/10515	Proposed Endangered

BIRDS

NAME	STATUS
Whooping Crane *Grus americana* Population: U.S.A. (AL, AR, CO, FL, GA, ID, IL, IN, IA, KY, LA, MI, MN, MS, MO, NC, NM, OH, SC, TN, UT, VA, WI, WV, western half of WY) No critical habitat has been designated for this species. Species profile: https://ecos.fws.gov/ecp/species/758	Experimental Population, Non-Essential

INSECTS

NAME	STATUS
Monarch Butterfly *Danaus plexippus* There is **proposed** critical habitat for this species. Your location does not overlap the critical habitat. Species profile: https://ecos.fws.gov/ecp/species/9743	Proposed Threatened
Suckley's Cuckoo Bumble Bee *Bombus suckleyi* Population: No critical habitat has been designated for this species. Species profile: https://ecos.fws.gov/ecp/species/10885	Proposed Endangered
Western Regal Fritillary *Argynnis idalia occidentalis* No critical habitat has been designated for this species. Species profile: https://ecos.fws.gov/ecp/species/12017	Proposed Threatened

CRITICAL HABITATS

THERE ARE NO CRITICAL HABITATS WITHIN YOUR PROJECT AREA UNDER THIS OFFICE'S JURISDICTION.

YOU ARE STILL REQUIRED TO DETERMINE IF YOUR PROJECT(S) MAY HAVE EFFECTS ON ALL ABOVE LISTED SPECIES.

USFWS NATIONAL WILDLIFE REFUGE LANDS AND FISH HATCHERIES

Any activity proposed on lands managed by the National Wildlife Refuge system must undergo a 'Compatibility Determination' conducted by the Refuge. Please contact the individual Refuges to discuss any questions or concerns.

THERE ARE NO REFUGE LANDS OR FISH HATCHERIES WITHIN YOUR PROJECT AREA.

BALD & GOLDEN EAGLES

Bald and Golden Eagles are protected under the Bald and Golden Eagle Protection Act [2] and the Migratory Bird Treaty Act (MBTA) [1]. Any person or organization who plans or conducts activities that may result in impacts to Bald or Golden Eagles, or their habitats, should follow appropriate regulations and consider implementing appropriate avoidance and minimization measures, as described in the various links on this page.

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1. The Bald and Golden Eagle Protection Act of 1940.
2. The Migratory Birds Treaty Act of 1918.
3. 50 C.F.R. Sec. 10.12 and 16 U.S.C. Sec. 668(a)

There are Bald Eagles and/or Golden Eagles in your project area.

Measures for Proactively Minimizing Eagle Impacts
For information on how to best avoid and minimize disturbance to nesting bald eagles, please review the National Bald Eagle Management Guidelines. You may employ the timing and activity-specific distance recommendations in this document when designing your project/ activity to avoid and minimize eagle impacts. For bald eagle information specific to Alaska, please refer to Bald Eagle Nesting and Sensitivity to Human Activity.

The FWS does not currently have guidelines for avoiding and minimizing disturbance to nesting Golden Eagles. For site-specific recommendations regarding nesting Golden Eagles, please consult with the appropriate Regional Migratory Bird Office or Ecological Services Field Office.

If disturbance or take of eagles cannot be avoided, an incidental take permit may be available to authorize any take that results from, but is not the purpose of, an otherwise lawful activity. For assistance making this determination for Bald Eagles, visit the Do I Need A Permit Tool. For assistance making this determination for golden eagles, please consult with the appropriate Regional Migratory Bird Office or Ecological Services Field Office.

Ensure Your Eagle List is Accurate and Complete
If your project area is in a poorly surveyed area in IPaC, your list may not be complete and you may need to rely on other resources to determine what species may be present (e.g. your local FWS field office, state surveys, your own surveys). Please review the Supplemental Information

on Migratory Birds and Eagles, to help you properly interpret the report for your specified location, including determining if there is sufficient data to ensure your list is accurate.

For guidance on when to schedule activities or implement avoidance and minimization measures to reduce impacts to bald or golden eagles on your list, see the "Probability of Presence Summary" below to see when these bald or golden eagles are most likely to be present and breeding in your project area.

NAME	BREEDING SEASON
Bald Eagle *Haliaeetus leucocephalus* This is not a Bird of Conservation Concern (BCC) in this area, but warrants attention because of the Eagle Act or for potential susceptibilities in offshore areas from certain types of development or activities. https://ecos.fws.gov/ecp/species/1626	Breeds Dec 1 to Aug 31

PROBABILITY OF PRESENCE SUMMARY

The graphs below provide our best understanding of when birds of concern are most likely to be present in your project area. This information can be used to tailor and schedule your project activities to avoid or minimize impacts to birds. Please make sure you read "Supplemental Information on Migratory Birds and Eagles", specifically the FAQ section titled "Proper Interpretation and Use of Your Migratory Bird Report" before using or attempting to interpret this report.

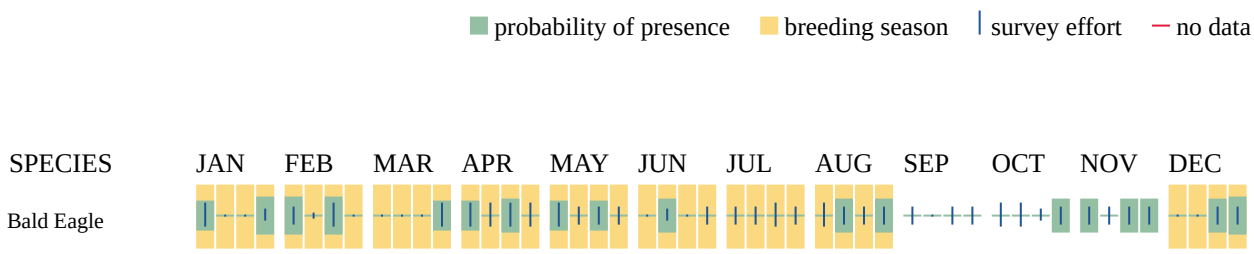
Probability of Presence (■)

Green bars; the bird's relative probability of presence in the 10km grid cell(s) your project overlaps during that week of the year.

Breeding Season (■)
Yellow bars; liberal estimate of the timeframe inside which the bird breeds across its entire range.

Survey Effort (|)
Vertical black lines; the number of surveys performed for that species in the 10km grid cell(s) your project area overlaps.

No Data (–)
A week is marked as having no data if there were no survey events for that week.



Non-BCC
Vulnerable

Additional information can be found using the following links:

- Eagle Management https://www.fws.gov/program/eagle-management
- Measures for avoiding and minimizing impacts to birds https://www.fws.gov/library/collections/avoiding-and-minimizing-incidental-take-migratory-birds
- Nationwide avoidance and minimization measures for birds https://www.fws.gov/sites/default/files/documents/nationwide-standard-conservation-measures.pdf
- Supplemental Information for Migratory Birds and Eagles in IPaC https://www.fws.gov/media/supplemental-information-migratory-birds-and-bald-and-golden-eagles-may-occur-project-action

MIGRATORY BIRDS

The Migratory Bird Treaty Act (MBTA) [1] prohibits the take (including killing, capturing, selling, trading, and transport) of protected migratory bird species without prior authorization by the Department of Interior U.S. Fish and Wildlife Service (Service).

---

1. The Migratory Birds Treaty Act of 1918.
2. The Bald and Golden Eagle Protection Act of 1940.
3. 50 C.F.R. Sec. 10.12 and 16 U.S.C. Sec. 668(a)

For guidance on when to schedule activities or implement avoidance and minimization measures to reduce impacts to migratory birds on your list, see the "Probability of Presence Summary" below to see when these birds are most likely to be present and breeding in your project area.

NAME	BREEDING SEASON
Bald Eagle *Haliaeetus leucocephalus* This is not a Bird of Conservation Concern (BCC) in this area, but warrants attention because of the Eagle Act or for potential susceptibilities in offshore areas from certain types of development or activities. https://ecos.fws.gov/ecp/species/1626	Breeds Dec 1 to Aug 31
Canada Warbler *Cardellina canadensis* This is a Bird of Conservation Concern (BCC) throughout its range in the continental USA and Alaska. https://ecos.fws.gov/ecp/species/9643	Breeds May 20 to Aug 10

NAME	BREEDING SEASON
Chimney Swift *Chaetura pelagica* This is a Bird of Conservation Concern (BCC) throughout its range in the continental USA and Alaska. https://ecos.fws.gov/ecp/species/9406	Breeds Mar 15 to Aug 25
Grasshopper Sparrow *Ammodramus savannarum perpallidus* This is a Bird of Conservation Concern (BCC) only in particular Bird Conservation Regions (BCRs) in the continental USA https://ecos.fws.gov/ecp/species/8329	Breeds Jun 1 to Aug 20
Red-headed Woodpecker *Melanerpes erythrocephalus* This is a Bird of Conservation Concern (BCC) throughout its range in the continental USA and Alaska. https://ecos.fws.gov/ecp/species/9398	Breeds May 10 to Sep 10
Rusty Blackbird *Euphagus carolinus* This is a Bird of Conservation Concern (BCC) only in particular Bird Conservation Regions (BCRs) in the continental USA https://ecos.fws.gov/ecp/species/9478	Breeds elsewhere

PROBABILITY OF PRESENCE SUMMARY

The graphs below provide our best understanding of when birds of concern are most likely to be present in your project area. This information can be used to tailor and schedule your project activities to avoid or minimize impacts to birds. Please make sure you read "Supplemental Information on Migratory Birds and Eagles", specifically the FAQ section titled "Proper Interpretation and Use of Your Migratory Bird Report" before using or attempting to interpret this report.

Probability of Presence (■)

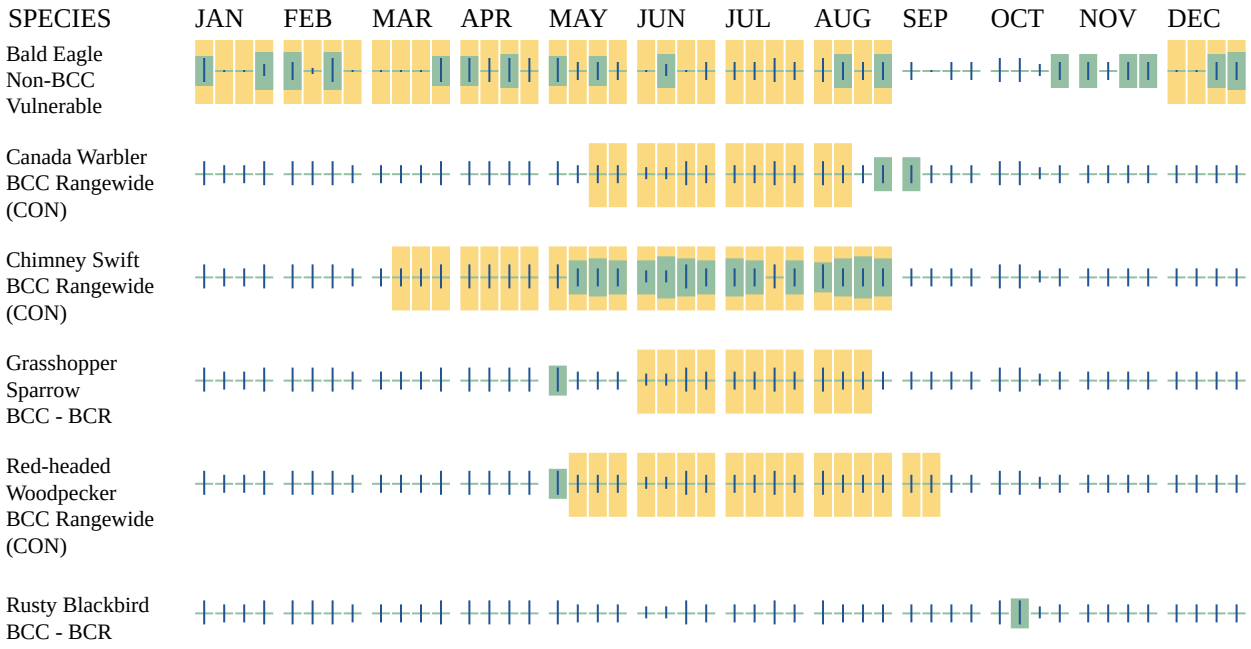
Green bars; the bird's relative probability of presence in the 10km grid cell(s) your project overlaps during that week of the year.

Breeding Season (■)
Yellow bars; liberal estimate of the timeframe inside which the bird breeds across its entire range.

Survey Effort (|)
Vertical black lines; the number of surveys performed for that species in the 10km grid cell(s) your project area overlaps.

No Data (–)
A week is marked as having no data if there were no survey events for that week.

■ probability of presence ■ breeding season | survey effort – no data



Additional information can be found using the following links:

- Eagle Management https://www.fws.gov/program/eagle-management
- Measures for avoiding and minimizing impacts to birds https://www.fws.gov/library/collections/avoiding-and-minimizing-incidental-take-migratory-birds
- Nationwide avoidance and minimization measures for birds
- Supplemental Information for Migratory Birds and Eagles in IPaC https://www.fws.gov/media/supplemental-information-migratory-birds-and-bald-and-golden-eagles-may-occur-project-action

WETLANDS

Impacts to NWI wetlands and other aquatic habitats may be subject to regulation under Section 404 of the Clean Water Act, or other State/Federal statutes.

For more information please contact the Regulatory Program of the local U.S. Army Corps of Engineers District.

Please note that the NWI data being shown may be out of date. We are currently working to update our NWI data set. We recommend you verify these results with a site visit to determine the actual extent of wetlands on site.

FRESHWATER POND

- PUBHx
- PUBH

FRESHWATER EMERGENT WETLAND

- PEM1A

IPAC USER CONTACT INFORMATION

Agency:	Private Entity
Name:	Mia Bauer
Address:	One Carlson Parkway
Address Line 2:	Suite 100
City:	Plymouth
State:	MN
Zip:	55447
Email	mia.bauer@stantec.com
Phone:	6124273725

United States Department of the Interior

FISH AND WILDLIFE SERVICE
Minnesota-Wisconsin Ecological Services Field Office
3815 American Blvd East
Bloomington, MN 55425-1659
Phone: (952) 858-0793

In Reply Refer To: 01/21/2026 17:07:28 UTC
Project code: 2025-0073129
Project Name: Niron Sartell Project

Subject: Technical Assistance letter for 'Niron Sartell Project' for specified threatened and endangered species that may occur in your proposed project location consistent with the Minnesota-Wisconsin Endangered Species Determination Key (Minnesota-Wisconsin DKey).

Dear Mia Bauer:

The U.S. Fish and Wildlife Service (Service) received on **January 21, 2026** your effect determination(s) for the 'Niron Sartell Project' (Action) using the Minnesota-Wisconsin DKey within the Service's Information for Planning and Consultation (IPaC) system. The Service developed this system in accordance with the Endangered Species Act of 1973 (ESA) (87 Stat. 884, as amended; 16 U.S.C 1531 et seq.).

Based on your responses to the Service's Minnesota-Wisconsin DKey, you made the following effect determination(s) for the proposed Action:

Species	Listing Status	Determination
Monarch Butterfly (*Danaus plexippus*)	Proposed Threatened	No effect
Whooping Crane (*Grus americana*)	Experimental Population, Non-Essential	No effect

Determination Information

Thank you for informing the Service of your "No Effect" determination(s). No further coordination is necessary for the species you determined will not be affected by the Action.

Additional Information

Sufficient project details: Please provide sufficient project details on your project homepage in IPaC (Define Project, Project Description) to support your conclusions. Failure to disclose important aspects of your project that would influence the outcome of your effects determinations may negate your determinations and invalidate this letter. If you have site-specific information that leads you to believe a different determination is more appropriate for your

project than what the Dkey concludes, you can and should proceed based on the best available information.

Future project changes: The Service recommends that you contact the Minnesota-Wisconsin Ecological Services Field Office or re-evaluate the project in IPaC if: 1) the scope or location of the proposed Action is changed; 2) new information reveals that the action may affect federally listed species or federally designated critical habitat in a manner or to an extent not previously considered; 3) the Action is modified in a manner that causes effects to listed species or designated critical habitat; or 4) a new species is listed or critical habitat designated. If any of the above conditions occurs, additional consultation with the Service should take place before project changes are final or resources committed.

Species-specific information

Bald and Golden Eagles: Bald eagles, golden eagles, and their nests are protected under the Bald and Golden Eagle Protection Act (54 Stat. 250, as amended, 16 U.S.C. 668a-d) (Eagle Act). The Eagle Act prohibits, except when authorized by an Eagle Act permit, the "taking" of bald and golden eagles and defines "take" as "pursue, shoot, shoot at, poison, wound, kill, capture, trap, collect, molest or disturb." The Eagle Act's implementing regulations define disturb as "… to agitate or bother a bald or golden eagle to a degree that causes, or is likely to cause, based on the best scientific information available, (1) injury to an eagle, (2) a decrease in its productivity, by substantially interfering with normal breeding, feeding, or sheltering behavior, or (3) nest abandonment, by substantially interfering with normal breeding, feeding, or sheltering behavior."

If you observe a bald eagle nest in the vicinity of your proposed project, you should follow the National Bald Eagle Management Guidelines (May 2007). For more information on eagles and conducting activities in the vicinity of an eagle nest, please visit our regional eagle website or contact Margaret at Margaret_Martin@fws.gov. If the Action may affect bald or golden eagles, additional coordination with the Service under the Eagle Act may be required.

Additional Species Requiring Review

In addition to the species described above, the following species or critical habitats may also occur in your project area and are not covered by this conclusion:

- Northern Long-eared Bat *Myotis septentrionalis* Endangered
- Suckley's Cuckoo Bumble Bee *Bombus suckleyi* Proposed Endangered
- Tricolored Bat *Perimyotis subflavus* Proposed Endangered
- Western Regal Fritillary *Argynnis idalia occidentalis* Proposed Threatened

Coordination with the Service is not complete if additional coordination is advised above for any species.

Action Description
You provided to IPaC the following name and description for the subject Action.

1. Name

Niron Sartell Project

2. Description

The following description was provided for the project 'Niron Sartell Project':

> Niron Magnetics proposes to construct a facility that produces industrial magnets. The process converts iron oxide into a magnetic material, iron nitride. The iron nitride is processed further and then pressed and formed into magnets of various shapes. The finished magnets are given a protective coating before shipping to customers. The processes may use gases or chemicals, and the specific processes and chemicals are still under development. The processes are enclosed and feedstocks are planned to be reused to the extent possible.
>
> The total square footage of all buildings will be less than 200,000 square feet. Additional outdoor structures like tanks or reactor columns will be installed. Controls like secondary containment, stormwater ponds, and waste management will be employed in the operation of the facility. Site clearing is expected to occur in fall 2025 with buildings and structures erected in 2026.

The approximate location of the project can be viewed in Google Maps: https://www.google.com/maps/@45.609588349999996,-94.20530387930691,14z



QUALIFICATION INTERVIEW

1. This determination key is intended to assist the user in evaluating the effects of their actions on Federally listed species in Minnesota and Wisconsin. It does not cover other prohibited activities under the Endangered Species Act (e.g., for wildlife: import/export, Interstate or foreign commerce, possession of illegally taken wildlife, etc.; for plants: import/export, reduce to possession, malicious destruction on Federal lands, commercial sale, etc.) or other statutes. Additionally, this key DOES NOT cover wind development, purposeful take (e.g., for research or surveys), communication towers that have guy wires or are over 450 feet in height, aerial or other large-scale application of any chemical (such as insecticide or herbicide), and approval of long-term permits or plans (e.g., FERC licenses, HCP's).

   Click **YES** to acknowledge that you must consider other prohibitions of the ESA or other statutes outside of this determination key.

   Yes
2. Is the action being funded, authorized, or carried out by a Federal agency?

   No
3. Is the action being conducted by or on behalf of a Federally recognized Tribe?

   No
4. Does the action involve the installation or operation of wind turbines?

   No
5. Does the action involve purposeful take of a listed animal?

   No
6. Does the action involve a new communications tower?

   No
7. Does the activity involve aerial or other large-scale application of ANY chemical, including pesticides (insecticide, herbicide, fungicide, rodenticide, etc)?

   No
8. Will your action permanently affect local hydrology?

   No
9. Will your action temporarily affect local hydrology?

   No
10. Will your project have any direct impacts to a stream or river (e.g., Horizontal Directional Drilling (HDD), hydrostatic testing, stream/road crossings, new stormwater outfall discharge, dams, other in-stream work, etc.)?

    No

11. Does your project have the potential to impact the riparian zone or indirectly impact a stream/river (e.g., cut and fill; horizontal directional drilling; construction; vegetation removal; pesticide or fertilizer application; discharge; runoff of sediment or pollutants; increase in erosion, etc.)?

    Note: Consider all potential effects of the action, including those that may happen later in time and outside and downstream of the immediate area involved in the action.

    Endangered Species Act regulation defines "effects of the action" to include all consequences to listed species or critical habitat that are caused by the proposed action, including the consequences of other activities that are caused by the proposed action. A consequence is caused by the proposed action if it would not occur but for the proposed action and it is reasonably certain to occur. Effects of the action may occur later in time and may include consequences occurring outside the immediate area involved in the action. (50 CFR 402.02).

    Yes

12. Will your action disturb the ground or existing vegetation?

    Note: This includes any off-road vehicle access, soil compaction (enough to collapse a rodent burrow), digging, seismic survey, directional drilling, heavy equipment, grading, trenching, placement of fill, pesticide application (herbicide, fungicide), vegetation management (including removal or maintenance using equipment or prescribed fire), cultivation, development, etc.

    Yes

13. Will your action include spraying insecticides?

    No

14. Does your action area occur entirely within an already developed area?

    Note: Already developed areas are already paved, covered by existing structures, manicured lawns, industrial sites, or cultivated cropland, AND do not contain trees that could be roosting habitat. Be aware that listed species may occur in areas with natural, or semi-natural, vegetation immediately adjacent to existing utilities (e.g. roadways, railways) or within utility rights-of-way such as overhead transmission line corridors, and can utilize suitable trees, bridges, or culverts for roosting even in urban dominated landscapes (so these are not considered "already developed areas" for the purposes of this question). If unsure, select NO..

    No

15. [Hidden Semantic] Does the action area intersect the monarch butterfly species list area?

    Automatically answered

    Yes

16. Under the ESA, monarchs remain warranted but precluded by listing actions of higher priority. The monarch is a candidate for listing at this time. The Endangered Species Act does not establish protections or consultation requirements for candidate species. Some Federal and State agencies may have policy requirements to consider candidate species in planning. We encourage implementing measures that will remove or reduce threats to these species and possibly make listing unnecessary.

    If your project will have no effect on monarch butterflies (for example, if your project won't affect their habitat or individuals), then you can make a "no effect" determination for this project.

    Are you making a "no effect" determination for monarch?

    Yes

IPAC USER CONTACT INFORMATION

Agency:	Private Entity
Name:	Mia Bauer
Address:	One Carlson Parkway
Address Line 2:	Suite 100
City:	Plymouth
State:	MN
Zip:	55447
Email	mia.bauer@stantec.com
Phone:	6124273725

United States Department of the Interior

FISH AND WILDLIFE SERVICE
Minnesota-Wisconsin Ecological Services Field Office
3815 American Blvd East
Bloomington, MN 55425-1659
Phone: (952) 858-0793

In Reply Refer To: 01/30/2026 20:55:29 UTC
Project code: 2025-0073129
Project Name: Niron Sartell Project

Federal Nexus: no
Federal Action Agency (if applicable):

Subject: Technical assistance for 'Niron Sartell Project'

Dear Mia Bauer:

This letter records your determination using the Information for Planning and Consultation (IPaC) system provided to the U.S. Fish and Wildlife Service (Service) on January 30, 2026, for 'Niron Sartell Project' (here forward, Project). This project has been assigned Project Code 2025-0073129 and all future correspondence should clearly reference this number. **Please carefully review this letter. Your Endangered Species Act (Act) requirements are not complete.**

Ensuring Accurate Determinations When Using IPaC

The Service developed the IPaC system and associated species' determination keys in accordance with the Endangered Species Act of 1973 (ESA; 87 Stat. 884, as amended; 16 U.S.C. 1531 et seq.) and based on a standing analysis. All information submitted by the Project proponent into IPaC must accurately represent the full scope and details of the Project. **Failure to accurately represent or implement the Project as detailed in IPaC or the Northern Long-eared Bat and Tricolored Bat Range-wide Determination Key (Dkey), invalidates this letter.**

Determination for the Northern Long-Eared Bat and Tricolored Bat

Based on your IPaC submission and a standing analysis completed by the Service, you determined the proposed Project will have the following effect determinations:

Species	Listing Status	Determination
Northern Long-eared Bat (*Myotis septentrionalis*)	Endangered	May affect
Tricolored Bat (*Perimyotis subflavus*)	Proposed Endangered	May affect

Federal agencies must consult with U.S. Fish and Wildlife Service under section 7(a)(2) of the Endangered Species Act (ESA) when an action *may affect* a listed species. Tricolored bat is proposed for listing as endangered under the ESA, but not yet listed. For actions that may affect a proposed species, agencies cannot consult, but they can *confer* under the authority of section 7(a)(4) of the ESA. Such conferences can follow the procedures for a consultation and be adopted as such if and when the proposed species is listed. Should the tricolored bat be listed, agencies must review projects that are not yet complete, or projects with ongoing effects within the tricolored bat range that previously received a NE or NLAA determination from the key to confirm that the determination is still accurate. Projects that receive a may affect determination for tricolored bat through the key, should contact the appropriate Ecological Services Field Office if they want to conference on this species.

Other Species and Critical Habitat that May be Present in the Action Area

The IPaC-assisted determination key for the northern long-eared bat and tricolored bat does not apply to the following ESA-protected species and/or critical habitat that also may occur in your Action area:

- Monarch Butterfly *Danaus plexippus* Proposed Threatened
- Suckley's Cuckoo Bumble Bee *Bombus suckleyi* Proposed Endangered
- Western Regal Fritillary *Argynnis idalia occidentalis* Proposed Threatened
- Whooping Crane *Grus americana* Experimental Population, Non-Essential

You may coordinate with our Office to determine whether the Action may cause prohibited take of the species listed above.

Conclusion

Further coordination with the Service is voluntary for those species with a determination of “May Affect.” A “May Affect” determination in this key indicates that the project, as entered, is not consistent with the questions in the key. Not all projects that reach a “May Affect” determination are anticipated to result in adverse impacts to listed species. Through the technical assistance process, the Service might be able to provide information that either indicates incidental take is not reasonably certain to occur, or the Service might be able to provide recommendations that enable the project to be conducted in a way that avoids the likelihood of incidentally taking listed bats. Please contact our Minnesota-Wisconsin Ecological Services Field Office for more information. The Service has developed interim voluntary guidance for non-federal actions involving forest habitat modification that may affect the northern long-eared bat. Review the guidance posted here for more information for NLEB: https://www.fws.gov/species/northern-long-eared-bat-myotis-septentrionalis and TCB: https://www.fws.gov/species/tricolored-bat-perimyotis-subflavus

Action Description
You provided to IPaC the following name and description for the subject Action.

1. Name

Niron Sartell Project

2. Description

The following description was provided for the project 'Niron Sartell Project':

> Niron Magnetics (Niron) proposes to construct a manufacturing facility that produces industrial magnets on an undeveloped site located on 4th Avenue South between Heritage Drive and 3rd Street South in Sartell, Minnesota. The process converts iron oxide into a magnetic material, iron nitride. The iron nitride is processed further and then pressed and formed into magnets of various shapes. The finished magnets are given a protective coating before shipping to customers. The processes may use gases or chemicals, and the specific processes and chemicals are still under development. The processes are enclosed and feedstocks are planned to be reused to the extent possible.
>
> Additional outdoor structures like tanks or reactor columns will be installed. Controls like secondary containment, stormwater ponds, and waste management will be employed in the operation of the facility. Site construction is anticipated to take up to four years and would be completed over two phases.
>
> A design change was implemented in January 2026 that increased the gross square footage above 200,000 square feet. The increase in proposed gross square footage was the result of adding a second floor to some buildings and did not expand the originally proposed and permitted overall ground disturbance footprint. The primary activities already completed are limited to preliminary grading and stockpiling of imported fill soil.

The approximate location of the project can be viewed in Google Maps: https://www.google.com/maps/@45.609588349999996,-94.20530387930691,14z


1050
STH AVE S
SUNSET AVE
MT THABOR RD
BENTON DR N
Mississippi River
RIVERSIDE AVE S

DETERMINATION KEY RESULT

Based on the answers provided, the proposed Action is consistent with a determination of “may affect” for a least one species covered by this determination key.

QUALIFICATION INTERVIEW

1. Does the proposed project include, or is it reasonably certain to cause, intentional take of listed bats or any other listed species?

   Note: Intentional take is defined as take that is the intended result of a project. Intentional take could refer to research, direct species management, surveys, and/or studies that include intentional handling/encountering, harassment, collection, or capturing of any individual of a federally listed threatened, endangered or proposed species?

   No

2. Is the action area wholly within Zone 2 of the year-round active area for northern long-eared bat and/or tricolored bat?

   Automatically answered
   No

3. Does the action area intersect Zone 1 of the year-round active area for northern long-eared bat and/or tricolored bat?

   Automatically answered
   No

4. Does any component of the action involve leasing, construction or operation of wind turbines? Answer 'yes' if the activities considered are conducted with the intention of gathering survey information to inform the leasing, construction, or operation of wind turbines.

   No

5. Is the proposed action authorized, permitted, licensed, funded, or being carried out by a Federal agency in whole or in part?

   Note for projects in Pennsylvania: Projects requiring authorization under Section 404 of the Clean Water Act and/or Section 10 of the Rivers and Harbors Act would be considered as having a federal nexus. Since the U.S. Army Corps of Engineers (Corps) has issued the Pennsylvania State Programmatic General Permit (PASPGP), which may be verified by the PA Department of Environmental Protection or certain Conservation Districts, the need to receive a Corps authorization to perform the work under the PASPGP serves as a federal nexus. As such, if proposing to use the PASPGP, you would answer ‘yes’ to this question.

   No

6. [Semantic] Is the action area located within 0.5 miles of a known bat hibernaculum or winter roost? Note: The map queried for this question contains proprietary information and cannot be displayed. If you need additional information, please contact your state wildlife agency.

   Automatically answered
   No

7. Does the action area contain any winter roosts or caves (or associated sinkholes, fissures, or other karst features), mines, rocky outcroppings, or tunnels that could provide habitat for hibernating bats?

   No

8. Does the action area contain (1) talus or (2) anthropogenic or naturally formed rock shelters or crevices in rocky outcrops, rock faces or cliffs?

   No

9. Will the action cause effects to a bridge?

   Note: Covered bridges should be considered as bridges in this question.

   No

10. Will the action result in effects to a culvert or tunnel at any time of year?

    No

11. Are trees present within 1000 feet of the action area?

    Note: If there are trees within the action area that are of a sufficient size to be potential roosts for bats answer "Yes". If unsure, additional information defining suitable summer habitat for the northern long-eared bat and tricolored bat can be found in Appendix A of the USFWS' Range-wide Indiana Bat and Northern long-eared bat Survey Guidelines at: https://www.fws.gov/media/range-wide-indiana-bat-and-northern-long-eared-bat-survey-guidelines.

    Yes

12. Does the action include the intentional exclusion of bats from a building or building-like structure? **Note:** Exclusion is conducted to deny bats' entry or reentry into a building. To be effective and to avoid harming bats, it should be done according to established standards. If your action includes bat exclusion and you are unsure whether northern long-eared bats or tricolored bats are present, answer "Yes." Answer "No" if there are no signs of bat use in the building/structure. If unsure, contact your local Ecological Services Field Office to help assess whether northern long-eared bats or tricolored bats may be present. Contact a Nuisance Wildlife Control Operator (NWCO) for help in how to exclude bats from a structure safely without causing harm to the bats (to find a NWCO certified in bat standards, search the Internet using the search term "National Wildlife Control Operators Association bats"). Also see the White-Nose Syndrome Response Team's guide for bat control in structures.

    No

13. Does the action involve removal, modification, or maintenance of a human-made building-like structure (barn, house, or other building) **known or suspected to contain roosting bats?**

    No

14. Will the action cause construction of one or more new roads open to the public?

    For federal actions, answer 'yes' when the construction or operation of these facilities is either (1) part of the federal action or (2) would not occur but for an action taken by a federal agency (federal permit, funding, etc.).

    No

15. Will the action include or cause any construction or other activity that is reasonably certain to increase average night-time traffic permanently or temporarily on one or more existing roads? **Note:** For federal actions, answer 'yes' when the construction or operation of these facilities is either (1) part of the federal action or (2) would not occur but for an action taken by a federal agency (federal permit, funding, etc.). .

    No

16. Will the action include or cause any construction or other activity that is reasonably certain to increase the number of travel lanes on an existing thoroughfare?

    For federal actions, answer 'yes' when the construction or operation of these facilities is either (1) part of the federal action or (2) would not occur but for an action taken by a federal agency (federal permit, funding, etc.).

    No

17. Will the proposed Action involve the creation of a new water-borne contaminant source (e.g., leachate pond, pits containing chemicals that are not NSF/ANSI 60 compliant)?

    Note: For information regarding NSF/ANSI 60 please visit https://www.nsf.org/knowledge-library/nsf-ansi-standard-60-drinking-water-treatment-chemicals-health-effects

    No

18. Will the proposed action involve the creation of a new point source discharge from a facility other than a water treatment plant or storm water system?

    No

19. Will the action include drilling or blasting?

    No

20. Will the action involve military training (e.g., smoke operations, obscurant operations, exploding munitions, artillery fire, range use, helicopter or fixed wing aircraft use at night)?

    No

21. Will the proposed action involve the use of herbicides or pesticides (e.g., fungicides, insecticides, or rodenticides)?

    No

22. Will the action include or cause activities that are reasonably certain to cause chronic or intense nighttime noise (above current levels of ambient noise in the area) in suitable summer habitat for the northern long-eared bat or tricolored bat during the active season?

    Chronic noise is noise that is continuous or occurs repeatedly again and again for a long time. Sources of chronic or intense noise that could cause adverse effects to bats may include, but are not limited to: road traffic; trains; aircraft; industrial activities; gas compressor stations; loud music; crowds; oil and gas extraction; construction; and mining.

    Note: Additional information defining suitable summer habitat for the northern long-eared bat and tricolored bat can be found in Appendix A of the USFWS' Range-wide Indiana Bat and Northern long-eared bat Survey Guidelines at: https://www.fws.gov/media/range-wide-indiana-bat-and-northern-long-eared-bat-survey-guidelines.

    No

23. Does the action include, or is it reasonably certain to cause, the use of permanent or temporary artificial lighting within 1000 feet of suitable northern long-eared bat or tricolored bat roosting habitat?

    Note: Additional information defining suitable summer habitat for the northern long-eared bat and tricolored bat can be found in Appendix A of the USFWS' Range-wide Indiana Bat and Northern long-eared bat Survey Guidelines at: https://www.fws.gov/media/range-wide-indiana-bat-and-northern-long-eared-bat-survey-guidelines.

    Yes

24. Will the action cause an increase in the extent of suitable forested habitat exposed to artificial lighting?

    Yes

25. Will the action use only downward-facing, full cut-off lens lights (with same intensity or less for replacement lighting) when installing new or replacing existing permanent lights?

    Or for those transportation agencies using the Backlight, Uplight, Glare (BUG) system developed by the Illuminating Engineering Society, will all three ratings (backlight, uplight, and glare) be as close to zero as is possible, with a priority of "uplight" of 0?

    Yes

26. Will the action direct any temporary lighting away from suitable northern long-eared bat or tricolored bat roosting habitat when bats may be present?

    Note: Additional information defining suitable summer habitat for the northern long-eared bat and tricolored bat can be found in Appendix A of the USFWS' Range-wide Indiana Bat and Northern long-eared bat Survey Guidelines at: https://www.fws.gov/media/range-wide-indiana-bat-and-northern-long-eared-bat-survey-guidelines.

    Yes

27. Will the action include tree cutting or other means of knocking down or bringing down trees, tree topping, or tree trimming?

    Yes

28. Is the project related to the production of coal, including projects that support the mining of coal, as well as the production and/or distribution of energy produced from coal?

    No

29. Will the proposed action occur exclusively in an already established and currently maintained utility right-of-way?

    No

30. Does the action include emergency cutting or trimming of hazard trees in order to remove an imminent threat to human safety or property? See hazard tree note at the bottom of the key for text that will be added to response letters

    Note: A "hazard tree" is a tree that is an immediate threat to lives, public health and safety, or improved property.

    No

31. Does the project intersect with the 0- 9.9% forest density category?

    Automatically answered
    Yes

32. Does the project intersect with the 10.0- 19.9% forest density category map?

    Automatically answered
    No

33. Does the project intersect with the 20.0- 29.9% forest density category map?

    Automatically answered
    No

34. Does the project intersect with the 30.0- 100% forest density category map?

    Automatically answered
    No

35. Will the action cause trees to be cut, knocked down, or otherwise brought down across an area greater than 0.5 acre in total extent?

    Yes

36. Does the action area intersect the northern long-eared bat species list area?

    Automatically answered
    Yes

37. [Semantic] Is the action area located within 0.5 miles of radius of an entrance/opening to any known NLEB hibernacula or winter roost? Note: The map queried for this question contains proprietary information and cannot be displayed. If you need additional information, please contact your State wildlife agency.

    Automatically answered
    No

38. [Semantic] Is the action area located within 0.25 miles of a culvert that is known to be occupied by northern long-eared or tricolored bats? **Note:** The map queried for this question contains proprietary information and cannot be displayed. If you need additional information, please contact your State wildlife agency.

    Automatically answered
    No

39. [Semantic] Is the action area located within 150 feet of a documented northern long-eared bat roost site?

    Note: The map queried for this question contains proprietary information and cannot be displayed. If you need additional information, please contact your State wildlife agency.Have you contacted the appropriate agency to determine if your action is within 150 feet of any documented northern long-eared bat roosts?

    Note: A document with links to Natural Heritage Inventory databases and other state-specific sources of information on the locations of northern long-eared bat roosts is available here. Location information for northern long-eared bat roosts is generally kept in state natural heritage inventory databases – the availability of this data varies by state. Many states provide online access to their data, either directly by providing maps or by providing the opportunity to make a data request. In some cases, to protect those resources, access to the information may be limited.

    Automatically answered
    No

40. Is suitable summer habitat for the northern long-eared bat present within 1000 feet of project activities?
    If unsure, answer "Yes."

    Note: Additional information defining suitable summer habitat for the northern long-eared bat and tricolored bat can be found in Appendix A of the USFWS' Range-wide Indiana Bat and Northern long-eared bat Survey Guidelines at: https://www.fws.gov/media/range-wide-indiana-bat-and-northern-long-eared-bat-survey-guidelines.

    Yes

41. Has a presence/probable absence summer bat survey targeting the northern long-eared bat following the Service's Range-wide Indiana Bat and Northern Long-Eared Bat Survey Guidelines been conducted within the project area?

    No

42. Does the action area intersect the tricolored bat species list area?

    Automatically answered
    Yes

43. Is the action area located within 0.5-mile of radius of an entrance/opening to any known tricolored bat hibernacula or winter roost?

    Note: The map queried for this question contains proprietary information and cannot be displayed. If you need additional information, please contact your state wildlife agency.

    Automatically answered
    No

44. [Semantic] Is the action area located within 0.25 miles of a culvert that is known to be occupied by northern long-eared or tricolored bats? **Note:** The map queried for this question contains proprietary information and cannot be displayed. If you need additional information, please contact your State wildlife agency.

    Automatically answered
    No

45. Has a presence/probable absence bat survey targeting the tricolored bat and following the Service's Range-wide Indiana Bat and Northern Long-Eared Bat Survey Guidelines been conducted within the project area?

    No

46. Is suitable summer habitat for the tricolored bat present within 1000 feet of project activities?
    (If unsure, answer ""Yes."")

    Note: If there are trees within the action area that may provide potential roosts for tricolored bats (e.g., clusters of leaves in live and dead deciduous trees, Spanish moss (Tillandsia usneoides), clusters of dead pine needles of large live pines) answer ""Yes."" For a complete definition of suitable summer habitat for the tricolored bat, please see Appendix A in the Service's Range-wide Indiana Bat and Northern long-eared Bat Survey Guidelines.

    Yes

47. Do you have any documents that you want to include with this submission?

    No

PROJECT QUESTIONNAIRE

Enter the extent of the action area (in acres) from which trees will be removed - round up to the nearest tenth of an acre. For this question, include the entire area where tree removal will take place, even if some live or dead trees will be left standing.

3.25

IPAC USER CONTACT INFORMATION

Agency:	Private Entity
Name:	Mia Bauer
Address:	One Carlson Parkway
Address Line 2:	Suite 100
City:	Plymouth
State:	MN
Zip:	55447
Email	mia.bauer@stantec.com
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Appendix F
GHG Calculations

Minnesota Climate Calculator: Project Summary Report

Date Prepared: 2/17/2026

The results shown below were generated using the Minnesota Climate Calculator. The emissions quantified account for the full greenhouse gas impact of a potential project throughout the construction and operational phases of the project. This includes emissions from project activities that occur on-site as well as emissions that occur upstream and downstream of the project. The results are based on user inputs and assumptions; actual project emissions may vary.

Background Information

Project Name	Niron Magnetics - Sartell Expansion
Project Category (primary)	Subp. 14, Industrial, commercial, institutional facilities
Project Category (secondary)	
Location (County)	Stearns
Construction Start Date	4/21/2026
Operational Year	2029
Operational Lifetime (Years)	50

Electricity Provider	Xcel Energy
Portion of Building Electricity Consumption to be Generated On-Site via Renewables or Supplied through the Purchase of Renewable Energy Credits (RECs)	0%
Portion of Building Natural Gas Consumption to be Supplied from Renewable Sources	0%

Building Construction Project?	Yes

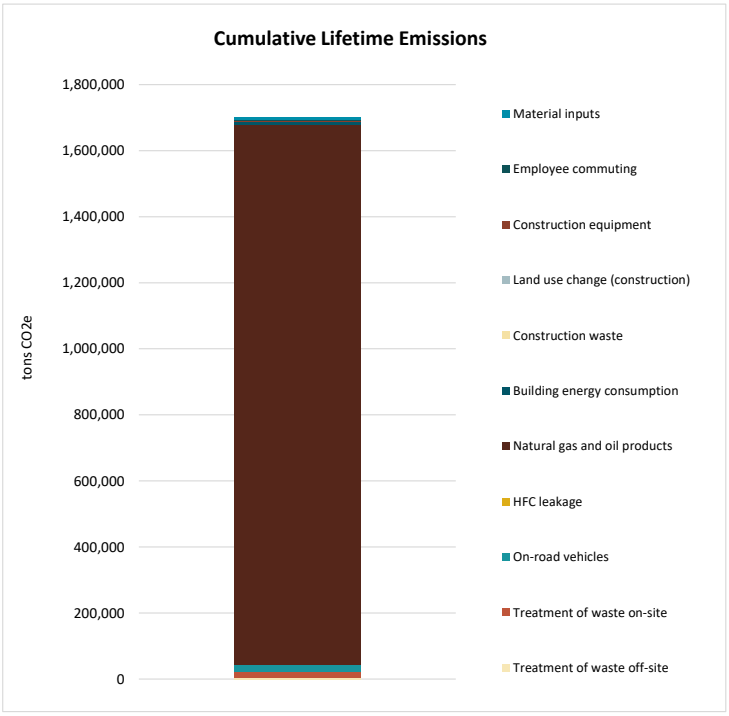
Construction Stage	Duration (Days)
Demolition	-
Site Preparation	39
Grading	77
Building Construction	609
Architectural Coatings	116
Paving and Landscaping	77

Summary Results

Project Lifetime	53
Unit	tons

Phase	CO_2e Emissions	
	Cumulative	Annualized
Construction		
Material inputs	6,187.16	116.74
Transportation of material inputs	141.52	2.67
Employee commuting	2,710.03	51.13
Construction equipment	1,509.52	28.48
Land use change (construction)	6.21	0.12
Construction waste	0.01	0.00
Operation		
Building energy consumption	11,217.99	211.66
Coal production	NA	NA
Natural gas and oil products	1,633,560.58	30,821.90
Industrial processes	NA	NA
HFC leakage	1,347.86	25.43
Land use change (operations)	NA	NA
On-road vehicles	19,786.20	373.32
Treatment of waste on-site	NA	NA
Treatment of wastewater on-site	NA	NA
Treatment of waste off-site	3,243.89	61.21
Enteric fermentation	NA	NA
Manure management	NA	NA
Total	**1,679,710.97**	**31,692.66**

Note: NA indicates that emissions were not quantified and/or are not applicable.



User Inputs

Note: NA indicates that emissions were not quantified and/or activity is not applicable.

Material Inputs

Material Type	Quantity	Unit	Geographical Sourcing
Aluminum	0.00	Tons	Unknown
Asphalt	741.64	Tons	Domestic
Brick	11.98	Tons	Domestic
Concrete	11,587.00	Cubic yards	Domestic
Glass	8.60	Tons	Domestic
Insulation (residential)	0.00	Tons	Domestic
Insulation (commercial)	158,000.00	Square feet	Domestic
Steel	1,360.00	Tons	Domestic
Wood Products	0.00	Tons	Domestic

Employee Commuting

Construction Stage	Daily Average Number of Employees Commuting
Demolition	0
Site Preparation	300
Grading	300
Building Construction	300
Architectural Coatings	300
Paving and Landscaping	300

Transportation Mode	Percent of Employees
Single Occupancy Vehicle	82%
Carpool	11%
Motorcycle	0%
Bus	2%
Transit Rail	2%
Bike/Walk	3%

Average One-Way Commute Length (miles)	13.2

Construction Equipment

Equipment Type	Fuel Type	Number of Hours per Day by Construction Stage					
		Demolition	Site Preparation	Grading	Building Construction	Architectural Coatings	Paving and Landscaping
Air Compressors	Diesel	0	0	0	0	6	0
Cement and Mortar Mixers	Diesel	0	0	0	0	0	0
Concrete/Industrial Saws	Diesel	0	0	0	0	0	0
Cranes	Diesel	0	0	0	7	0	0
Excavators	Diesel	0	0	16	0	0	0
Forklifts	Diesel	0	0	0	24	0	0
Generator Sets	Diesel	0	0	0	8	0	0
Graders	Diesel	0	0	8	0	0	0
Pavers	Diesel	0	0	0	0	0	16
Paving Equipment	Diesel	0	0	0	0	0	16
Rollers	Diesel	0	0	0	0	0	16
Rubber Tired Dozers	Diesel	0	24	8	0	0	0
Scrapers	Diesel	0	0	16	0	0	0
Tractors/Loaders/Backhoes	Diesel	0	32	16	21	0	0
Welders	Diesel	0	0	0	8	0	0

Land Use Change

Land Use Type	Acres		
	Pre-Construction	Post-Construction	Post-Operation
Wetlands, forested	0.00	0.00	NA
Wetlands, not forested	7.88	7.88	NA
Forest	11.51	9.51	NA
Rivers and streams	0.00	0.00	NA
Brush and grassland	43.50	11.20	NA
Cropland	0.00	0.00	NA
Livestock rangeland/pastureland	0.00	0.00	NA
Lawn/landscaping	0.00	5.70	NA
Green Infrastructure: Constructed wetlands, paved	0.00	0.00	NA
Green Infrastructure: Constructed wetlands, vegetated	0.00	0.00	NA
Green Infrastructure: Constructed green roofs	0.00	0.00	NA
Green Infrastructure: Constructed permeable pavements	0.00	0.00	NA
Impervious surface	0.00	23.60	NA
Stormwater pond (wet sedimentation basin)	0.13	5.13	NA

Trees	Number
Number of mature trees removed	261
Number of new trees planted	0

Construction Waste

Material Type	Quantity (tons)
Aluminum	0.00
Asphalt	0.00
Brick	0.04
Concrete	0.03
Glass	0.03
Insulation	0.10
Steel	0.00
Wood Products	0.05
Mixed Waste	0.00

Building Energy Consumption

Building Type	Energy Intensity (Btu/sq ft/year)			
	Electricity	Natural Gas	Propane	Kerosene or Fuel Oil
Residential	18,096.91	24,460.01	3,619.38	233.51
Commercial	30,766.13	35,534.88	0.00	1,661.56
Industrial	229,952.20	0.00	0.00	0.00
Institutional	46,860.06	48,219.03	0.00	3,659.93
Other	0.00	0.00	0.00	0.00

Emissions from Coal Production

Coal Type	Incremental Production (tons/year)
Mixed Coal	NA
Anthracite Coal	NA
Bituminous Coal	NA
Subbituminous Coal	NA
Lignite Coal	NA
Coal Coke	NA

Emissions from Natural Gas and Oil Products

Fuel Type	Incremental Throughput	Unit
Natural Gas	443407407.41	Cubic Feet/year
Renewable Natural Gas	0.00	Cubic Feet/year
Propane	0.00	Gallons/year
Gasoline	0.00	Gallons/year
Distillate Fuel Oil No. 1	0.00	Gallons/year
Distillate Fuel Oil No. 2	0.00	Gallons/year
Distillate Fuel Oil No. 4	0.00	Gallons/year
Residual Fuel Oil No. 5	0.00	Gallons/year
Residual Fuel Oil No. 6	0.00	Gallons/year
Liquified Petroleum Gas (LPG)	0.00	Gallons/year
Kerosene	0.00	Gallons/year
Kerosene Jet Fuel	0.00	Gallons/year
Biodiesel 100	0.00	Gallons/year
Biodiesel 20	0.00	Gallons/year
Renewable Diesel	0.00	Gallons/year

Natural Gas Assumptions

Percent Reduction in Leakage and Venting Emissions	0%
Leakage and Venting Emissions ($kgCO_2e$/MMBtu)	4.28

Industrial Processes

Product Type	Quantity (tons/year)	Emission Factor ($kgCO_2e$/ton)
Cement	NA	NA
Lime	NA	NA
Limestone Use	NA	NA
Magnesium	NA	NA
Iron and Steel	NA	NA
Ammonia	NA	NA
Aluminum	NA	NA
Nitric Acid	NA	NA

HFC Leakage

Building Type	Percent of Building Area Utilized
Residential	100%
Commercial	100%
Industrial	100%
Institutional	100%

On-Road Vehicles

Speed Bin (miles/hr)	Additional VMT (miles/year)
Fleet Average	1316607
0-30	0
31-55	0
56-75	0

Treatment of Waste On-Site

Waste Treatment Practice	Quantity of Waste Treated (tons/year)
	NA
	NA
	NA

Treatment of Wastewater On-Site

Population Served by Treatment Plant	NA

Product Type	Production (MT/year)
	NA

Treatment of Waste Off-Site

Activity	Quantity	Waste Generation Rate	Unit
Number of single family households	0	7.00	lb/household/day
Number of employees (commercial)	0	10.53	lb/employee/day
Number of employees (industrial)	70	8.93	lb/employee/day
Number of employees (institutional)	0	3.55	lb/employee/day
Visitors per year (public venues)	0	1.72	lb/visitor

Waste Treatment Practice	Percent of Waste
Recycled	0%
Composted	0%
Landfilled	57%
Combusted	43%

Enteric Fermentation and Manure Management

Livestock Type	Population	Percentage of Manure Management System											
		Anaerobic digester	Anaerobic lagoon - liquid	Cattle deep litter	Composting	Daily spread	Deep pit	Dry lot	Liquid/ slurry	Pasture, range, paddock	Poultry with litter	Poultry without litter	Solid storage
Bulls	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Beef cows	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Beef heifers	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Steer stockers	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Heifer stockers	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Feedlot beef	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Beef calves	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Dairy heifers	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Dairy cows	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Dairy calves	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Swine, <55 lbs	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Swine 55-330 lbs	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Swine 330+ lbs	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Poultry, layers	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Poultry, pullets	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Poultry, chickens	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Poultry, broilers	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Turkeys	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA

Percent of manure applied or sold for application to agricultural soils (pasture or cropland) as fertilizer	0%

Notes

General Notes	Emissions from the transportation of fill material and miscellaneous deliveries are not included in the Minnesota Climate Calculator spreadsheet and are provided separately. See the "Niron GHG Summary & Delivery Trucks_02-10-2026" spreadsheet for a summary of all project emissions.
Material inputs	Material estimates provided by Wood PLC. Aluminum usage is unknown. Wood usage is expected to be negligible. Density of asphalt assumed to be 1.1 kg/L from AP-42 Chapter 4.5 (7/79). Density of brick assumed to be 130 lb/ft3. Density of glass assumed to be 2.5 g/cm3 (156 lb/ft3).
Transportation of material inputs	All material will be sourced domestically. Emissions from the transportation of fill material and miscellaneous deliveries are not included in the Minnesota Climate Calculator spreadsheet and are provided separately.
Employee commuting	Estimate provided by Wood PLC. Site is greenfield, so no commuting is assumed for the demolition project phase.
Construction equipment	Default estimates from Minnesota Climate Calculator used. No demolition assumed as the site is greenfield.
Land use change (construction)	Provided by Niron. The number of trees to be replanted is currently unknown.
Construction waste	Default estimates from Minnesota Climate Calculator used.
Building energy consumption	Default estimates for industrial building types from Minnesota Climate Calculator used. The facility will not be used for residential, commercial, or institutional purposes.
Coal production	Not applicable to facility operations.
Natural gas and oil products	Natural gas-fired equipment includes heaters, industrial equipment, and emergency generators. Heaters and industrial equpiment assumed to operate 8,760 hours/yr. Emergency generators assumed to operate 500 hours/yr.
Industrial processes	Greenhouse gas emissions from facility industrial processes are from the combustion of natural gas and are included in emission calculations for natural gas and oil products.
HFC leakage	Default estimates for industrial building types from Minnesota Climate Calculator used.
Land use change (operations)	Not applicable to facility operations.
On-road vehicles	Assuming an average of 70 employees/day and 15 delivery trucks/week during operation and a daily commute of 50 miles/day per employee and per delivery truck. The fleet average speed was used.
Treatment of waste on-site	Not applicable to facility operations.
Treatment of wastewater on-site	Assuming an average of 70 employees/day only from industrial use. The facility will not be used for residential, commercial, or institutional purposes. Default waste generation rates were used.
Treatment of waste off-site	Default estimates from Minnesota Climate Calculator used.
Enteric fermentation	Not applicable to facility operations.
Manure management	Not applicable to facility operations.
Mitigation Measures	
Adaptation Strategies	

Niron GHG Summary and Delivery Trucks
GHG Emissions Summary

Scope	Project Phase	Cumulative CO2e Emissions (tons)	Annualized CO2e Emissions (tons)
Combustion (On-Road Mobile Sources)	Construction	3,239	61
Combustion (Off-Road Mobile Sources)	Construction	1,510	28
Building Materials	Construction	6,187	117
Land Use Change	Construction	6.21	0.12
Construction Emissions		**10,942**	**206**
Combustion (Stationary Sources)	Operation	1,633,561	30,822
Combustion (Mobile Sources)	Operation	19,786	373
HFC Leakage	Operation	1,348	25
Purchased Electricity	Operation	11,218	212
Off-Site Waste Management	Operation	3,244	61.2
Operation Emissions		**1,669,157**	**31,494**
Total Emissions		**1,680,098**	**31,700**

Construction Emissions - Mobile Sources
On-Road Delivery Vehicles During Construction

Duration of Construction =	3	years
Project Lifetime	50	years (estimate)
Construction and Delivery Trucks, Fill[1]	121,377	CY LV fill
	17	CY LV fill per truck
	7,140	trucks (total)
Construction and Delivery Trucks, General[1]	25	deliveries/week
	1300	deliveries/year
Truck Travel[1]	22	miles/trip (total)

							GHG Emission Factors[3]			Annualized (During 3 Years of Construction)				Annualized Over Project Lifetime GHG Emissions (metric tons per year)				Annualized (During 3 Years of Construction)				Annualized Over Project Lifetime GHG Emissions (short tons per year)			
Emissions Source	**Quantity of Round Trips Annually**	**Fuel Type**	**Miles per Round Trip[1]**	**Miles per Gallon[2]**	**Total Miles Annually**	**Total Fuel Usage (gal)/Year**	**CO2 (kg/gal)**	**CH4 (g/mile)**	**N2O (g/mile)**	**CO2**	**CH4**	**N2O**	**CO2e**	**CO2**	**CH4**	**N2O**	**CO2e**	**CO2**	**CH4**	**N2O**	**CO2e**	**CO2**	**CH4**	**N2O**	**CO2e**
Construction and Delivery Trucks																									
Diesel Construction & Delivery/Removal Vehicles (Model Years 2007-2022)	3,680	Diesel	22	7.1	80,959	11,403	10.21	0.01	0.043	116	7.69E-04	3.49E-03	117	6.59	4.35E-05	1.98E-04	6.64	128.1	8.46E-04	3.84E-03	129.1	7.25	4.79E-05	2.17E-04	7.31

1. Estimate
2. Average mpg values from the U.S. Department of Transportation, Federal Highway Administration, Highway Statistics 2024 (Updated February 2026), Table VM-1.
3. Source: U.S. EPA Emission Factors Hub (https://www.epa.gov/system/files/other-files/2025-01/ghg-emission-factors-hub-2025.xlsx)
4. On-road vehicle emissions for employees and the delivery of all other construction materials are calculated separately using EQB's Minnesota Climate Calculator.

Stantec

Stantec is a global leader in sustainable engineering, architecture, and environmental consulting. The diverse perspectives of our partners and interested parties drive us to think beyond what's previously been done on critical issues like climate change, digital transformation, and future-proofing our cities and infrastructure. We innovate at the intersection of community, creativity, and client relationships to advance communities everywhere, so that together we can redefine what's possible.

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Item 18 Greenhouse Gas (GHG) Emissions/Carbon Footprint

The guidance provided below will assist proposers and their consultants in responding to Item 18 Greenhouse Gas (GHG) Emissions/Carbon Footprint in the Environmental Assessment Worksheet (EAW) form. For additional guidance on greenhouse gas emissions calculations and Item 18, refer to the Minnesota Environmental Quality Board (EQB) EAW guidance for climate and adaptation and resilience.

18a. GHG quantifications

This section provides recommendations of tools to quantify GHG emissions, in which MPCA is the responsible government unit (RGU) per Minn. R. 4410.4300.

MPCA recommends users start with either the EQB Calculator or EPA's Simplified GHG Emissions Calculator (SEGC). Where available, additional tools can provide more refined results because of the requirement of detailed information. While most of tools recommended were designed by different organizations with different audience/purposes, and not EAW's for the State of Minnesota; after careful review, MPCA has determined that these tools are acceptable for use in an EAW application.

The level of data input and in-depth knowledge of the project varies with each tool. More refined data input can result in more refined results.

There are two sections necessary in quantifying GHG emissions under 18a:

- Construction: This includes GHG emissions associated with the construction of the project (i.e. new roads, new buildings, increasing land use for landfills). Project proposers should evaluate:
  - materials used during the constructions (i.e. tons of concrete, asphalt, etc.)
  - mobile emissions including construction equipment and increased traffic because of the construction work,
  - any change in land use (i.e. grassland converted to an impervious surface because of a new building); and
  - construction waste (i.e. any material that is disposed of because of the project).
- Operations: This includes GHG emissions associated with the day-to-day activities for the project such as:
  - combustion emissions from mobile equipment (i.e. vehicle activity such as transporting waste from the site to another location)
  - combustion from stationary equipment (i.e. energy consumption/usage from building operations)
  - non-combustion stationary equipment (i.e. enteric fermentation or wastewater treatment projects); and
  - waste management emissions (i.e. unwanted material that leaves the site)

Depending on the project, project proposers and their consultants may need to use a combination of tools to address all components of the project.

Note to Proposer: Some tools have other capabilities are not discussed in this document. Outputs of the tools vary. Users should convert units to short tons per year.

Table 1: GHG calculators.

Calculator name	Website	User guide link	Applicability (EAW category)	Description	Limitations (related to preparing EAWs)
Minnesota Climate Calculator	Climate assessments | Minnesota Environmental Quality Board	Climate Calculator, Version 1.1 Additional supporting guidance documents: • Anaerobic Digester Guide. • Feedlot Guide. • Wastewater Guide. • Landfill Guide.	All categories (with limitations)	An excel-based calculator designed specifically to address the quantification of GHG emissions from any potential project submitting an EAW.	Depending on the project category, the tool may be limited by the defaults or data entry. For example, the tool does not address the land application of biosolids from wastewater treatment plants.
EPA's Simplified GHG Emissions Calculator	Simplified GHG Emissions Calculator | US EPA	Simplified Guide to Greenhouse Gas Management for Organizations	All categories (with limitations)	An excel-based calculator designed to quantify emissions from several emission sources. This tool is excellent for quantifying emissions from mobile sources.	The tool does not provide calculation for emissions from feedlots and wastewater.
MPCA's Feedlot Tool	p-ear1-14a.xlsx	MPCA Feedlot Tool User's Guide	Subp. 29 Animal feedlots	A Minnesota specific excel-based calculator designed specifically to address the quantification of GHG emissions from feedlots (cattle, swine, and poultry).	There is limited customization of manure management strategies.
COMET Farm Tool	COMET-Farm Login	Quantifying Greenhouse Gas Fluxes in Agriculture and Forestry: Methods for Entity-Scale Inventory	Subp. 29 Animal feedlots	Web-based accounting tool that provides a full GHG assessment from on-farm emission sources based on specific operational inputs such as manure management strategies, feed, and housing.	Requires a high level of data input (such as crude protein).
Energy Performance and Carbon Emissions Assessment	ECAM v3	UserManual_FinalVersion.pdf Additional supporting guidance document:	Subp. 18 Wastewater systems	Web-based tool to model GHG emissions from the Urban Water Sector. For EAWs, a project proposer should only focus on the treatment stage. A support document is available to help	Requires a high level of data input (such as nitrogen load in the influent).

Calculator name	Website	User guide link	Applicability (EAW category)	Description	Limitations (related to preparing EAWs)
and Monitoring Tool		ECAM Guidance		project proposers understand how to use the tool to respond to EAW item 18.	
GREET 2025	GREET | Department of Energy 45ZCF-GREET	Guidelines to Determine Life Cycle Greenhouse Gas Emissions of Clean Transportation Fuel Production Pathways Using 45ZCF-GREET	Subp. 5 Fuel conversion	There are multiple excel-based GREET Models. Project Proposers of fuel conversion projects, such as ethanol production, should use the 45ZCF-GREET Model.	Requires a high level of data input and thorough understanding of the inputs. Certain parameters are fixed and may not be changed by the user.
WARM	Versions of the Waste Reduction Model | US EPA	Documentation Chapters for Greenhouse Gas Emission, Energy and Economic Factors Used in the Waste Reduction Model | US EPA	Subp. 5 Fuel Conversion and Subp. 17 Solid waste	Excel-based comparative tool for reviewing the differences in GHG emission across different waste management practices.	The tool does not include biosolids from wastewater treatment facilities, nor manure from feedlots.
Anaerobic Digestion Screening Tool	Anaerobic Digestion Screening Tool | Global Methane Initiative	User Manual, AD Screening Tool	EAWs where ADs are involved.	Excel-based tool designed as a pre-feasibility screening for multi-feedstock ADs. This tool can factor in multiple sources and combinations of feedstock, including biosolids from wastewater, animal manure, and municipal solid wastes.	Requires a high level of data input.

18b. GHG assessment

This section asks project proposers to discuss the possible mitigation of GHG emissions in three parts:

- Identify reasonably available mitigation options. Describe strategies or technologies that reduce construction and/or operational emissions (e.g., material substitutions, electrification of on-site equipment and fleets, energy efficiency, methane capture, organics diversion, process changes).
- Quantify expected reductions. For each selected mitigation, proposers should attempt to quantify the reduction in per year and summarize key assumptions so a reviewer could reproduce the estimate. Explain why a mitigation strategy is preferred.
- Discuss net lifetime emissions and state goals. Provide the project's net lifetime discuss alignment with Minnesota Next Generation Energy Act goals.

Further reading

For more information related to these topics visit:

- Revised Environmental Assessment Worksheet (EAW) Guidance
- Climate Action Framework | Our Minnesota Climate
- Greenhouse gas emissions in Minnesota 2005-2022 Legislative Report
- Intergovernmental Panel on Climate Change Assessment Report (IPCC 6)
- 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories

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TOPICAL REVIEW

Underestimates of methane from intensively raised animals could undermine goals of sustainable development

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Abstract

Greenhouse gas emissions from meat and dairy production are often highly uncertain; these emissions are typically estimated using inventory-based, 'bottom-up' models, which contain uncertainties that are difficult to quantify. Modeled emissions estimates can be corroborated using atmospheric measurements—taken above and downwind of animal production regions—to produce 'top-down' emissions estimates. Top-down and bottom-up estimates of animal methane show good agreement when considering global emissions. However, in the US, where animal production is predominantly highly intensified with confined feeding operations, animal methane emissions may be 39%–90% higher than bottom-up models predict (expressed as mean differences across studies). Animal emissions may grow in the future as meat and dairy demand increases in developing countries. We examine East and Southeast Asia as a test case, where emissions from increased meat and dairy production are expected to be offset by improved efficiency from intensive methods. We adjust the share of direct emissions projected to come from intensive systems by the intensities derived from US top-down estimates. We find that region-wide emissions from meat and milk production could reach 1.52 (1.41–1.62) $GtCO_2eq$ by 2050, an amount 21% (13%–29%) higher than previously predicted. Therefore, intensification may not be as effective in mitigating emissions in developing countries as is commonly assumed.

1. Introduction: the role of intensification in sustainable development

Global meat consumption is expected to increase by 50% in the coming decades (FAO 2018a). This increase is primarily driven by rising affluence in developing low- and middle-income countries. Animal agriculture has been reported to represent 15.6% of total annual greenhouse gas (GHG) emissions globally (FAO 2017 using a 100 year global warming potential (GWP_{100}) for non-CO_2 GHGs), with emissions expected to increase in the coming decades.

Limiting GHGs from agriculture is urgent because business-as-usual agricultural growth is likely incompatible with limiting warming below 1.5 °C (Clark *et al* 2020). Reducing emissions from food systems is therefore urgent, even in scenarios in which fossil fuel usage is rapidly phased out. Sustainable intensification offers a possible solution; it is defined as the production of more meat and dairy with fewer resources, like land and feed, and lower emissions per animal (Godfray *et al* 2010).

The majority of global agricultural emissions are estimated to come from lower efficiency, pastoral systems (Steinfeld *et al* 2006). These systems include long-range grazing, backyard, and mixed crop-livestock systems, although the latter category has wide variation, and could count as intensive or semi-intensive depending on the specifics of the system (Robinson *et al* 2011). These forms of animal agriculture are referred to as extensive production systems because of their larger land footprint, and they are becoming less common globally (Gerber *et al* 2013).

Conversely, intensive production systems, like those in North America and the EU, are likely

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responsible for fewer direct and indirect emissions, in total and per unit of meat or dairy produced (Gerber *et al* 2013). Intensively managed animals in these regions are often raised in 'landless' systems (as defined by the UN Food and Agriculture Organization, FAO), where feed inputs are traded commodities and are largely detached from the immediate local resource base (Robinson *et al* 2011). Animals like pigs and chickens are highly confined for all of their lives, while beef cattle spend the latter part of their lives being 'finished' on enriched feeds in feedlots. These systems in the US are also referred to as concentrated animal feeding operations (CAFOs). However, this term is a more stringent categorization—as CAFOs may not include a number of smaller-scale facilities that are nonetheless highly industrialized and entail confinement.

Animal feeding in intensive, landless systems is oriented toward rapid weight gain and productivity (Robinson *et al* 2011). Animals live shorter lives relative to extensively-raised animals to optimize feed requirements and other input resources (Herrero *et al* 2013). Intensive systems for raising chickens, pigs, and dairy cows, and facilities for fattening or 'finishing' mature beef cattle to reach market weight in the North America restrict animal movement. Intensive landless systems typically do not allow for the expression of natural behaviors, access to pasture, or the ability to graze or forage for food. This type of animal agricultural production, often referred to as 'industrialized production', is now proliferating globally through developing low- and middle-income countries.

Intensively-raised animal-sourced foods have lower land and feed requirements, relative to extensively-raised animal-sourced foods (Swain *et al* 2018). The benefits of improved feed requirements are commonly assumed to include fewer GHG emissions: both lower indirect emissions from feed production and grazing, and fewer direct emissions from wastes like manure, urine, and belches, per unit of food produced. However, the aggregate air and water pollution from landless facilities, along with resource depletion of fresh water, can create local problems and contribute to environmental degradation (Carrel *et al* 2016, Richter *et al* 2020).

Researchers have therefore recommended intensifying existing extensive and pastoral systems to reduce GHG emissions (e.g. Steinfeld *et al* 2006, Thornton and Herrero 2010, Swain *et al* 2018). North American meat and dairy companies frequently claim that their emissions are improving, directly attributing this trend toward more intensive management practices (Cattlemen's Beef Board 2018, McDonald's Canada 2018, National Pork Board 2020). In unity with these messages, governments and nongovernmental organizations alike have promoted intensification for food security, environmental improvements, and GHG mitigation in low and middle-income countries (De Oliveira Silva *et al* 2018, FAO 2018b, Enahoro *et al* 2019, ILRI 2019). International development banks further incentivize intensive methods through conditional lending and low-interest loans for confined production infrastructure (Wasley and Heal 2020, World Bank International Finance Corporation 2020).

Extensive production methods currently predominate in low- and middle-income regions. Animal-sourced food consumption is also likely to grow as these countries develop economically (Alexandratos and Bruinsma 2012), with rising population and rising income-related dietary shifts. However, there is an ongoing shift toward intensification in these countries, both as an economic response to rising meat and dairy production and government agendas to develop economies through 'green revolution' type programs of achieving efficiency through intensification.

This shift toward intensification is expected to offset a substantial fraction of GHG emissions. In the greater East and Southeast Asia (ESA) region, an area of both rapid consumption growth and industrialization, these two trends are expected to approximately counter-balance one another, with 39% more meat consumption in 2050 relative to present day, but little net change in total emissions (FAO 2018a), credited to the efficiency of intensification.

However, the hypothesis that intensification leads to GHG emissions mitigation, in particular that this mitigation is large enough to offset projected increases in production and consumption, has not been corroborated through independent assessments. The following review describes the model-based methods in which GHGs from animal-sourced food production are typically assessed and forecasted. We then contrast this approach with recent atmospheric measurement-based methods, along with a discussion of both methods' inherent uncertainties. Lastly, we conclude with a test case analyzing commonly-accepted emissions projections, adjusting the projection from ESA intensive systems by the same degree to which present-day emissions from North American intensive systems are possibly biased. These prospective results imply that emissions may increase in the region through 2050, contrary to existing predictions that they will plateau or decrease after 2030. This case study has important implications for the standard paradigm of agricultural development in low- and middle-income countries, as it implies that the GHG mitigation benefits of intensification may be overestimated.

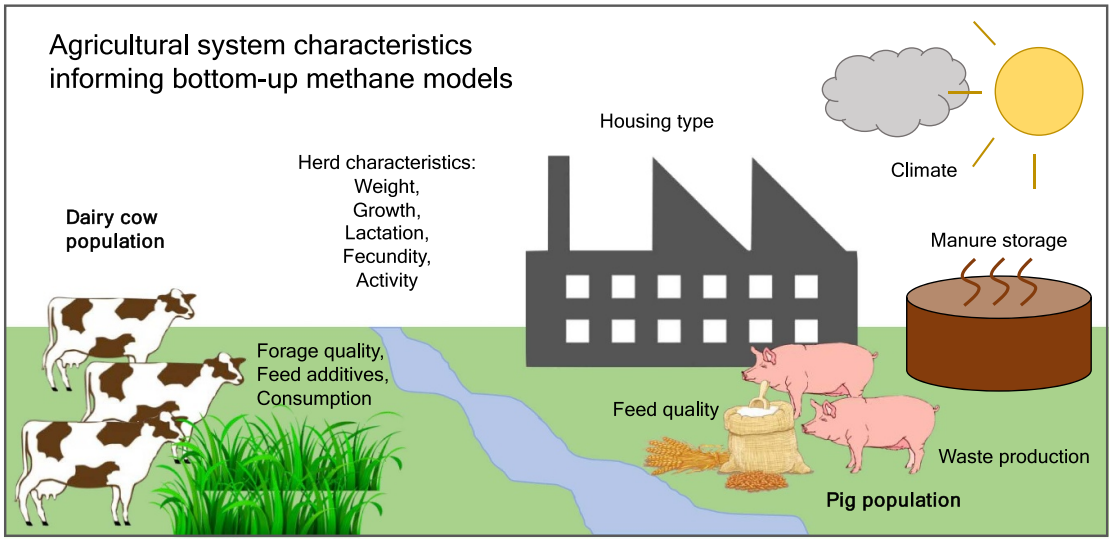


Figure 1. Characteristics of dairy cow and pig herds accounted for in bottom-up methane emissions models. Models use input variables, which are listed within this diagram and contain uncertainties, to calculate total enteric fermentation and manure management methane emissions. Models relate input variables to methane emissions using parameters (not shown), which also contain uncertainties.

2. Quantifying progress toward sustainable emissions

2.1. Bottom-up estimates of animal emissions

Present-day estimates of total GHG emissions in a given region are rarely measured directly. Rather, emissions estimates are based on animal emission models. Such models collect and integrate detailed information from multiple animals and production regions through counting, interviewing, and census-taking. Emissions models are referred to as 'bottom-up' estimates, because detailed information is collected at the ground-level, then multiplied and added up to calculate total emissions.

The predominant GHG from animal agriculture is methane. Methane is produced by enteric fermentation and manure management. Methane represents 50% of all animal emissions (direct + indirect) and 92% of direct animal emissions (FAO 2017).

Bottom-up estimates of methane are created by tallying up populations of each type of animal, known as activity data. These data are then multiplied by emissions factors—estimates of gas emitted by each animal daily or each operation annually. Separate emission factors are generally used for (a) enteric fermentation (belches) and the (b) handling and storage of their manure. Animal populations are subsequently multiplied by animal- and region-specific emissions factors, yielding an estimate of direct emissions produced. Bottom-up models are often also used to estimate indirect emissions from feed production and manure application to fields. However, this review mostly concerns direct emissions of animal agriculture, with some exceptions.

Emissions factors are calculated using detailed equations, provided in the IPCC guidelines of the Fourth Global Assessment Report (Dong *et al* 2006) and its 2019 refinement report (Gavrilova *et al* 2019). Multiple levels of detail or 'tiers' of estimates are provided, corresponding to different levels of aggregation and coarseness. Emissions factors are calculated at Tier 1 with fixed tabular values, Tier 2 with the more detailed equations that are standardized by the IPCC, or Tier 3 which are considered rigorous and detailed methods that are country-specific but nonetheless subjected to international peer review (Dong *et al* 2006). Each level reflects processed-based detailed input information on how animals are raised in each region, differing mainly in what level of detail is included by the modeler. The resulting emissions factors describe how much methane and nitrous oxide an average animal from each herd directly emits per day or year.

The development of these emissions factors requires information on how animals are raised in each region, including feed, physical activity, manure disposal, and local climate, along with their productivity, such as weight gain, lactation amount, and breeding rate (figure 1). Most of these local production and environmental characteristics are required inputs for all tiers of IPCC methods—including Tier 1 methods that rely on IPCC emissions factors and Tier 2 and 3 methods that provide detailed models that allow users to calculate their own emission factors. The remainder of this discussion will focus predominantly on Tier 2 emissions to provide a standard, if simplified framework for understanding, but there are commonalities among all three tiers.

The details used to develop methane emission factors can be incredibly fine-grained and include information on how much an average animal moves during a day, whether or not a dried crust is allowed

to form on top of the slurry tanks that handle liquid manure, the temperatures of a given animal operation and the seasonal cycle of weather conditions, and other highly specific details. This detailed information can be challenging to collect, even for countries with detailed agricultural censuses (Hristov *et al* 2017).

Detailed input information in bottom up emissions estimates contributes to their precision—the degree to which estimates can detect changes between one system or another. However, this detail does not guarantee estimates that are accurate—close to the true, real-world value. As more details are added and multiplied within the models, the model errors tend to increase. The errors in totaled emissions estimates are therefore considerably more uncertain than any single input. Ultimately, bottom-up estimates require simplifying assumptions and extrapolation from representative systems. They therefore may contain large uncertainties and compounding errors (Miller *et al* 2014, Miller and Michalak 2017) that make emissions difficult to accurately quantify, including estimates contained in national inventory reports.

The uncertainty envelopes in bottom-up emissions inventories may be underestimated, and are difficult to compare and scrutinize in existing sources. Uncertainties are required in the reporting from all UNFCCC annex-1 countries, including the United States. However, uncertainty ranges are not easily discoverable, are missing from a number of UNFCC reports and web portals, and do not clearly identify which types of the multiple types of model uncertainty they consider. The United States' inventory includes mention of uncertainty analysis performed on 185 input variables and categories, and reports resulting errors for enteric fermentation methane of approximately ±15% (US EPA O 2021). The details of the assessment are vague, stating that uncertainties for input variables 'were collected from published documents and other public sources; others were based on expert opinion and best estimates'. Conversely, the IPCC methodology states that Tier 1 and 2 uncertainty estimates for enteric fermentation may be on the order of 50% (Dong *et al* 2006), a substantially larger range than the US EPA and most other bottom up emissions inventories report. The 2019 update states that uncertainty estimates for enteric fermentation contains 'no refinement' (Gavrilova *et al* 2019). Uncertainty ranges in bottom-up estimates are possibly too small, even though they are intended to be fully comprehensive.

Furthermore, bottom-up inventories uncertainties often do not reflect uncertainties arriving from model structure and parameter selection, referred to as epistemic uncertainty (Sykes *et al* 2019), instead reflecting uncertainties arriving from input data. Bottom-up models structurally contain dozens of parameters that describe how inputs and outputs relate to one another. For instance, one commonly-used equation in Tier 1 and 2 methods for estimating the food consumption of cows uses multiple constant coefficients to relate live dairy cow body weight to quantity of dry matter ingested per day (equaions (10.18) in Dong *et al* 2006, Gavrilova *et al* 2019). These and other parameters are gleaned from small-scale studies, dating back to the early 1980s and 1990s (NRC 1989, 2001, references therein). Analyses of epistemic uncertainties studies have been done at the farm level (Sykes *et al* 2019) but are not explicitly utilized in the development of national inventories.

While these uncertainties have been detected across models may be common to all bottom-up estimates as they rely on similar assumptions and model parameters, introducing systematic biases that elude uncertainty analysis. The multiple sources of uncertainties in bottom-up estimates (input data, geographic distribution and allocation, model and parameter selection) are rarely analyzed holistically by existing studies. A recent analysis discovered that, while three different total US inventories of methane agree within 20%, their spatial discrepancies exceed 100% across certain US states (Hristov *et al* 2017). Altogether, the information used to develop bottom-up models, including input data and model parameters, may therefore lead to biases in reported estimates outcomes, due to their outdated nature, or due to a lack of representative information from the wide national and global variation in contemporary production systems (Wolf *et al* 2017).

In summary, bottom-up methods allow researchers to estimate animal emissions with a high level of precision, or fine-grained resolution, parsing out how GHG emissions differ between animal species, geographic regions, production systems, and food products, but not necessarily an accordingly high level of accuracy. The accuracy of these methods in different global regions remains poorly characterized, requiring independent methods to verify emissions estimates from animal agriculture.

2.2. Top-down estimates: evaluating animal emissions from the atmosphere

The GHG emissions estimates produced by bottom-up models can be compared against measurements taken from the air above animal operations, using sensors on tall towers, airplanes, and satellites.

Researchers use meteorological models and observations of wind direction, speed, and turbulence to link the measured GHG concentrations in the air back to their sources on the ground. These methods can be used to gauge the quantity of emissions from sources in the upwind footprint of the measurements over months or years—by measuring for prolonged periods of time and from multiple wind directions. Atmospheric estimates start by measuring GHGs in the sky, then trace those GHGs back to their source regions on the ground; these methods are referred to as 'top-down' estimates.

One limitation of top-down estimates is that these methods can only broadly distinguish among emission sources. The partitioning of sources typically depends upon differences in the spatial distribution of different source types, requiring accurate information regarding where these sources are distributed in geospatially gridded bottom-up data (e.g. Miller and Michalak 2017). For example, a top-down approach would struggle with this source partitioning if cattle are grazed amidst natural gas wells, or pig manure lagoons and natural wetlands are located in the same region.

The level of disaggregation or detail in emissions inventories also determines how finely top-down emissions estimates can be used to distinguish among source types. For example, top-down studies often employ a 'scaling factor inversion' to statistically partition sources—by scaling each emissions sector in a bottom-up inventory to match atmospheric observations. The number of these scaling factors is limited by the number of emissions categories present in the bottom-up gridded inventory and by the information content of the atmospheric observations used in the inverse model. The geospatially gridded inventories of animal emissions from EDGAR or the US EPA that are publicly available and used in the top-down analyses reviewed here are not disaggregated by type of animal or production type. Such disaggregated gridded bottom-up products would be useful for examining potential errors and biases, but could introduce further partitioning errors as the number of scaling factor coefficients would increase.

Another limitation is that top-down atmospheric estimates rely on wind observations and models with their own errors. Importantly, these atmospheric transport errors are different from the errors in bottom-up models (Pandey *et al* 2019). These errors are commonly reported in the literature and are non-compounding.

An additional challenge of top-down modeling is that these models are often under-constrained or under-determined by atmospheric observations. The number of atmospheric observation sites may be limited, while the spatial and temporal patterns of emissions can show complexity that exceeds the detection abilities of existing atmospheric observations. As a result, multiple configurations of the emissions or multiple solutions to a top-down estimation problem can reproduce the atmospheric observations within a specified error tolerance. Existing top-down models therefore have finite utility in constraining emissions at fine spatial scales. With that said, the uncertainties in top-down emissions estimate typically decrease at regional and national spatial scales (e.g. Miller *et al* 2013, 2019). The reported uncertainties at these scales are often smaller than the differences between bottom-up and top-down estimates, implying that top-down methane estimates are sufficiently robust to compare and contrast with bottom-up models at regional to continental scales (e.g. Turner *et al* 2015, Saunois *et al* 2020).

Top-down atmospheric estimates are therefore an independent way of testing the accuracy of the estimates produced by bottom-up emissions models across both small and large spatial scales, albeit with their own inherent uncertainties and limitations. To date, however, they cannot reliably distinguish between various sources that are co-located.

3. Comparing bottom-up and top-down estimates of US animal methane emissions

3.1. Quantifying differences between emissions estimates

We synthesized reports in the literature regarding top-down methane emissions estimates in regions of predominantly intensive production. We conducted literature searches on ISI Web of Science and Google Scholar for terms pertaining to top-down atmospheric estimates of methane, and filtered search results by spatial domain (state/province or larger) and whether they statistically partitioned livestock sector emissions from the total estimate. We present the results in table 1, alongside comparisons with bottom-up estimates.

Estimates from atmospheric measurements indicate that global animal methane emissions may be only slightly higher than the bottom-up models predict—about 5% higher—and within the margin of error (e.g. Turner *et al* 2015). A more recent comparison of methane estimates from total agricultural and waste sources from 2000 to 2017, which included all direct livestock emissions but also include rice crops and landfills, also found that bottom-up and top-down emissions estimates agree well within statistical uncertainty (Saunois *et al* 2020).

The difference is much greater in the United States; at least four top-down estimates of the contiguous US, representative of emissions occurring over at least one full year, indicate that direct animal methane emissions are 39%–90% higher than bottom-up models predict (Miller *et al* 2013, Wecht *et al* 2014, Turner *et al* 2015). Such comparisons are currently lacking for other predominantly intensified production regions, e.g. Europe.

This tendency is mirrored in smaller geographic regions within North America. Of five regional top-down studies, four found significantly higher methane emissions from areas of confined animal production than the bottom-up models suggest (Jeong *et al* 2016, Chen *et al* 2018, Desjardins *et al* 2018, Yu *et al* 2021). The exception is the Southeastern US, where there was close agreement between aircraft measurements and a short-term campaign (Sheng *et al* 2018). This and the Ontario Desjardins *et al* (2018) study were both conducted over an aircraft campaign lasting less than 2 months, meaning that these results may not be representative of the full annual

Table 1. Direct methane emissions from farmed animals in Tg CH_4. Scale factor refers to the relative magnitude of the top-down emissions estimate relative to the respective bottom-up estimate (e.g. 200% means top-down estimate is two times higher than bottom-up estimate). Emissions model abbreviations are EDGAR—Emissions Database for Global Atmospheric Research; EPA—Environmental Protection Agency; CALGEM—California GHG emissions measurement project. Bottom-up models reflect the models used to develop geospatially gridded datasets for comparison in the respective top-down analyses.

Region	Year	Bottom-up model	Bottom-up estimate	Top-down estimate	Scale factor	Reference
Globe USA	2009–2011	EDGAR	111 8.9	116 ± 10 14.8 ± 2.2	105% 166%	Turner *et al* (2015)
USA	2004	US EPA EDGAR	8.8 8.5	12.2 ± 1.3	139% 144%	Wecht *et al* (2014)
USA	2007–2008	US EPA EDGAR	9.3 8.9	17.0 ± 6.7	181% 190%	Miller *et al* (2013)
US Midwest	2016–2017	US EPA EDGAR	2.6 2.7	4.8 ± 1.5	185% 178%	Chen *et al* (2018)
US Upper Midwest	2017–2018	US EPA	3.3	4.11 ± 0.54	124%	Yu *et al* (2021)
California, USA	2013–2014	CALGEM	0.90	1.33 ± 0.40	149%	Jeong *et al* (2016)
E. Ontario, Canada	April–May 2011	IPCC Tier 2	0.013 ± 0.002	0.027 ± 0.006	217%	Desjardins *et al* (2018)
US Southeast	August–September 2013	US EPA	3 ± 0.5	2.9 ± 0.3	97%	Sheng *et al* (2018)

cycle. The Southeastern US is also an area of abundant wetland emissions (8–16 Tg CH_4 yr^{-1}), with close proximity to animal production areas, making accurate source partitioning challenging (Miller *et al* 2015).

The bottom-up models included in these sources use agricultural survey and census data on farmed animal populations, and use IPCC standards (predominantly Tier 2) to calculate their emissions factors. The bottom-up estimates (table 1, column 4) correspond to various base years and bottom-up models (table 1, columns 2 and 3 respectively) and model versions. Future work is therefore needed to compare bottom-up and top-down emissions estimates using the most recent bottom-up model versions across their respective regions and base years. While the models differ in assumptions made to calculate emissions factors, i.e. assumptions reflecting how animals are fed, housed, and raised, feeds tend to be energy-rich and animal production methods are intensive and confined throughout the US and Canada.

The discrepancies between bottom-up and top-down estimates in the US and Canada imply that models may under-predict the emissions intensity of animals raised in intensive, predominantly confined systems. This pattern furthermore suggests that a greater proportion of total global methane emissions from animals is coming from intensive systems than is routinely reported.

3.2. Why North American emissions may be underestimated by models

It is unclear why the modeled methane emissions from farmed animals in the US are often lower than emissions inferred from atmospheric measurements. Discrepancies do not seem specific to one animal or system. For example, Jeong *et al* (2016) analyzed airborne measurements from California and were able to partition emissions between dairy cattle and other animals. They found dairy cattle and other non-dairy animals' emissions were 45% and 69% higher, respectively, than the bottom-up model predicted. Therefore, emissions from multiple animal species may be underestimated by the bottom-up emissions models.

Bottom-up models also appear to routinely underpredict emissions from manure. Models of manure emissions are based on laboratory experiments within controlled test chambers. When methane is measured outside of the lab, in the air directly above manure tanks, pits, and piles, emissions tend to be greater than models predict, sometimes by more than 300% (Owen and Silver 2015). However, because manure represents approximately 11% of animal methane emissions, this difference is still not large enough to explain the gap in US animal methane emissions (Wolf *et al* 2017).

High methane emissions may also stem from animal disease. Infections in animals are widespread in intensive production systems; approximately one

quarter of US dairy cows have mastitis—a swelling and infection of udders accompanied by secretion of somatic cells into the milk (USDA 2016). Among beef cattle, nearly all feedlots have at least some cattle affected by bovine respiratory disease complex (BRDC or 'shipping fever') or lameness; BRDC has been detected in 16%, digestive disorders in 4%, and lameness in 2% of the entire US feedlot beef cattle population (USDA 2013). Digestive disorders and infectious parasites have multiple adverse effects on enteric fermentation emissions; they (a) decrease digestion efficiency, hence increasing overall feed requirements and methane output per unit of production (Houdijk *et al* 2017, Fox *et al* 2018) and (b) increase methane yield per unit of feed. The former tendency may be missed by bottom-up models if entirely healthy cattle are being taken as representative of the entire herd. The latter tendency cannot be represented at all by Tier 2 emissions methods models (Dong *et al* 2006, Gavrilova *et al* 2019), and would require new methods that could account for unhealthy/infected proportions of the herd. A full accounting for animal diseases, which are prevalent in modernized intensive systems, may result in bottom-up emissions that are higher than commonly reported.

The current body of top-down estimates is insufficient to understand precisely why bottom-up models may underpredict animal emissions. The metabolic processes that generate emissions (e.g. manure and belches) are highly co-located relative to the large and distant spatial scales at which atmospheric measurements for top-down estimates occur. Multiple inputs and metabolic processes contribute to the rate of methane conversion in an individual animal or manure storage system. In the future, a greater number of atmospheric measurements performed at smaller spatial scales, located in closer proximity to facilities where manure storage is separated animals enteric fermentation, could be utilized to better partition which types of animals, processes, and production systems are most responsible for driving the discrepancies.

4. Animal emissions in an international development context

4.1. Case study: intensification in East and Southeast Asia

Intensification in ESA, which includes mainland China, is expected to reduce marginal emissions substantially (Wang *et al* 2017, Yu *et al* 2018, FAO 2018a). A recent analysis of animal emissions in China recommends increasing per-capita production of animal products (Yu *et al* 2018), finding that improved efficiency will offset the increase in production and provide net methane emission reductions overall. The benefits of intensification, however, vary case by case, and by the proportions of direct and indirect GHG emissions, which can vary widely geographically (Poore and Nemecek 2018).

The following synthesis aims to approximately correct or scale future GHG emissions projections in the ESA region for direct animal emissions. We adjust the proportion of direct emissions in bottom-up emissions estimates by a mean and range of scaling factors derived from the USA top-down emissions scaling factors. This analysis serves as a prospective correction, outlining a possible consequence of business-as-usual development, but it is not a definitive prediction. The specific metabolic processes and source categories that can fully explain the discrepancy in North American emissions (table 1) are still unknown, including but not limited to manure methane fluxes influenced by climate and geography (Dong *et al* 2006). However, we expect that this analysis will approximately account for changes in the increased use of landless, intensive systems in the region, with common industrial production characteristics that are increasingly deployed in the ESA region and throughout the developing world (Wasley and Heal 2020).

The 2050 projections were taken from FAO, using regionally appropriate emissions factors from IPCC (FAO 2018a). The data are available on the online FAO data portal 'Food and Agriculture Projections through 2050 (www.fao.org/global-perspectives-studies/food-agriculture-projections-to-2050/en/). We used agricultural emissions and livestock herd size data from the 'business-as-usual' projection (FAO 2018a) and disaggregated further where necessary by supplementing this data with public data from FAO GLEAM, which further partitions emissions into production categories GHGs, and lifecycle processes (FAO 2017).

Total demand for animal-sourced foods is increasing in ESA concurrently with intensification. Emissions of each unit of production are assumed to decrease in the near future according to prospective bottom-up estimates (figure 2(A)). As a result of these two counterbalancing forces, animal emissions are expected to increase by 2030, then gradually go down until they return to early 2000s levels by 2050 (figure 2(B)). However, these bottom-up emission projections may overestimate the benefit of intensification.

If the share of direct GHG emissions projected to come from intensive systems is scaled in proportion with top-down US estimates (scaled up by 65%, the average inferred from top-down estimates, provided in table 1), future emissions per unit of meat and dairy will not decrease as much as FAO bottom-up estimates predict (figure 2(C)). Multiplying this emission intensity by total consumption, we find that the ESA region could reach 1.52 (1.41–1.62 total range) $GtCO_2eq$ by 2050, an amount 21% (13%–29%) higher than previously predicted (figure 2(D)).

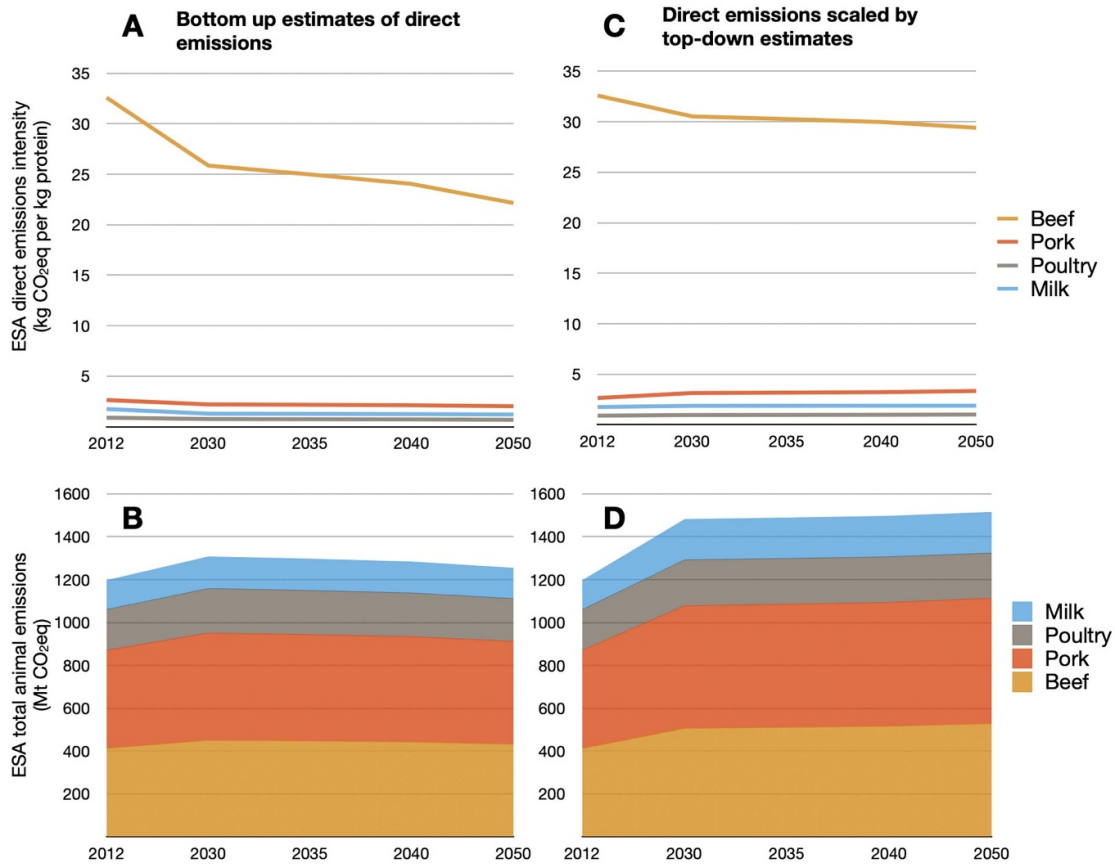


Figure 2. Present and future emissions intensities and total emissions from animal production in ESA, as estimated by bottom-up emissions models (A)–(B) and direct emissions from intensive production adjusted by a scale factor (1.65) derived from the average of top-down emissions estimates in the US (C)–(D).

Indirect emissions account for approximately 40%–50% of animal agriculture's emissions. This prospective analysis leaves indirect emissions unaltered (e.g. nitrous oxide from fertilizer applied to animal feeds and CO_2 emissions from land use change) while adjusting direct CH_4 emissions and also N_2O emissions from manure management; N_2O emissions appear to be similarly or more dramatically higher than bottom-up estimates when assessed using top-down methods (Owen and Silver 2015). Estimates of CO_2 from fossil fuel and land use change, which are indirect emissions processes in animal agricultural production, generally show good agreement among bottom-up and top-down assessments (Friedlingstein *et al* 2020). However, the implications for animal agriculture in developing contexts is highly uncertain, due to large geographic and seasonal variation in the discrepancies between emissions patterns and because patterns of feed crop trade through 2050 are uncertain. These complexities would make assessing the effects of indirect emissions estimates adjustments substantially more speculative, hence an assessment of indirect emissions estimate corrections was outside of our scope. By not altering indirect emissions, we produce a conservative estimate.

This case study is limited in terms of the confidence with which we can project and scale such differences, however. Uncertainties are not reported by FAO in their ESA regional emissions through 2050, which is a common tendency in bottom-up emissions estimates and projections. We discuss measures needed to improve uncertainty analysis in section 2.1. A fuller analysis regarding how uncertainties in this and other bottom-up emissions compound is outside of the scope of this review and prospective analysis, but is urgently needed.

We express emissions in our ESA case study in CO_2 equivalence (CO_2e) using GWP_{100}, although we acknowledge that this is limited in by placing short- and long-lived gases on the same scale. Recent analyses and commentary have proposed a new approach of GWP*, which includes information about the rate of change in shorter-lived pollutants like methane (Collins *et al* 2020, Lynch *et al* 2020). We share the concerns motivating the development of an alternative CO_2 equivalence metric. However, we did not adopt this new method for recalculating CO_2e due to (a) maintaining consistency for a comparison with previous FAO summary findings and (b) a lack of consensus regarding the appropriateness of assumptions embedded in GWP*, still inspiring active debate on topic (e.g. Rogelj and Schleussner 2019, Smith and Balmford 2020). Ultimately, there are limitations to any method of calculating an equivalence of all

climate pollutants to just one chemical species, rather than directly calculating their effects on temperature. However, this is only a limitation of our ESA case study and not the discrepancies found in our review of methane emissions themselves (table 1), in which we compare Tg of CH_4 directly.

Our prospective analysis demonstrates that animal emissions in the ESA region may not plateau in by 2030, as has previously been projected. While the majority of emissions increase is expected to occur by 2030 (figure 2(B)), this increase may be higher than expected (figure 2(D)) and total emissions may still slightly increase for multiple decades as consumer demand in the region continues to rise.

Despite this uncertainty, our illustrative example of ESA demonstrates that widescale adaptation of intensive production methods in low- and middle-income countries may have limited benefits to GHG emissions, especially if demand continues to grow.

4.2. The limits of intensification for sustainable development

Recommendations to intensify animal production are ubiquitous in the scientific literature (Thornton and Herrero 2010, Gerber *et al* 2013, Swain *et al* 2018, Grossi *et al* 2019). Such suggestions shape policies that disseminate intensive production technologies to low- and middle-income countries. Such policies include sustainable lending criteria from international development banks (World Bank International Finance Corporation 2012), and government subsidies and incentives, which in turn influence and are influenced by the actions of multinational meat and dairy producers (Lazarus *et al* 2021).

Policies that incentivize landless and industrialized animal production methods risk amplifying other public health and environmental harms. Low-interest loans for such animal production operations cover the capital costs of building large shed-like facilities that confine tens to hundreds of thousands of animals indoors (Wasley and Heal 2020) in a manner that often highly restricts their movement and expressions of natural behavior (Prunier *et al* 2010, Grandin 2016, Widowski *et al* 2016). Such facilities require high levels of subtherapeutic antibiotics (Silbergeld *et al* 2008), leading to antibiotic resistance, and encourage the rapid transmission and mutation of viruses with pandemic potential (Alders *et al* 2014, Millman *et al* 2017, Lycett *et al* 2019) including highly pathogenic avian influenzas (HPAI, also known as 'bird flu'). Intensified animal production poses a litany of zoonotic disease risks (UNEP and ILRI 2020). Large concentrated quantities of production and storage also create point and non-point sources of groundwater pollution and can degrade air quality (Secchi and Mcdonald 2019, Domingo *et al* 2021).

While the efficiency of feeding and fattening allowed by intensified animal production can reduce indirect land use, confined forms of animal production including landless and industrialized systems Intensification can lead to further homogeneity of food systems and exacerbates zoonotic disease risks (UNEP and ILRI 2020) including interspecies transmissions of and other infectious viruses.

Public and private institutions must fully evaluate socio-environmental externalities and risks of intensified animal production systems in their policies that finance and incentivize their expansion. Continuing to export these technologies and practices to developing regions could achieve less GHG mitigation than commonly assumed while exacerbating other socio-environmental harms.

4.3. The climate mitigation potential of agricultural development

The climate impacts of growing demand for meat and dairy have implications for keeping global warming within safe limits. Most countries have not committed to reducing non-CO_2 gases (Climate Action Tracker, Wang *et al* 2018), including methane and nitrous oxide from animals. Previous analysis has demonstrated that if countries aggressively limit CO_2 from fossil fuels, growth in meat and dairy consumption would be sufficient to cause warming of above 2 °C even with aggressive mitigation in other sectors (Harwatt *et al* 2020) and business-as-usual growth in animal sourced food production, efficiency, and consumption would exceed the entire GHG budget compatible with a 1.5 °C threshold of warming (Clark *et al* 2020). The aforementioned findings were all informed by bottom-up models, which may underestimate emissions from intensive production systems that are proliferating globally. Growth in meat and dairy production and consumption therefore may be even more incompatible with limiting global warming than previously reported.

Our prospective analysis demonstrates that GHG emissions could increase as developing regions intensify production. On one hand, intensive systems could achieve GHG mitigation with improved technologies such as anaerobic manure digestors that capture biomethane for fuel usage (Paolini *et al* 2018) and concentrated feeds supplemented with enteric fermentation suppressants such as 3-nitrooxypropanol and seaweeds (Machado *et al* 2016, Jayanegara *et al* 2018). On the other hand, ambitious interventions and improvements in efficiencies have the potential to mitigate less than a quarter of annual agricultural emissions relative to business-as-usual (Höglund-Isaksson *et al* 2020).

GHG emissions are not the only indicator of sustainability, and GHG suppression measures for intensively-raised animals could incentivize animal concentration at larger scales, exacerbating co-impacts such as water pollution load and antimicrobial resistance, especially if such technologies require additional subsidies to remain economically

viable (Eker *et al* 2019). Sustainability encompasses multiple dimensions, including multiple environmental impacts, social equity, and economic feasibility. Effective sustainable development strategies for food systems are uncommon because they must provide benefits across multiple dimensions and goals (Rasmussen *et al* 2018).

Socio-environmental benefits could be realized by providing resources in areas of pastoral production for intensification practices that do not involve confinement to similar levels of intensive US 'landless' systems. Such practices include improved animal veterinary care, improved forage seeds and pasture management, and more precise nutrient application. Improved coordination between smallholder and midsize producers, government, and NGOs can hasten these benefits (Swain *et al* 2018, FAO 2018b, IPCC 2019). Intensification may be effective in optimizing co-benefits in some circumstances, especially in regions where indirect emissions are large (e.g. ongoing land-use change, including deforestation).

Reducing externalities of further intensification also depends upon limiting overall consumer demand, particularly in regions where animal-sourced food consumption already exceeds nutritional requirements. Improved productivity and lower prices can lead to runaway effects of stimulating greater demand a feedback process known as Jevons Paradox (Garnett *et al* 2015), and stimulate more production by decreasing input costs (Kreidenweis *et al* 2018). Feedback effects between supply and demand can therefore undermine or worsen the environmental impacts that intensification efforts seek to mitigate. Mitigation policies should address the overconsumption of animal-sourced foods to avoid these feedback effects, rather than merely focusing on improving production.

Managing both supply and demand of animal-sourced foods must be considered within efforts to reform and develop food systems sustainably while mitigating climate change (IPCC 2019, Clark *et al* 2020, Harwatt *et al* 2020). Such efforts could include reforming dietary recommendations to reflect regional environmental impacts and planetary boundaries (Willett *et al* 2019, Springmann *et al* 2020), developing public-private partnerships to stimulate production and demand of plant-based proteins (Attwood *et al* 2019), and changing taxation and subsidy structures to reflect the true environmental costs of meat and dairy production across multiple impacts (IPCC 2019).

In addition to limiting overall consumption, more steps are necessary to ensure that intensification strategies maximize co-benefits and constrain potential externalities. These include (a) marrying intensification with strong environmental conservation policies (Garrett *et al* 2018, Kreidenweis *et al* 2018) (b) improving farmer livelihoods and disincentivizing industry consolidation that can crowd out smallholder producers, and (c) avoiding extreme forms of confinement entailed in many landless and industrialized systems, which also promote zoonotic disease emergence and antimicrobial resistance (UNEP and ILRI 2020). This last criterion may prove an exceedingly difficult needle to thread if demand for animal-sourced foods continues to increase unabated. All of the above and more is required to ensure that the intensification of animal agriculture does not further amplify multiple environmental risks including climate change, biodiversity loss, and the emergence of potentially pandemic zoonotic diseases.

Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

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References

Alders R, Awuni J A, Bagnol B, Farrell P and De Haan N 2014 Impact of avian influenza on village poultry production globally *Ecohealth* **11** 63–72

Alexandratos N and Bruinsma J 2012 World agriculture towards 2030/2050: the 2012 revision *FAO* **20** 375

Attwood S, Voorheis P, Mercer C, Davies K and Vennard D 2019 *Playbook for Guiding Diners toward Plant-Rich Dishes in Food Service* (Washington, DC: World Resources Institute (WRI))

Carrel M, Young S G and Tate E 2016 Pigs in space: determining the environmental justice landscape of swine concentrated animal feeding operations (CAFOS) in Iowa *Int. J. Environ. Res. Public Health* **13** 849

Cattlemen's Beef Board 2018 Beef sustainability (available at: www.beefitswhatsfordinner.com/raising-beef/beef-sustainability)

Chen Z, Griffis T J, Baker J M, Millet D B, Wood J D, Dlugokencky E J, Andrews A E, Sweeney C, Hu C and Kolka R K 2018 Source partitioning of methane emissions and its seasonality in the U.S. Midwest *J. Geophys. Res. Biogeosci.* **123** 646–59

Clark M A, Domingo N G G, Colgan K, Thakrar S K, Tilman D, Lynch J, Azevedo I L and Hill J D 2020 Global food system emissions could preclude achieving the 1.5° and 2°C climate change targets *Science* **370** 705–8

Climate Action Tracker Climate action tracker (available at: https://climateactiontracker.org/)

Collins W J, Frame D J, Fuglestvedt J S and Shine K P 2020 Stable climate metrics for emissions of short and long-lived species—combining steps and pulses *Environ. Res. Lett.* **15** 024018

De Oliveira Silva R, Barioni L G, Queiroz Pellegrino G and Moran D 2018 The role of agricultural intensification in Brazil's nationally determined contribution on emissions mitigation *Agric. Syst.* **161** 102–12

Desjardins R L, Worth D E, Pattey E, VanderZaag A, Srinivasan R, Mauder M, Worthy D, Sweeney C and Metzger S 2018 The challenge of reconciling bottom-up agricultural methane emissions inventories with top-down measurements *Agric. For. Meteorol.* **248** 48–59

Domingo N G G *et al* 2021 Air quality–related health damages of food *Proc. Natl Acad. Sci.* **118** e2013637118

Dong H, Mangino J and McAllister T A 2006 IPCC 2006 guidelines chapter for national greenhouse gas inventories: chapter 10—emissions from livestock and manure management *Clim. Change* **4** 87

Eker S, Reese G and Obersteiner M 2019 Modelling the drivers of a widespread shift to sustainable diets *Nat. Sustain.* **2** 725–35

Enahoro D, Mason-D'Croz D, Mul M, Rich K M, Robinson T P, Thornton P and Staal S S 2019 Supporting sustainable expansion of livestock production in South Asia and Sub-Saharan Africa: scenario analysis of investment options *Glob. Food Sec.* **20** 114–21

FAO 2017 Global livestock environmental assessment model (GLEAM) 2.0—assessment of greenhouse gas emissions and mitigation potential (available at: www.fao.org/gleam/results/en/)

FAO 2018a The future of food and agriculture—alternative pathways to 2050 (Rome) (available at: www.fao.org/3/I8429EN/i8429en.pdf)

FAO 2018b World Livestock: transforming the livestock sector through the sustainable development goals (Rome: Search Results Web Result with Site Links Food and Agriculture Organization of the United Nations) (available at: www.fao.org/3/CA1201EN/ca1201en.pdf)

Fox N J, Smith L A, Houdijk J G M, Athanasiadou S and Hutchings M R 2018 Ubiquitous parasites drive a 33% increase in methane yield from livestock *Int. J. Parasitol.* **48** 1017–21

Friedlingstein P *et al* 2020 Global carbon budget 2020 *Earth Syst. Sci. Data* **12** 3269–340

Garnett T, Röös E and Little D 2015 Lean, green, mean, obscene..? What is efficiency and is it sustainable? (available at: https://decorrespondent.nl/3912/Waarom-minder-vlees-eten-zo-moeilijk-is/297946166496-3b400346%5Cnpapers3://publication/uuid/A50BCD2F-2BC4-4758-B74B-13D0CB148F1E)

Garrett R D, Koh I, Lambin E F, Le Polain De Waroux Y, Kastens J H and Brown J C 2018 Intensification in agriculture-forest frontiers: land use responses to development and conservation policies in Brazil *Glob. Environ. Change* **53** 233–43

Gavrilova O *et al* 2019 Refinement to the 2006 IPCC guidlines for national greenhouse gas inventories, volume 4: agriculture, forestry and other land use: emissions from livestock and manure management *Forestry* **4** 87

Gerber P J, Steinfeld H, Henderson B, Mottet A, Opio C, Dijkman J, Falcucci A and Tempio G 2013 *Tackling Climate Change through livestock—A Global Assessment of Emissions and Mitigation Opportunities* (Rome: Food and Agriculture Organization of the United Nations (FAO))

Godfray H C J, Beddington J R, Crute I R, Haddad L, Lawrence D, Muir J F, Pretty J, Robinson S, Thomas S M and Toulmin C 2010 Food security: the challenge of feeding 9 billion people *Science* **327** 812–8

Grandin T 2016 Evaluation of the welfare of cattle housed in outdoor feedlot pens *Vet. Anim. Sci.* **1–2** 23–8

Grossi G, Goglio P, Vitali A and Williams A G 2019 Livestock and climate change: impact of livestock on climate and mitigation strategies *Anim. Front.* **9** 69–76

Harwatt H, Ripple W J, Chaudhary A, Betts M G and Hayek M N 2020 Scientists call for renewed Paris pledges to transform agriculture *Lancet Planet. Health* **4** e9–10

Herrero M, Havlík P, Valin H, Notenbaert A, Rufino M C, Thornton P K, Blümmel M, Weiss F, Grace D and Obersteiner M 2013 Biomass use, production, feed efficiencies, and greenhouse gas emissions from global livestock systems *Proc. Natl Acad. Sci.* **110** 20888–93

Höglund-Isaksson L, Gómez-Sanabria A, Klimont Z, Rafaj P and Schöpp W 2020 Technical potentials and costs for reducing global anthropogenic methane emissions in the 2050 timeframe—results from the GAINS model *Environ. Res. Commun.* **2** 025004

Houdijk J G M, Tolkamp B J, Rooke J A and Hutchings M R 2017 Animal health and greenhouse gas intensity: the paradox of periparturient parasitism *Int. J. Parasitol.* **47** 633–41

Hristov A N, Harper M, Meinen R, Day R, Lopes J, Ott T, Venkatesh A and Randles C A 2017 Discrepancies and uncertainties in bottom-up gridded inventories of livestock methane emissions for the Contiguous United States *Environ. Sci. Technol.* **51** acs.est.7b03332

ILRI 2019 Expanding livestock production in Asia and Africa key to environmental as well as human welfare gains *ILRI News* (available at: https://news.ilri.org/2019/03/31/expanding-livestock-production-in-asia-and-africa-key-to-environmental-as-well-as-human-welfare-gains-new-study/)

IPCC 2019 Climate change and land an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems *Head of TSU (Operations) IT/Web Manager Senior Administrat* (available at: www.ipcc.ch)

Jayanegara A, Sarwono K A, Kondo M, Matsui H, Ridla M, Laconi E B and Nahrowi N 2018 Use of 3-nitrooxypropanol as feed additive for mitigating enteric methane emissions from ruminants: a meta-analysis *Ital. J. Anim. Sci.* **17** 650–6

Jeong S *et al* 2016 Estimating methane emissions in California's urban and rural regions using multitower observations *J. Geophys. Res.* **121** 13,031–13,049

Kreidenweis U, Humpenöder F, Kehoe L, Kuemmerle T, Bodirsky B L, Lotze-Campen H and Popp A 2018 Pasture intensification is insufficient to relieve pressure on conservation priority areas in open agricultural markets *Glob. Change Biol.* **24** 3199–213

Lazarus O, McDermid S and Jacquet J 2021 The climate responsibilities of industrial meat and dairy producers *Clim. Change* **165** 30

Lycett S J, Duchatel F and Digard P 2019 A brief history of bird flu *Phil. Trans. R. Soc.* B **374** 0–3

Lynch J, Cain M, Pierrehumbert R and Allen M 2020 Demonstrating GWP*: a means of reporting warming-equivalent emissions that captures the contrasting impacts of short- and long-lived climate pollutants *Environ. Res. Lett.* **15** 044023

Machado L, Magnusson M, Paul N A, Kinley R, De Nys R and Tomkins N 2016 Identification of bioactives from the red seaweed Asparagopsis taxiformis that promote antimethanogenic activity *in vitro J. Appl. Phycol.* **28** 3117–26

McDonald's Canada 2018 Beef sustainability | the journey ahead | McDonald's Canada *YouTube* (available at: www.youtube.com/watch?v=w8ubbgW3jZw)

Miller S M *et al* 2013 Anthropogenic emissions of methane in the United States *Proc. Natl Acad. Sci.* **110** 20018–22

Miller S M, Hayek M N, Andrews A E, Fung I and Liu J 2015 Biases in atmospheric CO_2 estimates from correlated meteorology modeling errors *Atmos. Chem. Phys.* **15** 2903–14

Miller S M and Michalak A M 2017 Constraining sector-specific CO_2 and CH_4 emissions in the US *Atmos. Chem. Phys.* **17** 3963–85

Miller S M, Michalak A M, Detmers R G, Hasekamp O P, Bruhwiler L M P and Schwietzke S 2019 China's coal mine methane regulations have not curbed growing emissions *Nat. Commun.* **10** 303

Miller S M, Michalak A M and Wofsy S C 2014 Reply to Hristov *et al*: linking methane emissions inventories with atmospheric observations *Proc. Natl Acad. Sci.* **111** E1321

Millman C, Christley R, Rigby D, Dennis D, O'Brien S J and Williams N 2017 "Catch 22": biosecurity awareness,

interpretation and practice amongst poultry catchers *Prev. Vet. Med.* **141** 22–32
National Pork Board 2020 Pork industry releases new sustainability report *Pork Checkoff* (available at: www.pork.org/news/pork-industry-releases-new-sustainability-report/)
NRC 1989 *Nutrient Requirements of Dairy Cattle* (Washington, DC: National Academy of Sciences)
NRC 2001 *Nutrient Requirements of Dairy Cattle* 7th revised edn (Washington, DC: The National Academies Press) (available at: www.nap.edu/catalog/9825/nutrient-requirements-of-dairy-cattle-seventh-revised-edition-2001)
Owen J J and Silver W L 2015 Greenhouse gas emissions from dairy manure management: a review of field-based studies *Glob. Change Biol.* **21** 550–65
Pandey S, Houweling S, Krol M, Aben I, Nechita-Banda N, Thoning K, Röckmann T, Yin Y, Segers A and Dlugokencky E J 2019 Influence of atmospheric transport on estimates of variability in the global methane burden *Geophys. Res. Lett.* **46** 2302–11
Paolini V, Petracchini F, Segreto M, Tomassetti L, Naja N and Cecinato A 2018 Environmental impact of biogas: a short review of current knowledge *J. Environ. Sci. Health* A **53** 899–906
Poore J and Nemecek T 2018 Reducing food's environmental impacts through producers and consumers *Science* **360** 987–92
Prunier A, Heinonen M and Quesnel H 2010 High physiological demands in intensively raised pigs: impact on health and welfare *Animal* **4** 886–98
Rasmussen L V, Coolsaet B, Martin A, Mertz O, Pascual U, Corbera E, Dawson N, Fisher J A, Franks P and Ryan C M 2018 Social-ecological outcomes of agricultural intensification *Nat. Sustain.* **1** 275–82
Richter B D *et al* 2020 Water scarcity and fish imperilment driven by beef production *Nat. Sustain.* **3** 319–28
Robinson T *et al* 2011 *Global Livestock Production Systems* (available at: www.fao.org/3/i2414e/i2414e00.htm)
Rogelj J and Schleussner C-F 2019 Unintentional unfairness when applying new greenhouse gas emissions metrics at country level *Environ. Res. Lett.* **14** 114039
Saunois M *et al* 2020 The global methane budget 2000–2017 *Earth Syst. Sci. Data* **12** 1561–623
Secchi S and Mcdonald M 2019 The state of water quality strategies in the Mississippi River Basin: is cooperative federalism working? *Sci. Total Environ.* **677** 241–9
Sheng J-X, Jacob D J, Turner A J, Maasakkers J D, Sulprizio M P, Bloom A A, Andrews A E and Wunch D 2018 High-resolution inversion of methane emissions in the Southeast US using SEAC^{4}RS aircraft observations of atmospheric methane: anthropogenic and wetland sources *Atmos. Chem. Phys.* **18** 6483–91
Silbergeld E K, Graham J and Price L B 2008 Industrial food animal production, antimicrobial resistance, and human health *Annu. Rev. Public Health* **29** 151–69
Smith P and Balmford A 2020 Climate change: 'no get out of jail free card' *Vet. Rec.* **186** 71
Springmann M, Spajic L, Clark M A, Poore J, Herforth A, Webb P, Rayner M and Scarborough P 2020 The healthiness and sustainability of national and global food-based dietary guidelines: a modelling study *BMJ* **370** 1–16
Steinfeld H, Wassenaar T and Jutzi S 2006 *Livestock's Long Shadow* (available at: www.globalmethane.org/expo-docs/china07/postexpo/ag_gerber.pdf)
Swain M, Blomqvist L, McNamara J and Ripple W J 2018 Reducing the environmental impact of global diets *Sci. Total Environ.* **610–611** 1207–9
Sykes A J, Topp C F E and Rees R M 2019 Understanding uncertainty in the carbon footprint of beef production *J. Clean. Prod.* **234** 423–35
Thornton P K and Herrero M 2010 Potential for reduced methane and carbon dioxide emissions from livestock and pasture management in the tropics *Proc. Natl Acad. Sci. USA* **107** 19667–72
Turner A J *et al* 2015 Estimating global and North American methane emissions with high spatial resolution using GOSAT satellite data *Atmos. Chem. Phys.* **15** 7049–69
UNEP and ILRI 2020 Preventing the next pandemic—zoonotic diseases and how to break the chain of transmission (Nairobi) (available at: www.unenvironment.org/resources/report/preventing-future-zoonotic-disease-outbreaks-protecting-environment-animals-and)
US EPA O 2021 *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990–2019* (available at: www.epa.gov/ghgemissions/inventory-us-greenhouse-gas-emissions-and-sinks-1990-2019)
USDA 2013 *Feedlot 2011—Part IV: Health and Health Management on U.S. Feedlots with a Capacity of 1,000 or More Head* (available at: www.aphis.usda.gov/animal_health/nahms/feedlot/downloads/feedlot2011/Feed11_dr_PartIV_1.pdf)
USDA 2016 *Dairy 2014—Milk Quality, Milking Procedures, and Mastitis on U.S. Dairies, 2014* (Fort Collins, CO) (available at: www.aphis.usda.gov/animal_health/nahms/dairy/downloads/dairy14/Dairy14_dr_Mastitis.pdf)
Wang L, Xue B and Yan T 2017 Greenhouse gas emissions from pig and poultry production sectors in China from 1960 to 2010 *J. Integr. Agric.* **16** 221–8
Wang X, Teng F, Zhang J, Khanna N and Lin J 2018 Challenges to addressing non-CO_2 greenhouse gases in China's long-term climate strategy *Clim. Change* **18** 1059–65
Wasley A and Heal A 2020 Revealed: development banks funding industrial livestock farms around the world *Guard.* | *Environ.* (available at: www.theguardian.com/environment/2020/jul/02/revealed-development-banks-funding-industrial-livestock-farms-around-the-world)
Wecht K J, Jacob D J, Frankenberg C, Jiang Z and Blake D R 2014 Mapping of North American methane emissions with high spatial resolution by inversion of SCIAMACHY satellite data *J. Geophys. Res. Atmos.* **119** 7741–56
Widowski T M, Hemsworth P H, Barnett J L and Rault J-L 2016 Laying hen welfare I. Social environment and space *Worlds Poult. Sci. J.* **72** 333–42
Willett W *et al* 2019 Food in the anthropocene: the EAT–Lancet Commission on healthy diets from sustainable food systems *Lancet* **6736** 3–49
Wolf J, Asrar G R and West T O 2017 Revised methane emissions factors and spatially distributed annual carbon fluxes for global livestock *Carbon Balance Manage.* **12** 16
World Bank International Finance Corporation 2012 Performance standard 3: resource efficiency and pollution prevention *IFC Sustain. Stand. Policies* (available at: www.ifc.org/wps/wcm/connect/topics_ext_content/ifc_external_corporate_site/sustainability-at-ifc/policies-standards/performance-standards/ps3)
World Bank International Finance Corporation 2020 GXYX ASF disclosure *IFC Proj. Inf. Data Portal* (available at: https://disclosures.ifc.org/#/projectDetail/ESRS/43384)
Yu J, Peng S, Chang J, Ciais P, Dumas P, Lin X and Piao S 2018 Inventory of methane emissions from livestock in China from 1980 to 2013 *Atmos. Environ.* **184** 69–76
Yu X *et al* 2021 Aircraft-based inversions quantify the importance of wetlands and livestock for Upper Midwest methane emissions *Atmos. Chem. Phys.* **21** 951–71

CHAPTER 10

EMISSIONS FROM LIVESTOCK AND MANURE MANAGEMENT

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10. EMISSIONS FROM LIVESTOCK AND MANURE MANAGEMENT

Users are expected to go to Mapping Tables in Annex 1 Volume 4 (AFOLU), before reading this chapter. This is required to correctly understand both the refinements made and how the elements in this chapter relate to the corresponding chapter in the 2006 IPCC Guidelines.

10.1 INTRODUCTION

This chapter provides guidance on methods to estimate emissions of methane from Enteric Fermentation in livestock, and methane and nitrous oxide emissions from Manure Management. Carbon dioxide (CO_2) emissions from livestock are not estimated because annual net CO_2 emissions are assumed to be zero – the CO_2 photosynthesized by plants is returned to the atmosphere as respired CO_2. A portion of the C is returned as methane (CH_4) and for this reason CH_4 requires separate consideration.

Livestock production can result in CH_4 emissions from enteric fermentation and both CH_4 and nitrous oxide (N_2O) emissions from livestock manure management systems. Cattle are an important source of CH_4 in many countries because of their large population and high CH_4 emission rate due to their ruminant digestive system. Methane emissions from manure management tend to be smaller than enteric emissions, with the most substantial emissions associated with confined animal management operations where manure is handled in liquid-based systems. Nitrous oxide emissions from manure management vary significantly between the types of management system used and can also result in indirect emissions due to other forms of nitrogen loss from the system. The calculation of the nitrogen loss from manure management systems is also an important step in determining the amount of nitrogen that will ultimately be available in manure applied to managed soils, or used for feed, fuel, or construction purposes – emissions that are calculated in Chapter 11, Section 11.2 (N_2O emissions from managed soils).

The methods for estimating CH_4 and N_2O emissions from livestock require definitions of livestock subcategories, annual populations and, for higher Tier methods, feed intake and characterisation. The procedures employed to define livestock subcategories, develop population data, and characterize feed are described in Section 10.2 (Livestock Population and Feed Characterisation). Suggested feed digestibility coefficients for various livestock categories have been provided to help estimation of feed intake for use in calculation of emissions from enteric and manure sources. A coordinated livestock characterisation as described in Section 10.2 should be used to ensure consistency across the following source categories:

Section 10.3 - CH_4 emissions from Enteric Fermentation;

Section 10.4 - CH_4 emissions from Manure Management;

Section 10.5 - N_2O emissions from Manure Management (direct and indirect);

Chapter 11, Section 11.2 - N_2O emissions from Managed Soils (direct and indirect).

In calculating agricultural emissions, it is important to establish consistency among the different emission sources. Key drivers of emissions such as animal weight and productivity must be treated using the same parameters for emissions of enteric and manure management CH_4, as well as N_2O from manure management. Further, Section 10.5.4 discusses the coordination between N_2O emissions from Manure Management and Managed Soils. Emissions of N_2O from nitrogen excretion should be assessed following a nitrogen mass flow approach which is further explained in Section 10.5.6 and illustrated in Figure 10.5.

10.2 LIVESTOCK POPULATION AND FEED CHARACTERISATION

10.2.1 Steps to define categories and subcategories of livestock

No refinement.

10.2.2 Choice of method

TIER 1: BASIC CHARACTERISATION FOR LIVESTOCK POPULATIONS

Basic characterisation for Tier 1 is likely to be sufficient for most animal species in most countries. For this approach it is *good practice* to collect the following livestock characterisation data to support the emissions estimates:

Livestock species : A complete list of all livestock populations by species that have default emission factor values must be developed (e.g., dairy cows, other cattle, buffalo, sheep, goats, camels, llamas, alpacas, deer, horses, rabbits, mules and asses, swine, and poultry) if these species are relevant to the country. Populations by species can also be further subdivided by category. Category refers to classification inside a species by different relevant attributes as sex, age or productive purpose in a relevant production system in any given country (e.g. in the case of cattle: mature males and females, replacement heifers, calves, etc.). More detailed categories should be used if the data are available. For example, more accurate emission estimates can be made if poultry populations are further subdivided (e.g., layers, broilers, turkeys, ducks, and other poultry), as the waste characteristics among these different populations vary significantly.

Annual population: If possible, inventory compilers should use population data from official national statistics or industry sources. Food and Agriculture Organisation (FAO) data, FAOSTAT and other FAO statistics, can be used if national data are unavailable. Seasonal births or slaughters may cause the population size to expand or contract at different times of the year which will require the population numbers to be adjusted accordingly. It is important to fully document the method used to estimate the annual population, including any adjustments to the original form of the population data as it was received from national statistical agencies or from other sources. When population by species is subdivided by categories it is important to fully document any adjustments done in the population to match the categories used in the inventory compilation.

Compilers could consider to communicate/share the annual population data needs with the national statistical agency and/or the other sources from which the data was obtained, so this sources are better aware of the needs of inventory compilers. In addition, national statistical agencies and agencies responsible for inventory compilation can work closely together to ensure that official statistics better meet the needs of the inventory compilers.

Annual average populations are referred to as the number of head of livestock species per category within a given country ($N_{(T)}$). This can be estimated in various ways, depending on the available data and the nature of the animal population. In the case of static animal populations (e.g. dairy cows, breeding swine, layers), estimating the number of head of a given livestock species in the country ($N_{(T)}$) may be as simple as obtaining data related to one-time animal inventory data. However, estimating $N_{(T)}$ for a growing population (e.g., meat animals, such as broilers, turkeys, beef cattle, and market swine) requires more evaluation. Most animals in these growing populations are alive for only part of a complete year. Animals should be included in the populations regardless if they were slaughtered for human consumption or die of natural causes. Equation 10.1 estimates $N_{(T)}$.

EQUATION 10.1 (UPDATED)
ANNUAL AVERAGE POPULATION

$$N_T = Days_alive \bullet \left(\frac{NAPA}{365} \right)$$

Where:

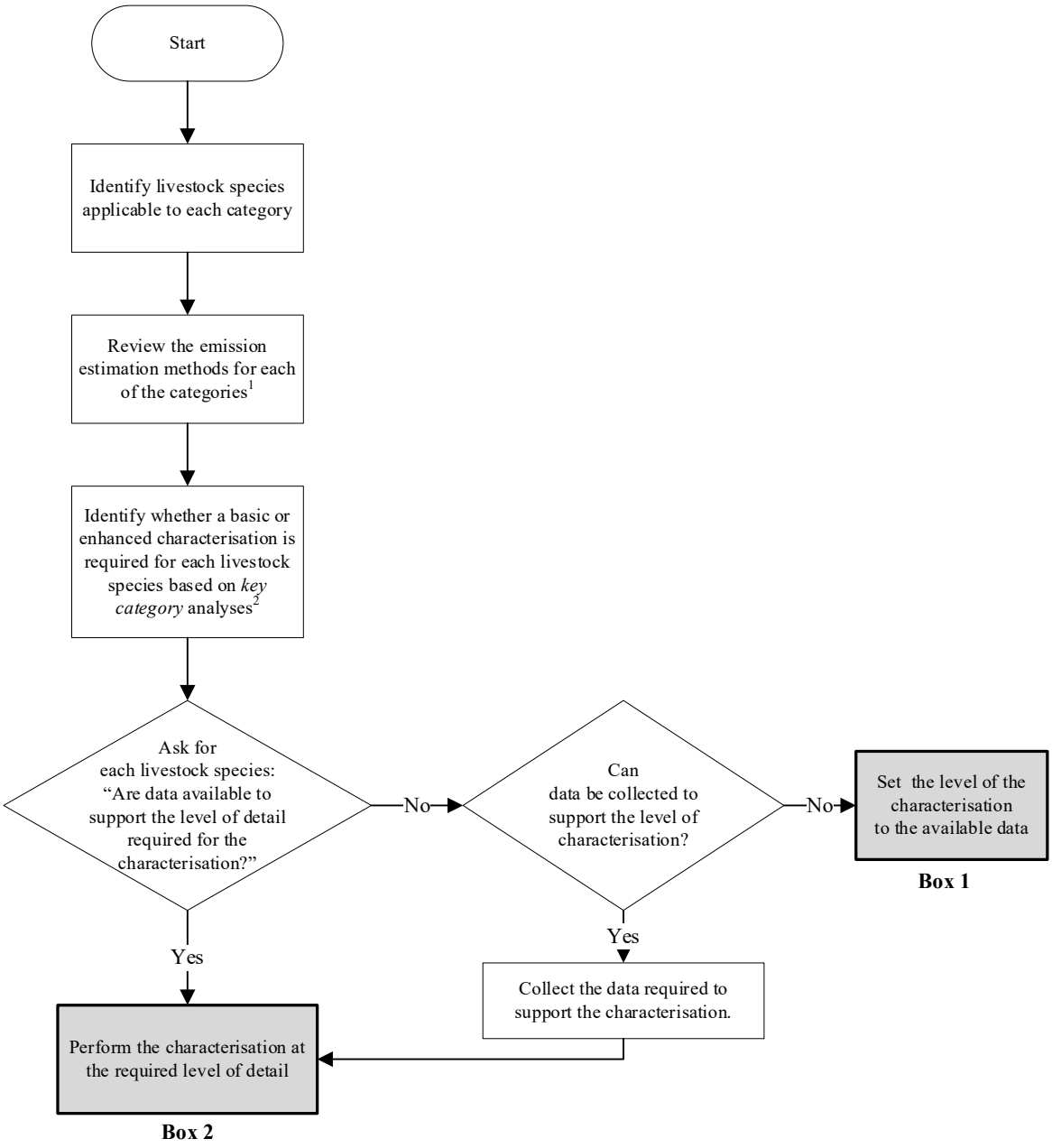
N_T = the number of head of livestock species / category T in the country (equivalent to annual average population)

$NAPA$ = number of animals produced annually

Broiler chickens are typically grown approximately 60 days before slaughter. Estimating $N_{(T)}$ as the number of grown and slaughtered over the course of a year would greatly overestimate the population, as it would assume each lived the equivalent of 365 days. Instead, one should estimate the average annual population as the number of animals grown divided by the number of growing cycles per year. For example, if broiler chickens are typically grown in flocks for 60 days, an operation could turn over approximately 6 flocks of chickens over the period of one year. Therefore, if the operation grew 60,000 chickens in a year, their average annual population would be 9,863 chickens. For this example the equation would be:

Annual average population = 60 days * 60,000 / 365 days / yr = 9,863 chickens

Figure 10.1 Decision tree for livestock population characterisation



Note:

1: These categories include: CH_4 from Enteric Fermentation, CH_4 from Manure Management, N_2O from Manure Management.

2: See Volume 1 Chapter 4, "Methodological Choice and Identification of Key Categories" (noting Section 4.1.2 on limited resources), for discussion of *key categories* and use of decision trees.

Consideration of differing Productivity systems (Tier 1a)

In certain countries agricultural production systems may be transitioning from low productivity local subsistence systems to higher productivity systems aimed at fulfilling national and export markets or may simply have dual agricultural systems, with coexistence of low and high productivity systems clearly identified. In these cases inventory compilers may wish to use the Tier 1a approach in which they are able to better track the transitions and

changes in the productivity of their agricultural systems and related emissions over time. Tier 1a emission factors (on a per head basis) have been developed for use with basic population estimates separated by low and high productivity systems according to the definitions below.

In this case animal populations by species may be divided by productivity systems. For each animal species high and low productivity systems may be defined according to characteristics such as: feedbase, genetics, purpose (draft, cultural reasons, self-consumption, market), production objectives (e.g. milk, meat, eggs), and level of inputs and outputs.

Definitions of High and Low Productivity Systems

Dairy Cattle and milk production:

The dairy cow population is estimated separately from other cattle (see Table 10.1). Dairy cows are defined in this method as mature cows (first lactation and beyond) that are producing milk in commercial quantities for consumption. This definition corresponds to the dairy cow population reported in FAO, IDF, IFCN (2014). Dairy cow population should not be confused with multi-purpose cows that may be used for more than one production purpose milk, meat or draft.

In some countries the dairy cow population is comprised of two well-defined segments:

High-productivity systems are based on high-yielding dairy cows that are concentrated in confinement production systems or grazing on high quality pastures with supplements. The farms are 100 percent market oriented for commercial milk production, for national markets and/or export; Purebred or crossbred cattle are genetically improved through selective breeding for milk production (FAO, IDF, IFCN 2014). Indicative levels of high milk productivity by cow corresponding to a given region are included in Table 10.11 to guide the selection of the emission factors.

Low productivity systems are based on low-yielding dairy cows, grazing non-improved pastures, and using locally produced roughage (e.g. crop residues), and agro-industrial by-products. Local breeds or crossbred cows are bred locally, without intensive selection for milk productivity. Milk production is mostly for local market and local consumption (FAO, IDF, IFCN. 2014). Indicative levels of low milk productivity by cow corresponding to a given region are included in Table 10.11 to guide the selection of the emission factors.

Dairy buffalo may be categorized in a similar manner to dairy cows.

Other cattle:

High-productivity systems are based on animal feeding systems using forage (e.g. high-quality grass) and concentrates in confinement production systems or grazing with supplements or on improved pastures, producing high rates of daily weight gain. Animals can be purebred or crossbred and are genetically improved through selective breeding for improved commercial meat production. Growing cattle may be finished young in "intensive grazing with supplements" or feedlot systems, and meat is produced for national markets and/or export (FAO, IDF, IFCN 2014).

Low productivity systems are based on animal feeding systems where locally produced roughage (e.g. crop residues) or low quality rangelands represent the major source of feed utilized, producing low rates of daily weight gain. Animals can be represented by local breeds or may be crossbred and can also be used for multiple purposes such as draft, meat and milk for self consumption and markets (FAO, IDF, IFCN 2014).

Other livestock species:

High-productivity systems, which are 100 percent market oriented with high level of capital input requirements and high level of overall herd (flock) performance. Feed is purchased from local or international market or intensively produced on farm. Animals are improved through breeding practices for commercial production. The high-productivity systems are common in swine, poultry, goats and sheep production (MacLeod *et al*. 2017).

Low productivity systems which are mainly driven by local market or by self-consumption, with low capital input requirements and low level of overall herd (fowl) performance typically using large areas for production or backyards. Locally produced feed represents the major source of feed utilized or animals are kept-free range for major part or all of their production cycle, the yield of the activity being linked to the natural fertility of the land and the seasonal production of the pastures. The low-productivity systems are common in swine, poultry, goats and sheep production (MacLeod *et al*. 2017).

International statistics sources for activity data, parameters and tools related to animal population

FAO provides international statistical information for livestock characterization, including population and production. Relevant sources are: FAOSTAT Production database and FAO World Census of Agriculture 2020. Additionally, FAO provides a free access e-learning course to support developing countries in the preparation of the national GHG inventory for the agriculture sector. FAO also provides tools that may be useful for inventory compilers in the agriculture sector as the FAOSTAT Emissions Analysis Tools, to identify data gaps and perform QA/QC analysis. Another tool is the Global Livestock Environmental Accounting Model (GLEAM), which is a GIS-based model for livestock production activities and related resource flows in all countries. The FAO-IPCC-IFAD workshop report (IPCC, 2015), identifies the list of all FAOSTAT and other FAO data sources in support of National Inventory compilation in the AFOLU sector.

TIER 2: ENHANCED CHARACTERISATION FOR LIVESTOCK POPULATIONS

The Tier 2 livestock characterisation requires detailed information on:

- Definitions for livestock subcategories;
- Livestock population by subcategory, with consideration for estimation of annual population as per Tier 1; and
- Feed intake estimates for the typical animal in each subcategory.

The livestock population subcategories are defined to create relatively homogenous sub-groupings of animals. By dividing the population into these subcategories, country-specific variations in age structure and animal performance within the overall livestock population can be reflected.

The Tier 2 characterisation methodology seeks to define animals, animal productivity, diet quality and management circumstances to support a more accurate estimate of feed intake for use in estimating methane production from enteric fermentation. The same feed intake estimates should be used to provide harmonised estimates of manure and nitrogen excretion rates to improve the accuracy and consistency of CH_4 and N_2O emissions from manure management.

Definitions for livestock subcategories

It is *good practice* to classify livestock populations into subcategories for each species according to age, type of production, and sex. Representative livestock categories for doing this are shown in Table 10.1. Further subcategories are also possible:

- Cattle and buffalo populations should be classified into at least three main subcategories: mature dairy, other mature, and growing cattle. Depending on the level of detail in the emissions estimation method, subcategories can be further classified based on animal or feed characteristics. For example, growing / fattening cattle could be further subdivided into those cattle that are fed with a high-grain diet and housed in dry lot vs. those cattle that are grown and finished solely on pasture.
- Subdivisions similar to those used for cattle and buffalo can be used to further segregate the sheep population in order to create subcategories with relatively homogenous characteristics. For example, growing lambs could be further segregated into lambs finished on pasture vs. lambs finished in a feedlot. The same approach applies to national goat herds.
- Subcategories of swine could be further segregated based on production conditions. For example, growing swine could be further subdivided into growing swine housed in intensive production facilities vs. swine that are grown under free-range conditions.
- Subcategories of poultry could be further segregated based on production conditions. For example, poultry could be divided on the basis of production under confined or free-range conditions.

TABLE 10.1 (UPDATED)
Representative livestock categories[1,2]

Main categories	Production categories Tier 1a	Subcategories
Mature Dairy Cow or Mature Dairy Buffalo	High Productivity Systems	High-producing cows that have calved at least once and are used principally for milk production
	Low Productivity Systems	Low-producing cows that have calved at least once and are used principally for milk production
Other Mature Cattle or Mature Non-dairy Buffalo	High Productivity Systems	Females:
		• Cows used to produce offspring for meat
		• Cows used for more than one production purpose: milk, meat, draft
		Males:
		• Bulls used principally for breeding purposes
	Low Productivity Systems	Females:
		• Cows that may be used for more than one production purpose: milk, meat, draft
		Males:
		• Bulloks used principally for draft power
Growing Cattle or Growing Buffalo	High Productivity Systems	• Calves pre-weaning
		• Replacement dairy heifers
		• Growing / fattening cattle or buffalo post-weaning
		• Feedlot-fed cattle on diets containing > 85% concentrates
	Low Productivity Systems	• Calves pre-weaning
		• Growing / fattening cattle or buffalo post-weaning
Mature Sheep	High productivity systems	• Breeding ewes for production of offspring and wool production
		• Milking ewes where commercial milk production is the primary purpose
		• Other Mature Sheep (> 1 year)
	Low productivity systems	• Breeding ewes for production of offspring and wool production
		• Other Mature Sheep (> 1 year)
Growing Sheep (lambs)	High productivity systems	• Intact Males, Castrates and Females, concentrate-fed.
	Low productivity systems	• Castrates and Females, grass-fed.

TABLE 10.1 (UPDATED) (CONTINUED)
Representative livestock categories[1,2]

Main categories	Production categories Tier 1a	Subcategories
Goats	High productivity systems	• Dairy Does
		• Mature does
		• Yearlings
		• Bucks
		• Kids (<1 yr)
	Low productivity systems	• Mature does
		• Yearlings
		• Bucks
		• Kids (<1 yr)
Mature Swine	High Productivity Systems	• Sows in gestation
		• Sows which have farrowed and are nursing young
		• Boars that are used for breeding purposes
	Low Productivity Systems	• Sows in gestation
		• Sows which have farrowed and are nursing young
		• Boars that are used for breeding purposes
Growing Swine	High Productivity Systems	• Nursery
		• Growing/Finishing
		• Gilts that will be used for breeding purposes
		• Growing boars that will be used for breeding purposes
	Low Productivity Systems	• Growing / fattening swine
		• Free-range growing swine
		• Gilts/boars that will be used for breeding purposes
Chickens	High Productivity Systems	• Broiler chickens grown for producing meat in confinement systems • Breeder Broiler chickens grown in confinement systems
		• Layer chickens for producing eggs, where manure is managed in dry systems (e.g., high-rise houses)
		• Layer chickens for producing eggs, where manure is managed in wet systems (e.g., lagoons)
		• Chickens under free-range conditions for egg or meat production
	Low Productivity Systems	• Chickens under free-range conditions for egg or meat production
Turkeys	High Productivity Systems	• Breeding turkeys in confinement systems
		• Turkeys grown for producing meat in confinement systems
		• Turkeys under free-range conditions for meat production
	Low Productivity Systems	• Turkeys under free-range conditions for meat production

TABLE 10.1 (UPDATED) (CONTINUED) Representative livestock categories[1,2]		
Main categories	**Production categories Tier 1a**	**Subcategories**
Ducks	• Breeding ducks	
	• Ducks grown for producing meat	
Others (for example)	• Camels	
	• Mules and Asses	
	• Llamas, Alpacas	
	• Fur bearing animals	
	• Rabbits	
	• Horses	
	• Deer	
	• Ostrich	
	• Geese	
[1] Source IPCC Expert Group [2] Emissions should only be considered for livestock species used to produce food, fodder or raw materials used for industrial processes.		

For large countries or for countries with distinct regional differences, it may be useful to designate regions and then define categories within those regions. Regional subdivisions may be used to represent differences in climate, feeding systems, diet, and manure management. However, this further segregation is only useful if correspondingly detailed data are available on feeding and manure management system usage by these livestock categories.

The livestock classification that is chosen should be consistent for all emission sources, enteric and manure management methane and N_2O from manure management. For each of the representative animal categories defined, the following information is required:

- Annual average population (number of livestock or poultry as per calculations for Tier 1);
- Average daily feed intake (megajoules (MJ) per day or kg per day); and
- Methane conversion factor (Y_m) percentage of feed energy converted to methane;

Generally, data on average daily feed intake are not available, particularly for grazing livestock. Consequently, the following general data should be collected for estimating the feed intake for each representative animal category;

- Weight (kg);
- Average weight gain per day (kg)[1];
- Feeding situation: confined, grazing, pasture conditions;
- Average milk production per day (kg/day), fat and protein content;
- Average amount of work performed per day (hours day^{-1});
- Percentage of females that give birth in a year[2];
- Wool growth;
- Number of offspring;
- Digestibility of feed, expressed as the percentage of digestible energy in feed gross energy (DE, percent);
- Crude protein in diet (CP, percent);

[1] This may be assumed to be zero for mature animals.

[2] This is only relevant for mature females.

- Neutral Detergent Fibre (NDF, % DMI), proportion of feed composed of insoluble fibres, hemicellulose, cellulose, lignin and some protein fractions.

Feed intake estimates

Tier 2 emissions estimates require feed intakes for a representative animal in each subcategory. Feed intake is typically measured in terms of gross energy (e.g., mega joules (MJ) per day) or dry matter (e.g., kilograms (kg)) consumed per day. Dry matter is the amount of feed consumed (kg) after it has been corrected for the water content in the complete diet. For example, consumption of 10 kg of a diet that contains 70 percent dry matter would result in a dry matter intake of 7 kg. To support the enteric fermentation Tier 2 method for cattle, buffalo, and sheep (see Section 10.3), detailed data requirements and equations to estimate feed intake are included in the guidance below. Constants in the equations have been combined to simplify overall equation formats. The remainder of this subsection presents the typical data requirements and equations used to estimate feed intake for cattle, buffalo, sheep and goats. Feed intake for other species can be estimated using similar country-specific methods appropriate for each.

For all estimates of feed intake, *good practice* is to:

- Collect data to describe the animal's typical diet and performance in each subcategory;
- Estimate feed intake required from the animal performance and diet data for each subcategory.

In some cases, the equations may be applied on a seasonal basis, for example under conditions in which livestock gain weight in one season and lose weight in another. This approach may require a more refined variation of Tier 2 or more complex Tier 3 type methodology.

The following animal performance data are required for each animal subcategory to estimate feed intake for the subcategory:

Weight (W), kg: Live-weight data should be collected for each animal subcategory. It is unrealistic to perform a complete census of live-weights, so live-weight data should be obtained from representative sample studies or statistical databases if these already exist. Comparing live-weight data with slaughter-weight data is a useful cross-check to assess whether the live-weight data are representative of country conditions. However, slaughter-weight data should not be used in place of live-weight data as it fails to account for the complete weight of the animal. Additionally, it should be noted that the relationship between live-weight and slaughter-weight varies with breed and body condition. For cattle, buffalo and mature sheep, the yearly average weight for each animal category (e.g., mature beef cows) is needed. For young animals, weights are needed at birth, weaning, one year of age or at slaughter if slaughter occurs within the year. Slaughter weights can be utilized in live weight estimations if slaughter ages, dressing percentages and growth curves are also available.

Average weight gain per day (WG), kg day^{-1}: Data on average weight gain are generally collected for feedlot animals and young growing animals. Mature animals are generally assumed to have no net weight gain or loss over an entire year. Mature animals frequently lose weight during the dry season or during temperature extremes and gain weight during the following season. However, increased emissions associated with this weight change are likely to be small. Reduced intakes and emissions associated with weight loss are largely balanced by increased intakes and emissions during the periods of gain in body weight.

Mature weight (MW), kg: The mature weight of the adult animal of the inventoried group is required to define a growth pattern, including the feed and energy required for growth. For example, mature weight of a breed or category of cattle or buffalo is generally considered to be the body weight at which skeletal development is complete. The mature weight will vary among breeds and should reflect the animal's weight when in moderate body condition. This is termed 'reference weight' (AAC 1990) or 'final shrunk body weight' (NRC 1996). Estimates of mature weight are typically available from livestock specialists and producers. Mature weights of bulls may be 1.5 times higher than cows in the same genotype (Doren *et al*. 1989).

Average number of hours worked per day: For draft animals, the average number of hours worked per day must be determined.

Feeding situation: The feeding situation that most accurately represents the animal subcategory must be determined using the definitions shown below (Table 10.5). If the feeding situation is intermediate to the definitions given, the feeding situation should be described in detail. This detailed information may be needed when calculating the enteric fermentation emissions, because interpolation between the feeding situations may be necessary to assign the most appropriate coefficient value. Table 10.5 defines the feeding situations for cattle, buffalo, sheep and goats. For poultry and swine, the feeding situation is assumed to be under confinement conditions and consequently the activity coefficient (C_a) is assumed to be zero as under these conditions very little energy is expended in acquiring feed. Activity coefficients have not been developed for free-ranging swine or

poultry, but in most instances these livestock subcategories are likely to represent a small proportion of the national inventory.

Mean winter temperature (ºC): Detailed feed intake models consider ambient temperature, wind speed, hair and tissue insulation and the heat of fermentation (NRC, 2001; AAC, 1990) and are likely more appropriate in Tier 3 applications. A more general relationship adapted from North America data suggest adjusting the Cf_i of Equation 10.3 during the cold months for maintenance requirements of open-lot fed cattle in colder climates according to the following equation (Johnson, 1986):

EQUATION 10.2
COEFFICIENT FOR CALCULATING NET ENERGY FOR MAINTENANCE

$$Cf_i(in_cold) = Cf_i + 0.0048 \bullet (20 - °C)$$

Where:

Cf_i = a coefficient which varies for each animal category as shown in Table 10.4 (Coefficients for calculating NE_m), MJ day^{-1} kg^{-1}

$°C$ = mean daily temperature during winter season

Considering the average temperature during winter months, net energy for maintenance (NE_m) requirements may increase by as much as 30 percent in northern North America. This increase in feed use for maintenance leads to greater methane emissions. The Nutrient Requirements of Beef Cattle, 8th Revised Edition (2016) cautions that the general response to cold temperature can vary with thermal susceptibility of the animal, acclimation, and diet. Thus, Equation 10.2 may not be applicable for adapted animals, or for those protected by wind-breaks or shelter during cold weather. The equation should be applied to adjust the annual Cf_i for unsheltered animals during the period in which they are first exposed to sub-zero (ºC) temperatures, prior to their acclimation (a period of one to two months depending on the region).

Average daily milk production (kg day^{-1}): These data are for milking ewes, milking does, dairy cows and buffalo. The average daily production should be calculated by dividing the total annual production by 365, or reported as average daily production along with days of lactation per year, or estimated seasonal production divided by number of days per season. If using seasonal production data, the emission factor must be developed for seasonal period.

Fat content (percent): Average fat content of milk is required for lactating cows, buffalo, sheep and goats producing milk for human consumption.

Protein content (percent): Average protein content of milk is required for lactating cows, buffalo, sheep, and goats producing milk for human consumption.

Percent of females that give birth in a year: This is collected for cattle, buffalo, sheep and goats.

Number of off spring produced per year: This is relevant to female livestock that have multiple births per year (e.g., ewes).

Weaning age of calves: Prior to weaning and to the development of an active rumen, calves do not emit methane. Since calves pre-weaning is a livestock subcategory, it will in any case be necessary for a country to determine the weaning age and the diet composition pre-weaning to choose the appropriate emission factor.

Feed digestibility (DE): The portion of gross energy (GE) in the feed not excreted in the faeces is known as digestible energy expressed as a percentage (percent). Feed digestibility is commonly expressed as a percentage of GE or as TDN (total digestible nutrients). The percentage of feed that is not digested represents the percent of GE intake that will be excreted as faeces. Typical digestibility (DE) values for a range of livestock classes and diet types are presented in Table 10.2 as a guideline. The values have been refined compared to the *2006 IPCC Guidelines*, based on more recent information (Table 10.2). For ruminants, common ranges of feed digestibility are 45-55 percent for crop by-products and range lands[3]; 55-80 percent for managed pastures, well preserved forages, crop by-products and grain supplemented forage-based diets; and 72-85 percent for grain-based diets fed

[3] Rangelands are defined as land primarily covered by natural grasslands, savannas, woodlands (not meeting the definition of Forest Land) and shrublands, including introduced plant species that are naturalised (Grice *et al*. 2008).

in feedlots. Variation in diet digestibility results directly in major variation in the estimated amount of feed needed to meet animal requirements and consequently is a main cause of variation in associated methane emissions and in the amounts of manure excreted (next to variation in yield of methane per unit of digested GE as explained further in Section 10.3).

A low digestibility of feed will lead to lower feed intake and consequently reduced growth but at the same time a larger production of associated methane per unit of growth or production. Conversely, feeds with high digestibility will often result in higher feed intake and increased growth but at the same time a smaller amount of feed required per unit of growth and consequently lower associated methane production per unit growth or production. A factor directly affecting feed digestibility is the rate of passage of feed in the digestive tract, in particular in high productivity dairy cows (NRC 2001; Nousiainen *et al*. 2009) with direct impact on methane production as well, though in current Tier 2 methodology this impact is resolved through the selection of appropriate methane conversion rates instead of appropriate digestibility estimates (see Section 10.3.2).

A change of 10 percent in DE will be magnified to change in 12 to 20 percent when estimating methane emissions and even more (20 to 45 percent) for amounts of manure excreted (volatile solids). It is important to note that feed requirements, feed digestibility, production and growth, and yield of methane from digested GE (explained further in Section 10.3) are co-dependent phenomena.

Digestibility data should be based on measured values for the dominant feeds or forages being consumed by livestock with consideration for seasonal variation. In general, the digestibility of forages decreases with increasing maturity and is typically lowest during hot weather or dry season. Due to significant variation, digestibility values should be obtained from local scientific data wherever possible. Although a complete census of digestibility is considered unrealistic, at a minimum digestibility data from research studies should be consulted. While developing the digestibility data, associated feed characteristic data should also be recorded when available, such as feed content of neutral detergent fiber (NDF), acid detergent fiber (ADF), crude protein, crude fat, ash and the presence of anti-nutritional factors (e.g., alkaloids, phenolics). NDF and ADF are feed characteristics measured in the laboratory that are used to indicate the nutritive value of the feed for ruminant livestock. Determination of these values can enable DE to be predicted as defined in the last dairy National Research Council (2008) publication. The concentration of crude protein in the feed can be used in the process of estimating nitrogen excretion (Section 10.5.2). Accurate estimation of the crude fat content of feed is important, especially in the case of high-fat feeds, for accurate estimation of the GE content in feed, which is needed to calculate feed intake needed to achieve GE requirements (Section 10.2.2.).

Protein content in diet (CP, percent) – the total amount of protein present in animal diet. It is determined by analysing the nitrogen content in animal feed and multiplying by 6.25. The data on CP percent is required for the calculation of N excretion using a Tier 2 method.

Average annual wool production per sheep and goats (kg yr^{-1}): The amount of wool produced in kilograms (after drying out but before scouring) is needed to estimate the amount of energy allocated for wool production. For goats this is only applicable if the country has relevant numbers of fibre-producing goats.

TABLE 10.2 (UPDATED)
REPRESENTATIVE FEED DIGESTIBILITY FOR VARIOUS LIVESTOCK CATEGORIES

Main categories	Class	Digestibility (DE as percent)
Swine[1]	Mature Swine – confinement	70 - 80
	Growing Swine - confinement	80 - 90
	Swine – free range	50 - 70
Cattle and other ruminants	Feedlot animals fed with > 85% concentrate or high-grain diet	72 - 85
	Pasture / mixed-diet fed animals	55 - 80
	Animals fed – low quality forage	45 - 55
Poultry[1]	Broiler Chickens –confinement	85 - 93
	Layer Hens – confinement	70 - 80
	Poultry – free range	55 - 90[1]
	Turkeys – confinement	85 - 93
	Geese – confinement	80 - 90

[1] The range in digestibility of feed consumed by free-range swine and poultry is extremely variable due to the selective nature of these diets. Often it is likely that the amount of manure produced in these classes will be limited by the amount of feed available for consumption as opposed to its degree of digestibility. In instances where feed is not limiting and high quality feed sources are readily accessible for consumption, digestibility may approach values that are similar to those measured under confinement conditions.

Gross energy calculations

Animal performance and diet data are used to estimate feed intake which is the amount of energy (MJ/day) animal needs for maintenance and for such as growth, lactation, and pregnancy. For inventory compilers who have well-documented and recognised country-specific methods for estimating intake based on animal performance data, it is *good practice* to use the country-specific methods. The following section provides methods for estimating gross energy intake for the key ruminant categories of cattle, buffalo, sheep and goats. The equations listed in Table 10.3 are used to derive this estimate. If no country-specific methods are available, intake should be calculated using the equations listed in Table 10.3. As shown in the table, separate equations are used to estimate net energy requirements for sheep and goats as compared with cattle and buffalo. The equations used to calculate GE are as follows:

TABLE 10.3 (UPDATED)
SUMMARY OF THE EQUATIONS USED TO ESTIMATE DAILY GROSS ENERGY INTAKE FOR CATTLE, BUFFALO AND SHEEP AND GOATS

Metabolic functions and other estimates	Equations for cattle and buffalo	Equations for sheep and goats
Maintenance (NE_m)	Equation 10.3	Equation 10.3
Activity (NE_a)	Equation 10.4	Equation 10.5
Growth (NE_g)	Equation 10.6	Equation 10.7
Lactation (NE_l)*	Equation 10.8	Equations 10.9 and 10.10
Draft Power (NE_{work})	Equation 10.11	NA
Wool Production (NE_{wool})	NA	Equation 10.12
Pregnancy (NE_p)*	Equation 10.13	Equation 10.13
Ratio of net energy available in diet for maintenance to digestible energy consumed (REM)	Equation 10.14	Equation 10.14
Ratio of net energy available for growth in a diet to digestible energy consumed (REG)	Equation 10.15	Equation 10.15
Gross Energy	Equation 10.16	Equation 10.16

Source: Cattle and buffalo equations based on NRC (1996) and sheep and goats based on AFRC (1993; 1995).
NA means 'not applicable'.
* Applies only to the proportion of females that give birth.

Net energy for maintenance: (NE_m) is the net energy required for maintenance, which is the amount of energy needed to keep the animal in equilibrium where body energy is neither gained nor lost (Jurgens 1988).

EQUATION 10.3
NET ENERGY FOR MAINTENANCE

$$NE_m = Cf_i \bullet (Weight)^{0.75}$$

Where:

NE_m = net energy required by the animal for maintenance, MJ day^{-1}

Cf_i = a coefficient which varies for each animal category as shown in Table 10.4 (Coefficients for calculating NE_m), MJ day^{-1} kg^{-1}

Weight = live-weight of animal, kg

TABLE 10.4 (UPDATED)
COEFFICIENTS FOR CALCULATING NET ENERGY FOR MAINTENANCE (NE_M)

ANIMAL CATEGORY	C_{FI} (MJ D^{-1} KG^{-1})	COMMENTS
Cattle/Buffalo	0.322	All non-lactating cows, steers, heifers and calves
Cattle/Buffalo (lactating cows)	0.386	Maintenance energy requirements are 20% higher during lactation
Cattle/Buffalo (bulls)	0.370	Maintenance energy requirements are 15% higher for intact males than non lactating females
Sheep (lamb to 1 year)	0.236	This value can be increased by 15% for intact males
Sheep (older than 1 year)	0.217	This value can be increased by 15% for intact males.
Goats	0.315	

Source: NRC (1996) and AFRC (1993; 1995).

Net energy for activity: (NE_a) is the net energy for activity, or the energy needed for animals to obtain their food, water and shelter. It is based on its feeding situation rather than characteristics of the feed itself. As presented in Table 10.3, the equation for estimating NE_a for cattle and buffalo is different from the equation used for sheep and goats. Both equations are empirical with different definitions for the coefficient C_a.

EQUATION 10.4
NET ENERGY FOR ACTIVITY (FOR CATTLE AND BUFFALO)

$$NE_a = C_a \bullet NE_m$$

Where:

NE_a = net energy for animal activity, MJ day^{-1}

C_a = coefficient corresponding to animal's feeding situation (Table 10.5, Activity coefficients), dimensionless

NE_m = net energy required by the animal for maintenance (Equation 10.3), MJ day^{-1}

EQUATION 10.5
NET ENERGY FOR ACTIVITY (FOR SHEEP AND GOATS)

$$NE_a = C_a \bullet (weight)$$

Where:

NE_a = net energy for animal activity, MJ day^{-1}

C_a = coefficient corresponding to animal's feeding situation (Table 10.5), MJ day^{-1} kg^{-1}

weight = live-weight of animal, kg

For Equations 10.4 and 10.5, the coefficient C_a corresponds to a representative animal's feeding situation as described earlier. Values for C_a are shown in Table 10.5. If a mixture of these feeding situations occurs during the year, NE_a must be weighted accordingly.

TABLE 10.5 (UPDATED)
ACTIVITY COEFFICIENTS CORRESPONDING TO ANIMAL'S FEEDING SITUATION

Situation	Definition	C_a
Cattle and Buffalo (unit for C_a is dimensionless)		
Stall	Animals are confined to a small area (i.e., tethered, pen, barn) with the result that they expend very little or no energy to acquire feed.	0
Pasture	Animals are confined in areas with sufficient forage requiring modest energy expense to acquire feed.	0.17
Grazing large areas	Animals graze in open range land or hilly terrain and expend significant energy to acquire feed.	0.36
Sheep and goats (unit for C_a = MJ d^{-1} kg^{-1})		
Housed ewes	Animals are confined due to pregnancy in final trimester (50 days).	0.0096
Grazing flat pasture	Animals walk up to 1000 meters per day and expend very little energy to acquire feed.	0.0107
Grazing hilly pasture	Animals walk up to 5,000 meters per day and expend significant energy to acquire feed.	0.024
Housed fattening lambs	Animals are housed for fattening.	0.0067
Lowland goats	Animals walk and graze in lowland pasture.	0.019
Hill and mountain goats	Animals graze in open range land or hilly terrain and expend significant energy to acquire feed.	0.024

***Net energy for growth*:** (NE_g) is the net energy needed for growth (i.e., weight gain). Equation 10.6 is based on NRC (1996). Equation 10.7 is based on Gibbs *et al*. (2002). Constants for conversion from calories to joules and live to shrunk and empty body weight have been incorporated into the equation.

EQUATION 10.6
NET ENERGY FOR GROWTH (FOR CATTLE AND BUFFALO)

$$NE_g = 22.02 \bullet \left(\frac{BW}{C \bullet MW} \right)^{0.75} \bullet WG^{1.097}$$

Where:

NE_g = net energy needed for growth, MJ day^{-1}

BW = the average live body weight (BW) of the animals in the population, kg

C = a coefficient with a value of 0.8 for females, 1.0 for castrates and 1.2 for bulls (NRC, 1996)

MW = the mature body weight of an adult animal individually, mature females, mature males and steers) in moderate body condition[4], kg

WG = the average daily weight gain of the animals in the population, kg day^{-1}

[4] Since statistical offices may collect and report data on highly disaggregated number of cattle population (e.g., bovines less than one year old or bovines aged under 8 months, cattle aged between one and two years old), hence, this parameter (i.e., mature weight) may refer to target weight related to stage of growth. Herewith, the number of days needed for animals to reach from the beginning of growing stage to target weight of this growing stage should be taken into consideration.

EQUATION 10.7
NET ENERGY FOR GROWTH (FOR SHEEP AND GOATS) (UPDATED)

$$NE_g = \frac{WG_{lamb/kid} \bullet \left(a + 0.5b\left(BW_i + BW_f\right)\right)}{365}$$

Where:

NE_g = net energy needed for growth, MJ day^{-1}

$WG_{lamb/kid}$ = the weight gain ($BW_f - BW_i$), kg yr^{-1}

BW_i = the live bodyweight at weaning, kg

BW_f = the live bodyweight at 1-year old or at slaughter (live-weight) if slaughtered prior to 1 year of age, kg

a, b = constants as described in Table 10.6.

Note that lambs will be weaned over a period of weeks as they supplement a milk diet with pasture feed or supplied feed. The time of weaning should be taken as the time at which they are dependent on milk for half their energy supply.

The NE_g equation used for sheep and goats includes two empirical constants (a and b) that vary by animal species/category (Table 10.6).

TABLE 10.6 (UPDATED)
CONSTANTS FOR USE IN CALCULATING NE_G FOR SHEEP AND GOATS

Animal species/category	a (MJ kg^{-1})	b (MJ kg^{-1})
Intact males (Sheep)	2.5	0.35
Castrates (Sheep)	4.4	0.32
Females (Sheep)	2.1	0.45
Goats (all categories)	5.0	0.33

Source: AFRC (1993; 1995).

***Net energy for lactation*:** (NE_l) is the net energy for lactation. For cattle and buffalo the net energy for lactation is expressed as a function of the amount of milk produced and its fat content expressed as a percentage (e.g., 4 percent) (NRC 1989):

EQUATION 10.8
NET ENERGY FOR LACTATION (FOR BEEF CATTLE, DAIRY CATTLE AND BUFFALO)

$$NE_l = Milk \bullet \left(1.47 + 0.40 \bullet Fat\right)$$

Where:

NE_l = net energy for lactation, MJ day^{-1}

Milk = amount of milk produced, kg of milk day^{-1}

Fat = fat content of milk, percent by weight

Two methods for estimating the net energy required for lactation (NE_l) are presented for sheep. The first method (Equation 10.9) is used when the amount of milk produced is known, and the second method (Equation 10.10) is used when the amount of milk produced is not known. Generally, milk production is known for ewes kept for

commercial milk production, but it is not known for ewes that suckle their young to weaning. With a known amount of milk production, the total annual milk production is divided by 365 days to estimate the average daily milk production in kg/day (Equation 10.9). When milk production is not known, AFRC (1990) indicates that for a single birth, the milk yield is about 5 times the weight gain of the lamb. For multiple births, the total annual milk production can be estimated as five times the combined weight gain of all lambs birthed by a single ewe. The daily average milk production is estimated by dividing the resulting estimate by 365 days as shown in Equation 10.10.

EQUATION 10.9 (UPDATED)
NET ENERGY FOR LACTATION FOR SHEEP AND GOATS (MILK PRODUCTION KNOWN)

$$NE_1 = Milk \bullet EV_{milk}$$

Where:

NE_1 = net energy for lactation, MJ day^{-1}

$Milk$ = amount of milk produced, kg of milk day^{-1}

EV_{milk} = the net energy required to produce 1 kg of milk.

EQUATION 10.10
NET ENERGY FOR LACTATION FOR SHEEP AND GOATS (MILK PRODUCTION UNKNOWN)

$$NE_1 = \left[\frac{(5 \bullet WG_{wean})}{365} \right] \bullet EV_{milk}$$

Where:

NE_1 = net energy for lactation, MJ day^{-1}

WG_{wean} = the weight gain of the lamb between birth and weaning, kg

EV_{milk} = the energy required to produce 1 kg of milk, MJ kg^{-1}. A default EV_{milk} value of 4.6 MJ/kg (sheep) (AFRC 1993; AFRC 1995) and 3 MJ/kg (goats) (AFRC 1998) can be used which corresponds to a milk fat content of 7 percent and 3.8 percent by weight for sheep and goats, respectively. Milk fat can vary greatly among breeds. Compilers are encouraged to use country-specific milk fat content to derive EV_{milk} when available

***Net energy for work*:** (NE_{work}) is the net energy for work. It is used to estimate the energy required for draft power for cattle and buffalo. Various authors have summarised the energy intake requirements for providing draft power (Bamualim & Kartiarso 1985; Ibrahim 1985; Lawrence 1985). The strenuousness of the work performed by the animal influences the energy requirements, and consequently a wide range of energy requirements have been estimated. The values by Bamualim and Kartiarso show that about 10 percent of a day's NE_m requirements are required per hour for typical work for draft animals. This value is used as follows:

EQUATION 10.11
NET ENERGY FOR WORK (FOR CATTLE AND BUFFALO)

$$NE_{work} = 0.10 \bullet NE_m \bullet Hours$$

Where:

NE_{work} = net energy for work, MJ day^{-1}

NE_m = net energy required by the animal for maintenance (Equation 10.3), MJ day^{-1}

$Hours$ = number of hours of work per day

Net energy for wool production: (NE_{wool}) is the average daily net energy required for sheep to produce a year of wool. The NE_{wool} is calculated as follows:

EQUATION 10.12 (UPDATED)
NET ENERGY TO PRODUCE WOOL (FOR SHEEP AND GOATS)

$$NE_{wool} = \left(\frac{EV_{wool} \bullet Pr_{wool}}{365} \right)$$

Where:

NE_{wool} = net energy required to produce wool, MJ day^{-1}

EV_{wool} = the energy value of each kg of wool produced (weighed after drying but before scouring), MJ kg^{-1}. A default value of 24 MJ kg^{-1} can be used for sheep estimate. For goats this energy value is not considered unless fibre-producing goat numbers are relevant for a country (AFRC 1995).

Pr_{wool} = annual wool production per sheep/goat, kg yr^{-1}

For fibre-producing sheep NE_{wool} can be estimated that 0.25 MJ day^{-1} is retained in the fibre (AFRC 1993; AFRC 1995). For fibre-producing goats NE_{wool} can be estimated that 0.25 and 0.08 MJ/day for angora and cashmere breeds (AFRC 1993; AFRC 1995), respectively.

Net energy for pregnancy: (NE_p) is the energy required for pregnancy. For cattle and buffalo, the total energy requirement for pregnancy for a 281-day gestation period averaged over an entire year is calculated as 10 percent of NE_m. For sheep, the NE_p requirement is similarly estimated for the 147-day gestation period, although the percentage varies with the number of lambs born (Table 10.7, Constant for Use in Calculating NE_p in Equation 10.13). Equation 10.13 shows how these estimates are applied.

EQUATION 10.13 (UPDATED)
NET ENERGY FOR PREGNANCY (FOR CATTLE/BUFFALO AND SHEEP AND GOATS)

$$NE_p = C_{pregnancy} \bullet NE_m$$

Where:

NE_p = net energy required for pregnancy, MJ day^{-1}

$C_{pregnancy}$ = pregnancy coefficient (see Table 10.7)

NE_m = net energy required by the animal for maintenance (Equation 10.3), MJ day^{-1}

TABLE 10.7 (UPDATED)
CONSTANTS FOR USE IN CALCULATING NE_P IN EQUATION 10.13

Animal category	$C_{pregnancy}$
Cattle and Buffalo	0.10
Sheep/Goats	
Single birth	0.077
Double birth (twins)	0.126
Triple birth or more (triplets)	0.150

Source: Estimate for cattle and buffalo developed from data in NRC (1996). Estimates for sheep developed from data in AFRC (1993); AFRC (1995), taking into account the inefficiency of energy conversion.

When using NE_p to calculate GE for cattle, sheep and goats, the NE_p estimate must be weighted by the portion of the mature females that actually go through gestation in a year. For example, if 80 percent of the mature females in the animal category give birth in a year, then 80 percent of the NE_p value would be used in the GE equation below.

To determine the proper coefficient for sheep/goats, the portion of ewes/does that have single births, double births, and triple births is needed to estimate an average value for $C_{pregnancy}$. If these data are not available, the coefficient can be calculated as follows:

- If the number of lambs/kids born in a year divided by the number of ewes that are pregnant in a year is less than or equal to 1.0, then the coefficient for single births can be used.
- If the number of lambs/kids born in a year divided by the number of ewes/does that are pregnant in a year exceeds 1.0 and is less than 2.0, calculate the coefficient as follows:

$$C_{pregnancy} = [(0.126 \bullet \text{Double birth fraction}) + (0.077 \bullet \text{Single birth fraction})]$$

Where:

Double birth fraction = [(lambs born / pregnant ewes) – 1]

Single birth fraction = [1 – Double birth fraction]

***Ratio of net energy available in diet for maintenance to digestible energy consumed (REM)*:** For cattle, buffalo, sheep and goats, the ratio of net energy available in a diet for maintenance to digestible energy (REM) is estimated using the following equation (Gibbs & Johnson 1993):

EQUATION 10.14
RATIO OF NET ENERGY AVAILABLE IN A DIET FOR MAINTENANCE TO DIGESTIBLE ENERGY

$$REM = \left[1.123 - \left(4.092 \bullet 10^{-3} \bullet DE\right) + \left(1.126 \bullet 10^{-5} \bullet \left(DE\right)^2\right) - \left(\frac{25.4}{DE}\right)\right]$$

Where:

REM = ratio of net energy available in diet for maintenance to digestible energy

DE = digestibility of feed expressed as a fraction of gross energy (digestible energy/gross energy*100, i.e. DE%)

***Ratio of net energy available for growth in a diet to digestible energy consumed (REG)*:** For cattle, buffalo, sheep and goats the ratio of net energy available for growth (including wool growth) in a diet to digestible energy consumed (REG) is estimated using the following equation (Gibbs & Johnson 1993):

EQUATION 10.15
RATIO OF NET ENERGY AVAILABLE FOR GROWTH IN A DIET TO DIGESTIBLE ENERGY CONSUMED

$$REG = \left[1.164 - \left(5.16 \bullet 10^{-3} \bullet DE \right) + \left(1.308 \bullet 10^{-5} \bullet \left(DE \right)^2 \right) - \left(\frac{37.4}{DE} \right) \right]$$

Where:

REG = ratio of net energy available for growth in a diet to digestible energy consumed

DE = digestibility of feed expressed as a fraction of gross energy (digestible energy/gross energy*100, i.e. DE%)

Gross energy, GE: As shown in Equation 10.16, GE requirement is derived based on the summed net energy requirements and the energy availability characteristics of the feed(s). Equation 10.16 represents *good practice* for calculating GE requirements for cattle, buffalo, sheep and goats using the results of the equations presented above.

In using Equation 10.16, only those terms relevant to each animal category are used (see Table 10.3).

EQUATION 10.16 (UPDATED)
GROSS ENERGY FOR CATTLE/BUFFALO, SHEEP AND GOATS

$$GE = \left[\frac{\left(\frac{NE_m + NE_a + NE_l + NE_{work} + NE_p}{REM} \right) + \left(\frac{NE_g + NE_{wool}}{REG} \right)}{DE} \right]$$

Where:

GE = gross energy, MJ day^{-1}

NE_m = net energy required by the animal for maintenance (Equation 10.3), MJ day^{-1}

NE_a = net energy for animal activity (Equations 10.4 and 10.5), MJ day^{-1}

NE_l = net energy for lactation (Equations 10.8, 10.9, and 10.10), MJ day^{-1}

NE_{work} = net energy for work (Equation 10.11), MJ day^{-1}

NE_p = net energy required for pregnancy (Equation 10.13), MJ day^{-1}

REM = ratio of net energy available in a diet for maintenance to digestible energy (Equation 10.14)

NE_g = net energy needed for growth (Equations 10.6 and 10.7), MJ day^{-1}

REG = ratio of net energy available for growth in a diet to digestible energy consumed (Equation 10.15)

NE_{wool} = net energy required to produce a year of wool (Equation 10.12), MJ day^{-1}

DE = digestibility of feed expressed as a fraction of gross energy (digestible energy/gross energy, i.e. DE%/100)

Once the values for GE are calculated for each animal subcategory, the feed intake in units of kilograms of dry matter per day (kg day^{-1}) should also be calculated. To convert from GE in energy units to dry matter intake (DMI), divide GE by the energy density of the feed. A default value of 18.45 MJ kg^{-1} of dry matter can be used if feed-specific information is not available. The resulting daily dry matter intake should be in the order of 2 percent to 3 percent of the body weight of the mature or growing animals. In high producing milk cows, intakes may exceed 4 percent of body weight.

Feed intake estimates using a simplified Tier 2 method

Prediction of DMI for cattle based on body weight and estimated dietary net energy concentration (NE_{mf}) and digestibility values (DE): It is also possible to predict dry matter intake for mature and growing cattle based on body weight of the animal, and either the dietary net energy of maintenance concentration of the feed NE_{mf} (MJ kg^{-1} DM) (National Academies of Sciences, Engineering and Medicine 2016) or DE, and for lactating dairy cows, fat corrected milk production. Dietary NE_{mf} concentration can range from 3.0 to 9.0 MJ kg^{-1} of dry matter. Typical values for high, moderate and low quality diets are presented in Table 10.8a. These figures can also be used to estimate NE_{mf} values for mixed diets based on estimate of diet quality. For example, a mixed forage-grain diet could be assumed to have a NE_{mf} value similar to that of a high-quality forage diet. A mixed grain-straw diet could be assumed to have a NE_{mf} value similar to that of a moderate quality forage. Nutritionists within specific geographical areas should be able to provide advice with regard to the selection of NE_{mf} values that are more representative of locally fed diets.

Dry matter intake for calves is estimated using the following equation:

EQUATION 10.17 (NEW)
ESTIMATION OF DRY MATTER INTAKE FOR CALVES

$$DMI = BW^{0.75} \bullet \left[\frac{\left(0.0582 \bullet NE_{mf} - 0.00266 \bullet NE_{mf}^{2} - 0.1128\right)}{0.239 \bullet NE_{mf}} \right]$$

Where:

DMI = dry matter intake, kg day^{-1}

BW = live body weight, kg

NE_{mf} = estimated dietary net energy concentration of diet or default values in Table 10.8a, MJ kg^{-1}

Dry matter intake for growing cattle is estimated using the following equation:

EQUATION 10.18 (NEW)
ESTIMATION OF DRY MATTER INTAKE FOR GROWING CATTLE

$$DMI = BW^{0.75} \bullet \left[\frac{\left(0.0582 \bullet NE_{mf} - 0.00266 \bullet NE_{mf}^{2} - 0.0869\right)}{0.239 \bullet NE_{mf}} \right]$$

Where:

DMI = dry matter intake, kg day^{-1}

BW = live body weight, kg

NE_{mf} = estimated dietary net energy concentration of the feed or diet with default values in Table 10.8a, MJ kg^{-1} DM^{-1}

Dry matter intake for feedlot cattle (on high grain diets) is estimated using the following equation:

EQUATION 10.18A (UPDATED)
ESTIMATION OF DRY MATTER INTAKE FOR STEERS AND BULLS

$$DMI = 3.83 + 0.0143 \bullet BW \bullet 0.96$$

ESTIMATION OF DRY MATTER INTAKE FOR HEIFERS

$$DMI = 3.184 + 0.01536 \bullet BW \bullet 0.96$$

Where:

DMI = dry matter intake, kg day^{-1}

BW = live body weight, kg

For mature beef cows use the following values (National Academies of Sciences, Engineering and Medicine 2016)

TABLE 10.8 (NEW)
DMI REQUIRED BY MATURE NON DAIRY COWS BASED ON FORAGE QUALITY

Forage type	Digestibility (DE, %)	Forage DMI capacity (kg/day), % of BW (kg)	
		Non-lactating	Lactating
Low quality	<52	1.8	2.2
Average quality	52-59	2.2	2.5
High quality	>59	2.5	2.7

For lactating dairy cows the following equation can be used (Cornell Net Carbohydrate and Protein System (CNCPS), Fox *et al*. 1992) as modified by Arnerdal (2005):

EQUATION 10.18B (UPDATED)
ESTIMATION OF DRY MATTER INTAKE FOR LACTATING DAIRY COWS

$$DMI = 0.0185 \bullet BW + 0.305 \bullet FCM$$

Where:

DMI = dry matter intake, kg day^{-1}

BW = live body weight, kg

FCM = Fat corrected milk, kg day^{-1}, 3.5 percent * [(0.4324 * kg of milk) + (16.216 * kg of fat)].

Equations 10.17, 10.18, 10.18A and 10.18B and values in Table 10.8 provide a good check to the main Tier 2 method to predict feed intake. They can be viewed as asking 'what is an expected intake for a given diet quality?' and in the case that countries do not have the data required to carry out a full estimate of gross energy use for their catle herd, these equations could be used to independently predict DMI from BW, diet quality (NE_{mf} or DE percent) and milk production. In contrast, the main Tier 2 method predicts DMI based on how much feed must be consumed to meet estimated energy requirements (i.e., NE_m and NE_g) and does not consider the biological capacity of the animal to in fact consume the predicted quantity of feed. While the Tier 2 estimate of gross energy is the preferred method, the simplified Tier 2 method can be used to confirm that DMI values derived from the main Tier 2 method are biologically realistic. These estimates are also subject to the cross check that dry matter intake should be in the order of 2 percent to 3 percent of the bodyweight of the mature or growing animals and up to 4 percent for high yielding lactating dairy cattle.

TABLE 10.8A (UPDATED)
EXAMPLES OF NE_{MF} CONTENT OF TYPICAL DIETS FED TO CATTLE FOR ESTIMATION OF DRY MATTER INTAKE IN EQUATIONS 10.17 AND 10.18

Diet type	NE_{mf} (MJ (kg dry matter)$^{-1}$)
High grain diet > 90%	7.5 - 8.5
High quality forage (e.g., vegetative legumes & grasses)	6.5 - 7.5
Moderate quality forage (e.g., mid-season legume & grasses)	5.5 - 6.5
Low quality forage (e.g., straws, mature grasses)	3.5 - 5.5

Source: Estimates obtained from predictive models in NRC (1996), NE_{mf} can also be estimated using the equation: NE_{mf} = REM * 18.45 * DE%/100

10.2.3 Uncertainty assessment

No refinement.

10.2.4 Characterisation for livestock without species: Specific emission estimation methods

Some countries may have domesticated livestock for which there are currently no Tier 1 or Tier 2 emissions estimating methods (e.g., wapiti, bison or emus). *Good practice* in estimating emissions from these livestock is to first assess whether their emissions are likely to be significant enough to warrant characterising them and developing country-specific emission factors. Volume 1, Chapter 4 (Methodological Choice and Identification of *Key Categories*) presents guidance for assessing the significance of individual source categories within the national inventory. Similar approaches can be used to assess the importance of subsource categories (i.e. species) within a source category. If the emissions from a particular sub-species are determined to be significant, then country-specific emission factors should be developed, and a characterisation should be performed to support the development of the emission factors. Research into the estimation of emission levels from these non-characterized species should be encouraged. The data and methods used to characterise the animals should be well documented.

As emissions estimation methods are not available for these animals, approximate emission factors based on 'order of magnitude calculations' are appropriate for conducting the assessment of the significance of their emissions. One approach for developing the approximate emission factors is to use the Tier 1 emissions factor for an animal with a similar digestive system and to scale the emissions factor using the ratio of the weights of the animals raised to the 0.75 power. The Tier 1 emission factors can be classified by digestive system as follows:

- Ruminant animals: Cattle, Buffalo, Sheep, Goats, Camels;
- Non-ruminant herbivores: Horses, Mules/Asses;
- Poultry: Chickens, Ducks, Turkeys, Geese;
- Non-poultry monogastric animals: Swine.

For example, an approximate enteric fermentation methane emissions factor for wapiti could be estimated from the emissions factor for deer (also a ruminant animal) as follows:

Approximate emissions factor = $[(\text{wapiti weight}) / (\text{deer weight})]^{0.75}$ * deer emissions factor

Similarly, an approximate manure methane emissions factor could be estimated for emus using the Tier 1 emission factor for ostriches. Approximate emission factors developed using this method can only be used to assess the significance of the emissions from the animals, and are not considered sufficiently accurate for estimating emissions as part of a national inventory.

10.3 METHANE EMISSIONS FROM ENTERIC FERMENTATION

Methane is produced in herbivores as a by-product of enteric fermentation, a digestive process by which carbohydrates are broken down by micro-organisms into simple molecules for absorption into the bloodstream.

The amount of methane released depends on the type of digestive tract, age, and weight of the animal, and the quality and quantity of the feed consumed. Ruminant livestock (e.g., cattle, sheep) are major sources of methane with moderate amounts produced from non-ruminant livestock (e.g., pigs, horses). The ruminant gut structure fosters extensive enteric fermentation of their diet.

Digestive system

The type of digestive system has a significant influence on the rate of methane emission. Ruminant livestock have an expansive chamber known as the rumen, located at the fore-part of their digestive tract. The rumen supports intensive microbial fermentation of the diet, which yields several nutritional advantages including the capacity to digest cellulose (the major component of fiber). The main ruminant livestock are cattle, buffalo, goats, sheep, deer and camelids. Non-ruminant livestock (horses, mules, asses) and monogastric livestock (swine) have relatively lower methane emissions because much less methane-producing fermentation takes place in their digestive systems.

Feed intake

Methane is produced by the fermentation of feed within the animal's digestive system. Generally, the higher the feed intake, the higher the methane emission. Although, methane production is also affected by the composition of the diet. Feed intake is positively related to animal size, growth rate, and production (e.g., milk production, wool growth, or pregnancy).

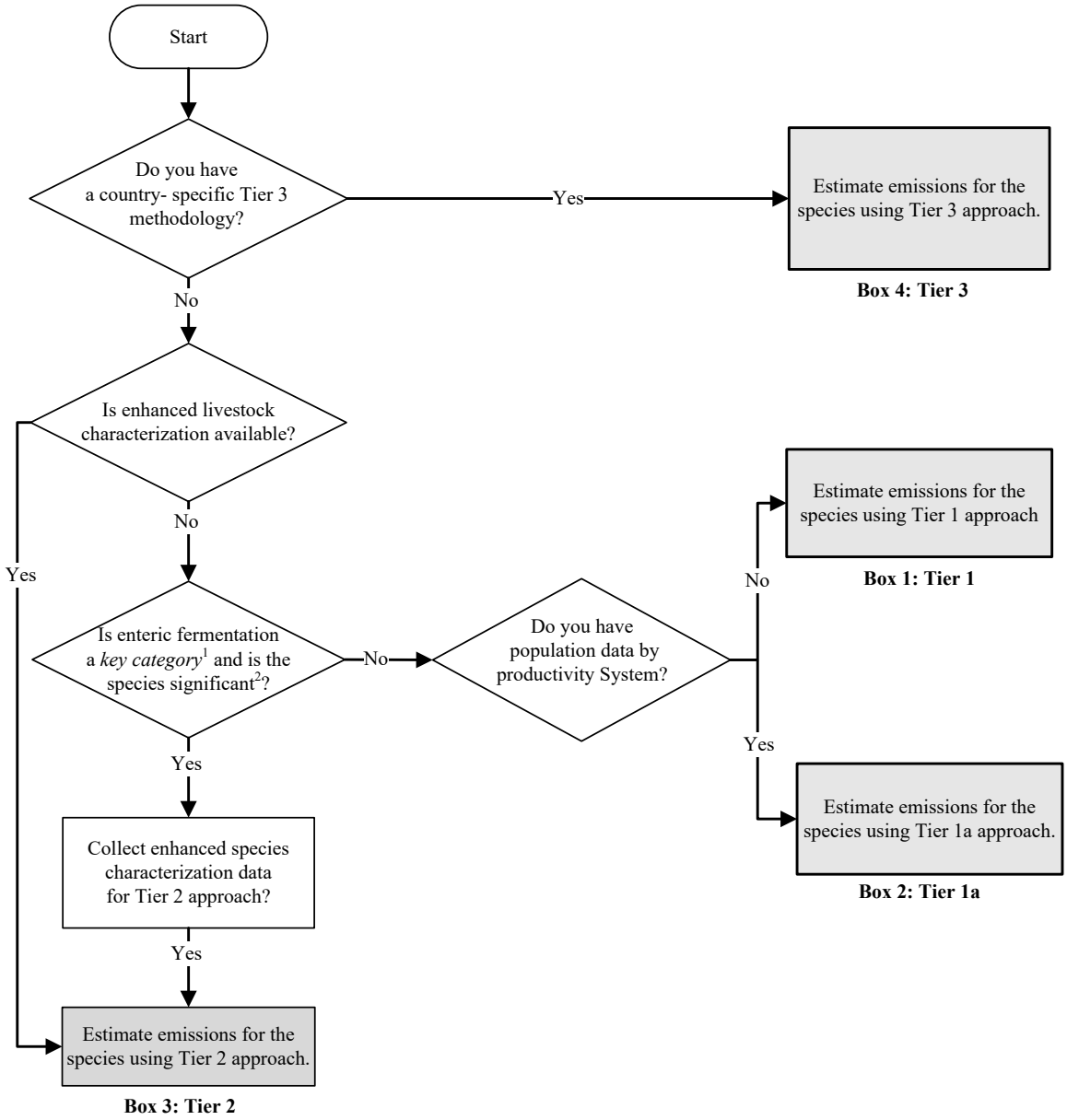
To reflect the variation in emission rates among animal species, the population of animals should be divided into subgroups, and an emission rate per animal is estimated for each subgroup. Types of population subgroups are provided in Section 10.2 (Livestock and Feed Characterisation). The amount of methane emitted by a population subgroup is calculated by multiplying the emission rate per animal by the number of animals within the subgroup.

Natural wild ruminants are not considered in the derivation of a country's emission estimate. Emissions should only be considered from animals under domestic management (e.g., farmed deer, elk, and buffalo).

10.3.1 Choice of method

It is *good practice* to choose the method for estimating methane emissions from enteric fermentation according to the decision tree in Figure 10.2. The method for estimating methane emission from enteric fermentation requires three basic steps:

Figure 10.2 (Updated) Decision Tree for CH_4 Emissions from Enteric Fermentation



Note:
1. See Volume 1 Chapter 4, 'Methodological Choice and Identification of *Key Categories*' (noting Section 4.1.2 on limited resources), for discussion of *key categories* and use of decision trees.
2. As a rule of thumb, a livestock species would be significant if it accounts for 25-30% or more of emissions from the source category.

Step 1: Divide the livestock population into subgroups and characterize each subgroup as described in Section 10.2. It is recommended that national experts use annual averages estimated with consideration for the impact of production cycles and seasonal influences on population numbers.

Step 2: Estimate emission factors for each subgroup in terms of kilograms of methane per animal per year.

Step 3: Multiply the subgroup emission factors by the subgroup populations to estimate subgroup emission, and sum across the subgroups to estimate total emission.

These three steps can be performed at varying levels of detail and complexity. This chapter presents the following three approaches:

Tier 1

A simplified approach that relies on default emission factors established in these guidelines that were either drawn from the literature or calculated using regional data taken from the literature and derived using the Tier 2 method.

The Tier 1 method is likely to be suitable for most animal species in countries where enteric fermentation is not a key source category, or where enhanced characterization data are not available. When approximate enteric emissions are derived by extrapolation from main livestock categories they should be considered to be a Tier 1 method.

Tier 1a

An advanced Tier 1 method, applicable in particular to countries that have differentiated production systems with coexistence of low and high productivity systems, or whose agricultural production systems are transitioning from low to high productivity. Countries can consider the split in their production systems, yet still use default emission factors, to customize their emission estimates based on populations of high and low productivity animals and therefore track change in their emissions related to improved productivity.

Tier 2

A more complex approach that requires detailed country-specific data on gross energy intake and methane conversion factors for specific livestock categories. The Tier 2 method should be used if enteric fermentation is a key source category for the animal category that represents a large portion of the country's total emissions.

Tier 3

Some countries for which livestock emissions are particularly important may wish to go beyond the Tier 2 method and incorporate additional country-specific information in their estimates. This approach could employ the development of sophisticated models that consider diet composition in detail, concentration of products arising from ruminant fermentation, seasonal variation in animal population or feed quality and availability, and possible mitigation strategies. Many of these estimates would be derived from direct experimental measurements. Although countries are encouraged to go beyond the Tier 2 method presented below when data are available, these more complex analyses are only briefly discussed here. A Tier 3 method should be subjected to a wide degree of international peer review such as that which occurs in peer-reviewed publications to ensure that they improve the accuracy and / or precision of estimates.

Countries with large populations of domesticated animal species for which there are no IPCC default emission factors (e.g., llamas and alpacas) are encouraged to develop national methods that are similar to the Tier 2 method and are based on well-documented research (if it is determined that emissions from these livestock are significant). The approach is described in Section 10.2.4 under the heading 'Characterisation for livestock without species-specific emission estimation methods' for more information.

Table 10.9 summarises the suggested approaches for the livestock emissions included in this inventory.

10.3.2 Choice of emission factors

Tier 1 Approach for methane emissions from Enteric Fermentation

This Tier 1 method is simplified so that only readily-available animal population data are needed to estimate emissions. Default emission factors are presented for each of the recommended population subgroups. Each step is discussed in turn.

Step 1: Animal population and productivity system

The animal population data should be obtained using the approach described in Section 10.2.

Step 2: Emission factors

The purpose of this step is to select emission factors that are most appropriate for the country's livestock characteristics. Default emission factors for enteric fermentation have been drawn from previous studies, and are organised by region and by productivity system for ease of use.

The data used to estimate the default emission factors for enteric fermentation are presented in Annex 10A.1.

TABLE 10.9 (UPDATED)
SUGGESTED EMISSIONS INVENTORY METHODS FOR ENTERIC FERMENTATION

Livestock	Suggested emissions inventory methods
Dairy Cow	Tier 2[a]/Tier 3
Other Cattle	Tier 2[a]/Tier 3
Buffalo	Tier 1/Tier 2
Sheep	Tier 1/Tier 2
Goats	Tier 1/Tier 2
Camels	Tier 1
Horses	Tier 1
Mules and Asses	Tier 1
Swine	Tier 1
Poultry	Not developed
Other (e.g., Llamas, Alpacas, Deer, Ostrich)	Tier 1

[a] The Tier 2 method is recommended for countries with large livestock populations. Implementing the Tier 2 method for additional livestock subgroups may be desirable when the category emissions are a large portion of total methane emissions for the country.

Table 10.10 shows the enteric fermentation emission factors for each of the animal species except cattle and buffalo. As shown in the table, emission factors for sheep, goats and swine vary for low and high productivity systems and it is important to consider that these conditions may exist within individual countries. The differences in the emission factors are driven by differences in feed intake (as related to animal size) and feed characteristic assumptions. Table 10.11 presents the enteric fermentation emission factors for cattle and buffaloes, accordingly. A range of emission factors is shown for typical regional conditions.

Animal size and milk production are important determinants of emission rates for dairy cows. Relatively smaller dairy cows with low levels of production are found in Asia, Africa, and the Indian subcontinent. Relatively larger dairy cows with high levels of production are found in North America, Western Europe and several countries of Latin America.

Animal size and population structure and production systems implemented are important determinants of emission rates for other cattle. Relatively smaller other cattle are found in Asia, Africa, and the Indian subcontinent. Also, many of the other cattle in these regions are young. Other cattle in North America, Western Europe and Oceania are larger, and young cattle constitute a smaller portion of the population.

For countries with highly differentiated agricultural systems in which there is a coexistence of low and high productivity systems or whose agricultural systems are transitioning from local low input productivity systems to higher productivity systems and do not have the information necessary for implementing Tier 2 method, the use of the diversification of emission factors given for an animal category provides an alternative or intermediary option. This approach can reflect changes in activity data and productivity with time, whereas the Tier 1a approach only takes into account changes in the number of animals in a country.

To select emission factors from Tables 10.10 and 10.11 identify the region most applicable to the country being evaluated. Scrutinise the tabulations in Annex 10A.1 to ensure that the underlying animal characteristics such as weight, growth rate and milk production used to develop the emission factors are similar to the conditions in the country. The data collected on the average annual milk production by dairy cows should be used to help select a dairy cow emission factor. If necessary, interpolate between dairy cow emission factors shown in the table using the data collected on average annual milk production per head.

Note that using the same Tier 1 emission factors for the inventories of successive years means that no allowance is being made for changing livestock productivity, such as increasing milk productivity or trend in live weight. If it is important to capture the trend in methane emission that results from a trend in livestock productivity, then livestock emissions can become a key source category based on trend and a Tier 2 calculation should be used.

TABLE 10.10 (UPDATED)[2,3]
ENTERIC FERMENTATION EMISSION FACTORS FOR TIER 1 METHOD (KG CH_4 $HEAD^{-1}$ YR^{-1})

Livestock	High Productivity Systems[1]	Low Productivity Systems	Liveweight[7]
Sheep	9	5	65 kg – high productivity systems 45 kg – low productivity systems
Swine[6]	1.5	1	72 kg - high productivity systems 52 kg - low productivity systems
Goats[5]	9	5	50 kg – high productivity systems 28 kg – low productivity systems
Horses	18		550 kg
Camels	46		570 kg
Mules and Asses	10		245 kg
Deer	20		120 kg
Ostrich[4]	5		120 kg
Poultry	Insufficient data for calculation		
Llamas and Alpacas	8		65 kg
Other (e.g., bison)	To be determined		
All estimates have an uncertainty of ±30-50%.			

Sources:

Emission factors: camels from Gibbs & Johnson (1993); Alpacas from Pinares-Patino *et al*. (2003); Deer from Clark *et al*. (2003); Sheep (High productivity systems) derived from Swainson *et al*. (2016). Sources and assumptions to calculate goats EFs are detailed in Annex 10B.3. Emission factors for other livestock from Crutzen *et al*. (1986),

[1] For the application of the simple Tier 1, for all regions other than North America, Europe and Oceania the Tier 1 default values are the low productivity EFs.

[2] One approach for developing the approximate emission factors is to use the Tier 1 emissions factor for an animal with a similar digestive system and to scale the emissions factor using the ratio of the weights of the animals raised to the 0.75 power. Liveweight values have been included for this purpose. Emission factors should be derived on the basis of characteristics of the livestock and feed of the animals and compilers should not base their decision of an emission factor entirely on regional characteristics.

[3] The enteric fermentation emission factor shall be applied for the whole livestock population including non-mature animals.

[4] CH_4 EF for ostrich was calculated based on Frei *et al*. (2015) and Danish NIR (Nielsen *et al*. 2018).

[5] Sources and assumptions to adjust weight of goats for low- and high-productivity systems are detailed in Annex 10B.3.

[6] The values of swine weight for low and high productivity systems were obtained from FAO GLEAM databases (FAO 2017). More detailed data on swine weight are reported in Annex 10A.2 (in Table 10A.5). Crutzen *et al*. (1986) did not report weights for swine. Regional Tier 2 calculations for swine have been carried out by the FAO GLEAM research group, countries could consult these values for consistency with their production systems for refinement to their emission factors.

[7] If a country-specific liveweight of animal category is different from those reported in Table 10.10, an inventory-compiler may use the approach presented in section 10.2.4 of the current chapter.

It is recommended to continue to use Tier 1 emission factor uncertainty ranges as defined in Section 10.3.4 of the *2006 IPCC Guidelines*.

Step 3: Total emission

To estimate total emission, the selected emission factors are multiplied by the associated animal population (Equation 10.19) and summed (Equation 10.20):

EQUATION 10.19 (UPDATED)
ENTERIC FERMENTATION EMISSIONS FROM A LIVESTOCK CATEGORY (TIER 1)

$$E_T = \sum_{(P)} EF_{(T,P)} \bullet \left(\frac{N_{(T,P)}}{10^6} \right)$$

Where:

E_T = methane emissions from Enteric Fermentation in animal category T, Gg CH_4 yr^{-1}

$EF_{(T,P)}$ = emission factor for the defined livestock population T and the productivity system P, in kg CH_4 $head^{-1}$ yr^{-1}

$N_{(T,P)}$ = the number of head of livestock species / category T in the country classified as productivity system P

T = species/category of livestock

P = productivity system, either high or low productivity for use in advanced Tier 1a – omitted if using Tier 1 approach

EQUATION 10.20 (UPDATED)
TOTAL EMISSIONS FROM LIVESTOCK ENTERIC FERMENTATION (TIER 1)

$$Total\ CH_{4\ Enteric} = \sum_{i,P} E_{i,P}$$

Where:

$Total\ CH_{4\ Enteric}$ = total methane emissions from Enteric Fermentation, Gg CH_4 yr^{-1}

$E_{i,P}$ = is the emissions for the ith livestock categories and subcategories based on production systems (P)

Tier 1 method entails multiplying the total number of livestock population and CH_4 emission factor for each category of livestock (Table 10.10 or Table 10.11). Tier 1a method relies on number of livestock population in each productivity system (i.e., low-productivity systems and high-productivity systems) and CH_4 emission factor for each category of livestock developed per head of animal kept in the specified productivity system (Table 10.10 or Table 10.11).

TABLE 10.11 (UPDATED)
TIER 1 AND TIER 1A ENTERIC FERMENTATION EMISSION FACTORS FOR CATTLE AND BUFFALO[1]

Regional characteristics[8]	Animal category	Tier 1 and Tier 1a Emission Factor[2,3] (kg CH_4 $head^{-1}$ yr^{-1})	Comments[7]
North America			
Cattle: Highly productive commercialised dairy sector feeding high quality forage and grain. Separate beef cow herd, primarily grazing with feed supplements seasonally. Fast-growing beef steers/heifers finished in feedlots on grain. Dairy cows are a small part of the population. There are no buffalo herds, but American bison may be raised.	**Dairy Cattle**	138	Average milk production of 10,250 kg $head^{-1}$ yr^{-1}.
	Other cattle	64	Includes mature males, mature females, calves, growing steers/heifers, and feedlot cattle.
Western Europe			
Cattle: Highly productive commercialised dairy sector feeding high quality forage and grain. Dairy cows also used for beef calf production. Separated beef cow herd. Minor amount of feedlot feeding with grains.	**Dairy Cattle**	126	Average milk production of 7,410 kg $head^{-1}$ yr^{-1}.
	Other cattle	52	Includes mature males, calves, and growing steers/heifers.
Buffalo: Buffalo farming system is exclusively intensive. The concentrates are largely used only during the lactation phase. Animals are maintained in paddocks, grazing practices are not widespread.	**Buffalo**	78	Includes mature females, mature males, growing animals and calves.
Eastern Europe			
Cattle: Commercialised dairy sector feeding based on forages and grains. Separate beef cow herd, primarily grazing. Minor amount of feedlot feeding with grains.	**Dairy cattle**	93	Average milk production of 4,000 kg $head^{-1}$ yr^{-1}.
	Other cattle	58	Includes mature males, mature females, growing and replacement animals, and calves.
Buffalo: Commercialized buffalo sector feeding primarily with roughages. Buffaloes are managed according to their categories. Animals are maintained paddock and tied up during the winter, in summer they are allowed to graze	**Buffalo**	68	Includes mature females, mature males, growing animals and calves.
Oceania[4]			
Cattle: Commercialised dairy sector based on grazing. Separate beef cow herd, primarily grazing rangelands[5] and hill country of widely varying forage quality. Growing amount of feedlot feeding with grains. Dairy cows are a small part of the population. No Buffalo herd.	**Dairy cattle**	93	Average milk production of 4,400 kg $head^{-1}$ yr^{-1}.
	Other cattle	63	Includes mature males, mature females and young.

TABLE 10.11 (UPDATED) (CONTINUED)
TIER 1 AND TIER 1A ENTERIC FERMENTATION EMISSION FACTORS FOR CATTLE AND BUFFALO[1]

Regional characteristics[8]	Animal category	Tier 1 and Tier 1a Emission Factor[2,3] (kg CH_4 $head^{-1}$ yr^{-1})	Comments[7]
Latin America			
Cattle: Commercialised dairy sector based on grazing. Separate beef cow herd grazing pastures and rangelands. Minor amount of feedlot feeding with grains. Growing non-dairy cattle comprise a large portion of the population.	**Dairy Cattle**	87	Average milk production of 2,050 kg $head^{-1}$ yr^{-1}
	High productivity systems	103	Average milk production of 3,400 kg $head^{-1}$ yr^{-1}
	Low productivity systems	78	Average milk production of 1,250 kg $head^{-1}$ yr^{-1}
	Other cattle	56	Includes mature females, mature males, growing steers/heifers and calves.
	High productivity systems	55	
	Low productivity systems	58	
Buffalo: Buffalo husbandry is based on extensive systems in native or cultivated pastures in lowlands and uplands, most often without supply of concentrated feed. Milk production is based on pasture with frequent supplementation of roughage (sugar cane, silage, etc.), with a predominance of one single milking.	**Buffalo**	68	Includes mature females, mature males, growing animals and calves.
Asia			
Cattle: Commercialised dairy sector is experienced fundamental changes due to increasing number of large farms with intensive production system based on grains and forage. Cattle kept in traditional production systems are multi-purpose, providing draft power and some milk within farming regions. Cattle of all types are smaller than those found in most other regions.	**Dairy cattle**	78	Average milk production of 3,200 kg $head^{-1}$ yr^{-1}
	High productivity systems	96	Average milk production of 5,000 kg $head^{-1}$ yr^{-1}
	Low productivity systems	71	Average milk production of 2,600 kg $head^{-1}$ yr^{-1}
	Other cattle	54	Includes mature males, mature females, growing and replacement animals, and calves.
	High productivity systems	43	
	Low productivity systems	56	
Buffalo: Buffaloes are generally swamp type. Buffaloes are raised by smallholder farmers as source of draft power. Animals are commonly grazed in field and fed on agriculture residual products. Milk yield per cow is low. Nevertheless, the dairy buffalo breeding is rapidly developing in countryside of Asia.	**Buffalo**	68	Includes mature females, mature males, growing animals and calves.

TABLE 10.11 (UPDATED) (CONTINUED)
TIER 1 AND TIER 1A ENTERIC FERMENTATION EMISSION FACTORS FOR CATTLE AND BUFFALO[1]

Regional characteristics[8]	Animal category	Tier 1 and Tier 1a Emission Factor[2,3] (kg CH_4 head^{-1} yr^{-1})	Comments[7]
Africa[6]			
Cattle: Commercialised dairy sector based on grazing with low production per cow. Most cattle are multi-purpose, providing draft power and some milk within farming regions. Some cattle graze over very large areas. Cattle are smaller than those found in most other regions.	**Dairy cattle**	76	Average milk production of 1,300 kg head^{-1} yr^{-1}
	High productivity systems	86	Average milk production of 2,200 kg head^{-1} yr^{-1}
	Low productivity systems	66	Average milk production of 500 kg head^{-1} yr^{-1}
	Other cattle	52	Includes mature males, multi-purpose mature females, growing and replacement animals, and calves.
	High productivity systems	60	
	Low productivity systems	48	
Buffalo: Small-scale buffalo sector well-integrated with cropland. Animals are raised for multi-purpose. Feeding primarily depends on roughages and crop-residues. Minor commercial dairy buffalo farms feeding with concentrate feed mixture.	**Buffalo**	81	Includes breeding and working males and females, growing animals and calves
Middle East			
Cattle: Majority of cattle population is still kept by small holders in the traditional production systems. The animals are fed primarily by crop residues and are grazed. Most animals are dual-purpose. In contrast to the small-scale farms, commercial dairy sector is generally intensive, mainly based on compound feed and grains.	**Dairy cattle**	76	Average milk production of 2,500 kg head^{-1} yr^{-1}
	High productivity systems	94	Average milk production of 3,900 kg head^{-1} yr^{-1}
	Low productivity systems	62	Average milk production of 1,300 kg head^{-1} yr^{-1}
	Other cattle	60	Includes mature males, multi-purpose mature females, growing and replacement animals, and calves.
	High productivity systems	61	
	Low productivity systems	55	
Buffalo: Buffalo farming system primarily based on smallholders rearing animals for meat, milk and draught. Animals obtain their feeding by grazing. Minor commercialized buffalo sector feeding forage and concentrate supplemented feed.	**Buffalo**	67	Includes breeding and working males and females, growing animals and calves

TABLE 10.11 (UPDATED) (CONTINUED)
TIER 1 AND TIER 1A ENTERIC FERMENTATION EMISSION FACTORS FOR CATTLE AND BUFFALO[1]

Regional characteristics[8]	Animal category	Tier 1 and Tier 1a Emission Factor[2,3] (kg CH_4 $head^{-1}$ yr^{-1})	Comments[7]
Indian Subcontinent			
Cattle: Commercialised dairy sector based on crop by-product feeding with low production per cow. Most bullocks provide draft power and cows provide some milk in farming regions. Cattle in this region are the smallest compared to cattle found in all other regions.	**Dairy cattle**	73	Average milk production of 1,900 kg $head^{-1}$ yr^{-1}
	High productivity systems	70	Average milk production of 2,600 kg $head^{-1}$ yr^{-1}
	Low productivity systems	74	Average milk production of 1,700 kg $head^{-1}$ yr^{-1}
	Other Cattle	46	Includes mature males, multi-purpose mature females, growing and replacement animals, and calves.
	High productivity systems	41	
	Low productivity systems	47	
Buffalo: Smallholder buffalo sector feeding poor quality roughages and crop-residues. Buffaloes are primarily free grazing. Concentrates are fed to dairy animals during last months of pregnancy. Dairy and meat production are intimately related. Animals are used as draft power. Minor commercialized buffalo sector providing animals with balanced ration.	**Buffalo**	85	Includes breeding and working males and females, growing animals and calves

[1] Emission factors should be derived on the basis of the characteristics of the cattle and feed of the animals and compilers should not base their decision of an emission factor entirely on regional characteristics.

[2] The values represent averages within region. Existing values were derived using Tier 2 method and the data in Tables 10A.1–10A.4. Data on a livestock population mix corresponding to low- and high-productivity systems were used.

[3] Uncertainty values from the *2006 IPCC Guidelines* were validated during the development of the emission factors using a Monte Carlo analysis in the *2019 Refinement*, based on data compiled during the emission factor development process. It is recommended to continue to use Tier 1 emission factor uncertainty ranges as defined in Section 10.3.4 of the *2006 IPCC Guidelines*.

[4] All data are weighted values, representative of Australia and New Zealand. For Pacific Island nations, GHG inventory compilers may refer to Asian values. GHG inventory compilers from the Island nations of Oceania who wish to use a Tier 1a method could use values from Asia for low productivity systems and the high productivity Tier 1a emission factor from Oceania, whichever is more representative of their production systems.

[5] Rangelands are defined as land primarily covered by woodlands, shrublands, grasslands and savannas, as well as introduced plant species that are naturalised (Grice *et al*. 2008).

[6] North African countries may wish to use values derived for the Middle East if productions systems are more similar.

[7] Buffalo mature females livestock sub-category includes lactating dairy mature females.

[8] Sources: *Cattle of Asia*: IPCC (2006); Ma *et al*. (2007); Ma *et al*. (2012); FAO *et al*. (2014) . *Cattle of Middle East*: Kamalzadeh *et al*. (2008); Karakok (2007); Yilmaz *et al*. (2012); Yilmaz & Wilson (2012); FAO et al. (2014). *Buffalo of Western Europe*: Borghese (2013); Neglia *et al*. (2014); Sabia *et al*. (2015). *Buffalo of Eastern Europe*: FAO (2005). *Buffalo of Latin America*: Bernardes (2007). *Buffalo of Asia*: Cruz (2007); Yang *et al*. (2007). *Buffalo of Africa*: Habeeb *et al*. (2016); Radwan (2016); Ali *et al*. (2009); Hassan & Abdel-Raheem (2013); Ibrahim (2012); Soliman (2009). Ali *et al*. (2009). *Buffalo of Middle East*: Azary *et al*. (2007); Soysal (2013); Dezfuli *et al*. (2011); Hossein-zadeh *et al*. (2012); Soysal *et al*. (2007); Naserian & Saremi (2007); Ermetin (2017). Dezfuli *et al*. (2011). *Buffalo of Indian subcontinent*: Ranjhan (2007); Anjum *et al*. (2012); Khan *et al*. (2008); Khadda *et al*. (2017); Ahirwar (2010); Khan *et al*. (2007); Chawla *et al*. (2009)

Tier 2 Approach for methane emissions from Enteric Fermentation

The Tier 2 method is applied to more disaggregated livestock population categories and used to calculate emission factors, as opposed to default values. The key considerations for the Tier 2 method are the development of emission factors and the collection of detailed activity data.

Step 1: Livestock population

The animal population data and related activity data should be obtained following the approach described in Section 10.2.

Step 2: Emission factors

When the Tier 2 method is used, emission factors are estimated for each animal category using the detailed data developed in Step 1.

The emission factors for each category of livestock are estimated based on the gross energy intake and methane conversion factor for the category. The gross energy intake data should be obtained using the approach described in Section 10.2. The following two sub-steps need to be completed to calculate the emission factor under the Tier 2 method:

1. Obtaining the methane conversion factor (Y_m)

The extent to which feed energy is converted to CH_4 depends on several interacting feed and animal factors and that rate of conversion is embodied in the methane conversion factor (Y_m), defined as the percentage of gross energy intake converted to methane.

There are a wide variety of factors that influence methane conversion rates and due to national circumstances related to breeds, genetic pools as well as particularities of feed and herd interactions, the Y_m factors may vary from region to region. Considering interactions between feed (type and quality) and animals (breed and genetics), it is *good practice* for countries to derive their own Y_m values considering their herds and their typical feed characteristics.

Nonetheless, numerous empirical studies demonstrate the statistical significance of improved feed quality on methane emission rates and biochemical modelling exhibits the biochemical processes that impact methane production with the introduction of improved feeds and concentrates to ruminant diets (Mills *et al.* 2001; Mills *et al.* 2003; Ellis *et al.* 2006; Ellis *et al.* 2007; Ellis *et al.* 2009; Ellis *et al.* 2010; Alemu *et al.* 2011; Bannink *et al.* 2011; Ellis *et al.* 2014; Escobar-Bahamondes *et al.* 2016; Kebreab *et al.* 2016). When country specific Y_m factors for cattle and buffalo are unavailable, the values provided in Table 10.12 can be used. These estimates are a guide based on the general feed characteristics and production practices found in many countries. It is *good practice* for compilers to justify their choice of Y_m factors based on detailed feed data and research.

In Table 10.12, the Y_m of dairy cows is linked to annual milk production levels and to feed quantity and quality. The lowest Y_m value is associated with highest producing dairy cattle that are fed diets of greater than 70 percent digestibility, and that have percentage of NDF in DMI of less than 35 percent. These diets may be further supplemented with additives or supplements that impact feed efficiency. In cases where countries are achieving high production on high quality silage diets that have digestibility greater than 70 percent but also NDF greater than 35 percent of DMI, compilers should use Y_m values that are midway between the high production and the mid-range productivity Y_m values (6.0 percent GEI).

Diets with digestible fractions that range from 63 to 70 percent and NDF greater than 37 percent DMI, consisting of good quality forages, silages and some grains and have associated milk production between 5000 to 8500 kg $year^{-1}$, are advised to use Y_m values of 6.3 percent GEI. For low production dairy systems with feed digestibility less than 62 percent and NDF fractions greater than 38 percent, the Y_m factor from the *2006 IPCC Guidelines* (6.5) has been maintained as there is a paucity of reliable globally representative data that could be used to revise that value. In cases where dairy cattle are strictly grazed on low quality forage diets, compilers should use the non-dairy low quality forage value of 7.0 percent GEI.

It is important for inventory compilers to base their decision to select the Y_m on a thorough understanding of national feeding systems. In the case of dairy cows, milk production is presented as a proxy for feed quality and Y_m values in Table 10.12 represent the relationship between feed quality and methane yield. It is possible for a country's national herd, or for parts of the national herd, to have production levels that are inconsistent with the feed quality bounds that are defined by the categories in Table 10.12. In these cases, it is *good practice* to develop their own country-specific Y_m factors, and they should also use their information on animal diets to validate their choice of Y_m against methane yield equations recommended in Niu *et al.* (2018).

With the non-dairy animal category, the non-feedlot diets can be differentiated between forage based diets for which the Y_m value of 7.0 should be used, and mixed concentrate diets or high quality forage diets for which compilers should use the value of 6.3. Reliable estimates for grazing cattle on very poor quality diets are not available, and due to the lack of data, the value of 7.0 is recommended. Countries that have large cattle herds consuming these types of diets are encouraged to develop country-specific values and research efforts should focus on providing more data on these cattle herds.

Emissions from feedlot animals are influenced by the type of grain fed to the animals during the finishing stage, the lowest value of 3.0 can be used when steam-flaked corn is fed at rates greater than 90 percent of the diet in combination with ionophores. Low forage diets of less than 15 percent that incorporate other grains are recommended to use the value of 4.0.

A methane conversion rate of zero is assumed for all juveniles consuming only milk (i.e., milk-fed lambs and calves). While some studies have demonstrated low level emissions from calves during the activation of their rumens (Gerrits *et al*. 2014), the Y_m for the addition of small quantities of emission from unweaned calves does not significantly influence emission factors. For weaned animals the Y_m values indicated for the non-dairy animal category are recommended.

Due to the importance of Y_m in driving emissions, ongoing research is aimed at improving estimates for different livestock and feed combinations. It is important to better understand the mechanisms involved in methanogenesis with a view to designing emission abatement strategies, as well as to identify different values for Y_m according to animal husbandry practices.

Significant improvements are needed for grazing animals in general, but in particular for low producing dairy cattle on diverse diets and grazing animals on low quality forages particularly in tropical regions as the available data are currently very sparse.

Regional, national and global estimates of enteric methane generation rely on small-scale determinations both of Y_m and of the influence of feed and animal properties upon Y_m. Traditional methods for measuring Y_m include the use of respiration calorimeters and head enclosures for housing individual animals (Johnson & Johnson 1995). A tracer technique using SF_6 enables methane emissions from individual animals to be estimated under both housed or grazing conditions (Johnson *et al.* 1994). Hammond *et al.* (2015) present an in-depth review of the advantages and limitations of methane measurement techniques used to determine Y_m values.

TABLE 10.12 (UPDATED)[6]
CATTLE/BUFFALO METHANE CONVERSION FACTORS (Y_M)

Livestock category	Description	Feed Digestibility (DE %) and Neutral Detergent Fibre (NDF, % DMI)	MY, g CH_4 kg DMI^{-1}	Y_m[3] (%)
[1,4]Dairy cows and Buffalo	High-producing cows[5] (>8500 kg/head/yr^{-1})	DE ≥ 70 NDF ≤ 35	19.0	5.7
	High-producing cows[5] (>8500 kg/head/yr^{-1})	DE ≥ 70 NDF ≥ 35	20.0	6.0
	Medium producing cows (5000 – 8500 kg yr^{-1})	DE 63-70 NDF > 37	21.0	6.3
	Low producing cows (<5000 kg yr^{-1})	DE ≤ 62 NDF >38	21.4	6.5
[2]Non dairy and multi-purpose Cattle and Buffalo	> 75 % forage	DE ≤ 62	23.3	7.0
	Rations of >75% high quality forage and/or mixed rations, forage of between 15 and 75% the total ration mixed with grain, and/or silage.	DE 62–71	21.0	6.3
	Feedlot (all other grains, 0-15% forage)	DE ≥ 72	13.6	4.0
	Feedlot (steam-flaked corn - 0-10% forage)	DE ≥ 75	10.0	3.0

[1]Expert judgement of IPCC authors in consideration of Appuhamy *et al.* (2016); Jayasundara *et al.* (2016) Hellwing *et al.* (2017) and Niu *et al.* (2018)

[2] Sources: Boadi and Wittenberg (2002); Pinares-Patiño *et al.* (2003); Boadi *et al.* (2004); Beauchemin and McGinn (2005); Beauchemin and McGinn (2006a); Beauchemin and McGinn (2006b); Chaves *et al.* (2006); Jordan *et al.* (2006a); Jordan *et al.* (2006b); Beauchemin *et al.* (2007); Hegarty *et al.* (2007); Hart *et al.* (2009); McGinn *et al.* (2009); Mc Geough *et al.* (2010a); Mc Geough *et al.* (2010b); Doreau *et al.* (2011); Hales *et al.* (2012); Kennedy and Charmley (2012); Staerfl *et al.* (2012); Chung *et al.* (2013); Hünerberg *et al.* (2013); Fiorentini *et al.* (2014); Hales *et al.* (2014); Hales *et al.* (2015); Troy *et al.* (2015); Nascimento *et al.* (2016); Vyas *et al.* (2016a); Vyas *et al.* (2016b); Baron *et al.* (2017); Hales *et al.* (2017).

[3] Uncertainty values are ± 20% based on published standard deviations from Niu *et al.* (2018) and data compilations for non dairy cattle as described in Annex 10B.2.

[4] Y_m cited for dairy cattle are for lactating dairy cows. For dairy cattle during their dry phase, in high and medium production systems, the non-dairy high quality forage value (6.3) should be selected and for low production systems with >75% low quality forage the value of (7.0) should be selected.

[5] The lowest Y_m factor for high producing cows refers to feeding situations in which additives or supplements may be used in production that stimulate feed use efficiency and/or milk production. The Y_m values given here do not yet account for any potential reducing effect of additives or supplements on Y_m.

[6] For details on the development of these values, refer to Annex 10B.2.

Table 10.13 proposes a common Y_m value for all sheep irrespective of feed quality values. This value is based on the mean value of raw data from New Zealand collated between 2009 and 2015 (Swainson *et al.* 2016). Data were derived from respiration chamber measurements where intake was accurately measured and covered a range of diet qualities. These replace values in the *2006 IPCC Guidelines* which were based on indirect measurements using the sulphur hexafluoride tracer technique where dry matter intake was generally estimated in grazing animals (Ulyatt *et al.* 2002a; Ulyatt *et al.* 2002b; Ulyatt *et al*. 2005). The mean value of 6.7 percent is most appropriate for situations where average dry matter intake per day is between 0.6 and 0.8 kg day^{-1} with a value of 7.0 percent being more appropriate where average intake is <0.6 kg day^{-1}, and a value of 6.5 percent being more appropriate where average intakes are >0.8kg day^{-1}. Table 10.13 also includes a Y_m value for goats (*2006 IPCC Guidelines* did not propose any specific value for goats). This value is based on the analysis of 65 studies that calculated in-vivo enteric CH_4 production from a varied sample of countries and goat breeds (sources and assumptions are explained in Annex 10B.3).

TABLE 10.13 (UPDATED)
SHEEP AND GOATS CH_4 CONVERSION FACTORS (Y_M)

Category	Y_m [1]
Sheep	6.7% ± 0.9
Goats	5.5% ± 1.0

Sources and assumptions to calculate the Y_m for goats are detailed in Annex 10B.3.
[1] The ± values are the standard deviation of the mean of the Y_m.

Note that in some cases, CH_4 conversion factors may not exist for specific livestock types. In these instances, CH_4 conversion factors from the reported livestock that most closely resembles those livestock types can be used. For example, CH_4 conversion factors for other cattle or buffalo could be applied to estimate an emission factor for camels.

2. Emission factor development

Using the energy balance Tier 2 approach an emission factor for each animal category should be developed following Equation 10.21:

EQUATION 10.21
METHANE EMISSION FACTORS FOR ENTERIC FERMENTATION FROM A LIVESTOCK CATEGORY

$$EF = \frac{GE \bullet \left(\frac{Y_m}{100}\right) \bullet 365}{55.65}$$

Where:

EF = emission factor, kg CH_4 head^{-1} yr^{-1}

GE = gross energy intake, MJ head^{-1} day^{-1}

Y_m = methane conversion factor, per cent of gross energy in feed converted to methane

The factor 55.65 (MJ/kg CH_4) is the energy content of methane

In cases in which the inventory compiler has used the simplified Tier 2 the emission factors should be calculated following equation 10.21a:

EQUATION 10.21A (NEW)
METHANE EMISSION FACTORS FOR ENTERIC FERMENTATION FROM A LIVESTOCK CATEGORY

$$EF = DMI \bullet \left(\frac{MY}{1000}\right) \bullet 365$$

Where:

EF = emission factor, kg CH_4 head^{-1} yr^{-1}

DMI = kg DMI day^{-1}

MY = Methane yield, g CH_4 kg DMI^{-1} (Table 10.12)

365 = days per year

1000 = conversion from g CH_4 to kg CH_4

These emission factor equations assume that the emission factors are being developed for an animal category for an entire year (365 days). While a full year emission factor is typically used, in some circumstances the animal category may be defined for a shorter period (e.g., for the wet season of the year or for a 150-day feedlot feeding period). In this case, the emission factor would be estimated for the specific period (e.g., the wet season) and the

365 days would be replaced by the number of days in the period. The definition of the period to which the emission factor applies is described in Section 10.2, defined according the the enhanced livestock characterisation that is used in calculation methodology.

Step 3: Total emissions

To estimate total emissions, the selected emission factors are multiplied by the associated animal population and summed. As described above under Tier 1, the emissions estimates should be reported in gigagrams (Gg).

Potential for refinement of Tier 2 or development of a Tier 3 method to enteric methane emission inventories

Increased accuracy and identification of causes of variation in emissions are at the heart of inventory purpose. Improvements in country methodology, whether as components of current Tier 1 or 2 or if additional refinements are implemented with Tier 3, are encouraged.

Tier 1 and Tier 2 enteric methane emissions factors and estimation procedures are driven by first estimating daily and annual gross energy consumption by individual animals within an inventory class which are then multiplied by an estimate of CH_4 loss per unit of feed (Y_m). There is considerable room for improvement in Tier 2 prediction of both feed intake and in Y_m. Factors potentially impacting feed requirements and/or consumption may include:

- depression in digestibility with increasing levels of consumption or due to rumen acidification, feed preparation or diet composition putting limits to feed intake;
- breed or genotype variation in maintenance requirement; and
- heat and cold stress effects on feed intake and maintenance requirements.

Likewise, a host of interacting factors cause variation in the rumen microbiome and its fermentation profile, and hence in hydrogen production which delivers the main substrate for methanogens. These factors lead to variation in Y_m that may include:

- variation in feed digestibility (DE);
- breed or genotype variation;
- level of feed intake;
- chemical composition of feed;
- kinetics of particle and fluid passage and of digestion, rumen volume, rumen fermentation profile; and
- other factors (such as secondary plant compounds, additives and other products) affecting the rumen microbiome.

The values in Table 10.12 capture some aspects of these factors as they are broadly related to feed quality and animal productivity, however these estimates can be improved for country-specific circumstances using higher tier methods. Accurate estimation of diet DE is singularly important in the estimation of feed intake and enteric methane emission, as previously emphasized. A change of 10 percent in DE will be magnified to a change in CH_4 emissions ranging from 12 to 20 percent depending on the dietary circumstances for which calculations are made. The depression in DE with increasing daily amounts of feed consumed (increasing rates of passage) is not inherently considered with Tier 2 and this neglect could underestimate feed intakes of high producing dairy cows consuming mixtures of concentrates and forages as is common in the North America and Europe, and hence underestimate methane emission. The balance between both effects (i.e. a reduction of feed digestibility and of Y_m) determines the net effect on methane emission which may vary with dietary circumstances. More complex models may be developed as Tier 3 to capture the intricacies of such effects.

There have been many attempts to refine estimates of Y_m. Several researchers have developed models which relate the chemical composition of the diet consumed, or in more detail, the composition of digested carbohydrate and other chemical components to Y_m. These models typically predict diet particle and chemical component rates of passage and digestion in each enteric compartment at varying intake and the resulting H_2 balance, volatile fatty acids, and microbial and CH_4 yields. These approaches have generated Y_m values that are consistent with direct measurements (Bannink *et al*. 2011; Gregorini *et al*. 2013; Huhtanen *et al*. 2015; Dougherty *et al*. 2017). A mechanistic model has been developed in the Netherlands that employs Tier 3 approach (Bannink *et al*. 2011) to estimate CH_4 yield from dairy cattle while the US use mechanistic models (Baldwin 1995; Kebreab *et al*. 2008) to refine estimates of Y_m for dairy and beef in different states within the US.

The literature contains many examples of the positive relationship of plant cell wall digestion to high acetic to propionic end-product ratios, and to high CH_4 yields. While fibrous carbohydrate digestion is the strongest indicator of CH_4 yield, the CH_4 per digested fiber is not constant and enteric fermentation of similar fibrous feeds can result in different Y_m values. For example, grass silage made from grass cut at different stages of maturity resulted in strongly different carbohydrate and protein composition, resulting in Y_m values varying from 5.5 to 6.9 percent with increased maturity and intake (Warner *et al*. 2017). Exchange of carbohydrates may also lead to a lower Y_m as demonstrated in studies where dietary starch content is increased through a higher proportion of corn silage (Hassanat *et al*. 2013; Benchaar *et al*. 2014) or through a higher proportion of starch containing concentrates (Aguerre *et al*. 2011). Prerequisite for the use of more complex prediction models for broad country inventories is that the data need to be provided to drive these more complex models of feed intake or Y_m. It is often difficult to define animal characteristics, productivity, and DE accurately for a livestock category in various regions or various production systems in a country. Of particular importance is a good characterization of roughages when they constitute a main part of the diet.

Ongoing global research, such as the use of direct methanogen inhibitors, 3-nitrooxypropanol (3-NOP), oxygen-rich anions, fats and oils, ionophores or condensed tannins, and also genetic selection suggests a need to address how they should be reflected in inventory compilation at Tier 2 or Tier 3. First, it is *good practice* that the inventory reflect only those technologies or genotypes developed through selection, conform to QA/QC principles and have attracted a wide degree of international acceptance such as through peer-reviewed articles that include a description of the technology, its efficacy and validation under field conditions. Second, it is *good practice* that the inventory be accompanied by evidence of the uptake of the technology in agricultural practice, and apply it only to emissions by those livestock where uptake can be validated. Mitigation measures and their representation in inventory compilation should be supported by peer-reviewed publications.

Concluding, approaches to improve estimates of feed intake (i.e. of diet composition, DE and dietary GE content) and Y_m, and approaches to account for specific mitigation measures are to be encouraged, given due care on limitations of the scope and on production circumstances where mitigation measures are applied and to which predictive models or relationships must apply as well.

10.3.3 Choice of activity data

Livestock population data should be obtained using the approach described in Section 10.2. If using default enteric emission factors for livestock (Tables 10.10, 10.11) to estimate enteric emissions, a basic (Tier 1) livestock population characterisation is sufficient. To estimate enteric emissions from livestock using estimation of Gross Energy Intake (Equations 10.21, or 10.21A), a Tier 2 characterisation is needed. As noted in Section 10.2, *good practice* in characterising livestock populations is to conduct a single characterisation that will provide the activity data for all emissions sources that depend on livestock population data.

10.3.4 Uncertainty assessment

Emission factors

No refinement.

Activity data

No refinement.

10.3.5 Completeness, Time series, Quality Assurance/Quality Control and Reporting

No refinement.

10.4 METHANE EMISSIONS FROM MANURE MANAGEMENT

This section describes how to estimate CH_4 produced during the storage and treatment of manure, and from manure deposited on pasture. The Tier 1 approach is based on default emission factors per unit volatile solid (VS) by animal category and manure storage system. The Tier 2 is based on country-specific estimates of volatile solids and the impact of interactions between manure management systems and animal categories on total CH_4 emissions during excretion and storage, including manure treatments such as the production of biogas.

The term 'manure' is used here collectively to include both dung and urine (i.e., the solids and the liquids) produced by livestock. The emissions associated with the burning of dung for fuel are to be reported under Volume 2 (Energy), or under Volume 5 (Waste) if burned without energy recovery. When manure is used in the production of biogas, the emissions reported under the manure management category are those occurring on the farm site not resulting from combustion. These include, on-farm storage of the digestion input materials - pre-digestion, leakage during the digestion process and emissions from the storage and application of digestate to agricultural fields (included in Volume 4, Chapter 11, Section 11.2, Nitrous oxide emissions from managed Soils). Emissions from biogas combustion during the production of energy, whether on or off farm should be reported under Volume 2 "Energy".

The decomposition of manure under anaerobic conditions (i.e., in the absence of oxygen), during storage and treatment, produces CH_4. These conditions occur most readily when large numbers of animals are managed in a confined area (e.g., dairy farms, beef feedlots, and swine and poultry farms), and where manure is disposed of in liquid-based systems. Emissions of CH_4 related to manure handling and storage are reported under 'Manure Management.'

The main factors affecting CH_4 emissions are the amount of manure produced and the portion of the manure that decomposes anaerobically. The former depends on the rate of waste production per animal and the number of animals, and the latter on how the manure is managed. When manure is stored or treated as a liquid (e.g., in lagoons, ponds, tanks, or pits), it decomposes anaerobically and can produce a significant quantity of CH_4. The temperature and the retention time of the storage unit greatly affect the amount of methane produced. When manure is handled as a solid (e.g., in stacks or piles) or when it is deposited on pastures and rangelands, it tends to decompose under more aerobic conditions and less CH_4 is produced.

10.4.1 Choice of method

There are three tiers to estimate CH_4 emissions from livestock manure as shown in the *2006 IPCC Guidelines*.

To be consistent with consideration of differing productivity classes in section of enteric fermentation, a new Tier 1 was developed. In some regions, particularly in developing countries, production systems can vary between high productivity systems aimed at commercial food production and low productivity systems, largely serving local food production. In this case countries may choose to use a Tier 1 method in which emission factors are defined for low and high productivity systems based on the updated volatile solids and B_0, and the values of volatile solids were aligned with the updated enteric fermentation section.

Guidance for determining which methods to use is shown in Figure 10.3 decision tree.

Tier 1

The Tier 1 method entails multiplying the total amount of VS excreted (from all livestock species/categories) in each type of manure management system by an emission factor for that type of livestock category in the specified climate zone and manure management system (see Equation 10.22). Emissions are summed over all manure management systems and livestock categories. The Tier 1 method is applied using IPCC default VS excretion rates (See Table 10.13a), default typical animal mass (see Table 10A.5), default CH_4 Emission Factors (see Table 10.14), and default animal waste management systems (AWMS). Animal waste management system (manure management systems) data have been collected for regions and countries by the FAO and average manure fractions treated by different management systems are presented in Annex 10A.2, Tables 10A.6 to 10A.9. As emissions from manure management systems are highly temperature dependent, it is *good practice* to consider the climate zone associated with the locations

where manure is managed. Breakdowns of manure management systems by regional climate zone and production system can be found in the supplemental data supplied with this chapter. Please refer to "Raw data for cattle and buffalo spreadsheet". Further finer-scale country-specific data is also available from FAO GLEAM databases (FAO 2017).

An advanced Tier 1a method has been developed as an alternative for countries with differentiated agricultural systems in which there is a coexistence of low and high productivity systems or whose agricultural systems are transitioning from local low input productivity systems to higher productivity systems. In this case, where countries do not have the information necessary for implementing Tier 2 systems, the use of the productivity based emission factors given for an animal category provides an alternative or intermediary option. The advanced Tier 1a approach will provide an estimate of the changes in both productivity and manure management that occur when a transition from lower productivity systems to higher productivity systems occurs.

Tier 2

A more complex method for estimating CH_4 emissions from manure management should be used where a particular livestock species/category represents a significant share of a country's emissions. This method requires detailed information on animal characteristics and manure management practices, which is used to develop emission factors specific to the conditions of the country.

The main differences between the Tier 1 and Tier 2 calculations is whether default information or country-specific information is used in the calculation of emissions from manure management system. The Tier 2 system provides a much wider group of options for estimating emissions from different manure management systems.

Tier 3

Some countries for which livestock emissions are particularly important may wish to go beyond the Tier 2 method and develop models for country-specific methodologies or use measurement–based approaches to quantify emission factors.

The method chosen will depend on data availability and national circumstances. *Good practice* in estimating CH_4 emissions from manure management systems entails making every effort to use the Tier 2 method, including calculating emission factors using country-specific information. The Tier 1 method should only be used if all possible avenues to use the Tier 2 method have been exhausted and/or it is determined that the source is not a *key category* or subcategory.

Regardless of the method chosen, the animal population must first be divided into categories as described in Section 10.2 that reflect the varying amounts of manure produced per animal.

The following steps are used to estimate CH_4 emissions from manure management:

Step 1: Collect population data based on the Livestock Population Characterization (see Section 10.2).

Step 2: Identify default (Table 10A.5) or collect country-specific typical animal mass (TAM) values. Calculate volatile solid excretion according to Equation 10.22a or develop country-specific volatile solid excretion rates according to Equation 10.24.

Step 3: Collect country-specific information on manure management system methods and develop country-specific manure management system fractions or use default manure storage fractions presented in Annex Tables 10A.6 to Tables 10A.9.

Step 4: Identify either default emission factors Table 10.14 or build country-specific emission factors for each livestock subcategory based on climate zones and manure management system fractions.

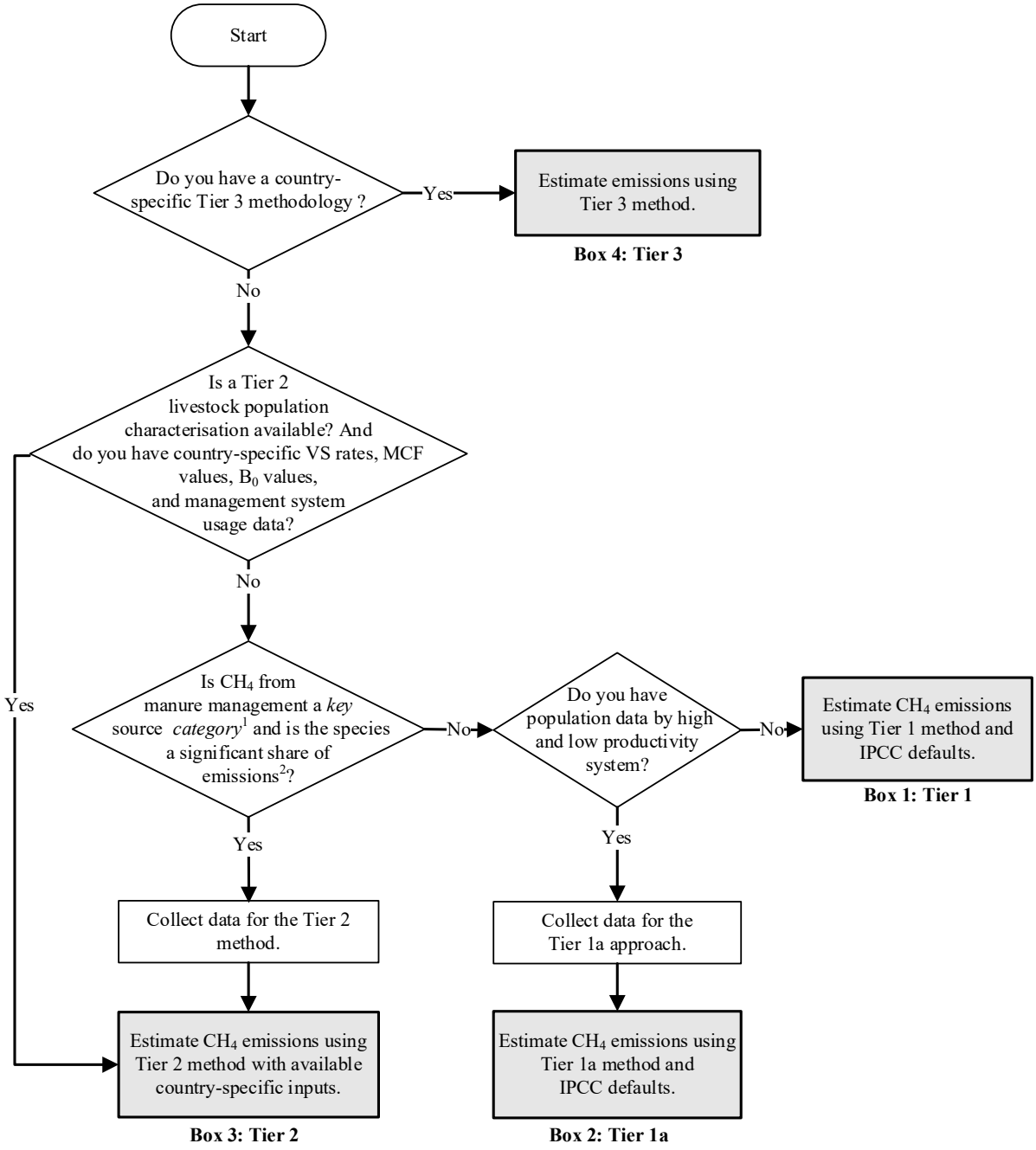
- Tier 1: Identify default values (Table 10.14) for emission factors for each livestock category in terms of grams of methane per kg VS per year for the appropriate climate zone and productivity class if using advanced Tier 1a.
- Tier 2: Select local manure management specific methane conversion factors (MCF's, Table 10.17) for different climate zones and the animal categories specific maximum methane producing capacity (B_0).

Step 5: Calculate methane emission for each livestock subcategory.

- Tier 1: According to Equation 10.22 for each livestock category, climate zone (include production level if using Tier 1a) multiply the livestock category population (**Step 1**) by quantity of volatile solid (**Step 2**) by the manure storage fraction (**Step 3**) and the default emission factor (**Step 4**).
- Tier 2: According to Equation 10.23, for each livestock category and climate zone calculate the country-specific emission factor based on the country-specific or default quantity of volatile solids (**Step 2**), the manure management system fraction (AWMS) and the MCF and B_0 factors (**Step 4**); To estimate total emissions, the country specific emission factor is then multiplied by the population number (**Step 1**).

Step 6: Sum emissions from all defined livestock categories to determine national emissions.

Figure 10.3 (Updated) Decision tree for CH_4 emissions from Manure Management



Note:
1: See Volume 1 Chapter 4, "Methodological Choice and Identification of Key Categories"(noting Section 4.1.2 on limited resources), for discussion *of key categories* and use of decision trees.
2:As a rule of thumb, a livestock species would be significant if it accounts for 25-30% or more of emissions from the source category.

The calculation of CH_4 emissions from manure management for Tier 1 uses Equation 10.22 for both simple Tier 1 or advanced Tier 1a methods.

EQUATION 10.22 (UPDATED)
CH_4 EMISSIONS FROM MANURE MANAGEMENT (TIER 1)

$$CH_{4(mm)} = \left[\sum_{T,S,P} \left(N_{(T,P)} \bullet VS_{(T,P)} \bullet AWMS_{(T,S,P)} \bullet EF_{T,S,P} \right) / 1000 \right]$$

Where:

$CH_{4(mm)}$ = CH_4 emissions from Manure Management in the country, kg CH_4 yr^{-1}

$N_{(T,P)}$ = number of head of livestock species/category *T* in the country, for productivity system *P*, when applicable

$VS_{(T,P)}$ = annual average VS excretion per head of species/category *T*, for productivity system *P*, when applicable in kg VS $animal^{-1}$ yr^{-1} (Table 10.13a calculated by Equation 10.22a)

$AWMS_{(T,S,P)}$ = fraction of total annual VS for each livestock species/category *T* that is managed in manure management system *S* in the country, for productivity system *P*, when applicable; dimensionless, default regionally specific AWMS fractions are found in Tables 10A.6 through 10A.9 in Annex 10A.2

$EF_{(T,S,P)}$ = emission factor for direct CH_4 emissions from manure management system *S,* by animal species/category *T*, in manure management system *S*, for productivity system *P*, when applicable (Table 10.14), g CH_4 kg VS^{-1}

S = manure management system

T = species/category of livestock

P = high productivity system or low productivity system for use in advanced Tier 1a – omitted if using a simple Tier 1 approach

10.4.2 Choice of emission factors

The best way to determine emission factors is to conduct non-invasive or non-disturbing measurements of emissions in actual systems representative of those in use in the country. These field results can be used to develop models to estimate emission factors (Tier 3). Such measurements are difficult to conduct, and require significant resources and expertise, and equipment that may not be available. Thus, while such an approach is recommended to improve accuracy, it is not required for *good practice*. This section provides two alternatives for developing emission factors, with the selection of emission factors depending on the method (i.e., Tier 1 or Tier 2) chosen for estimating emissions.

Tier 1

When using the Tier 1 method, methane emission factors per unit of VS by livestock category or subcategory are used. Default emission factors by animal productivity class, manure management system and climate zone are presented in Table 10.14 for each of the recommended population subcategories. These emission factors represent the range in manure management practices used in each region, as well as the difference in emissions due to climate zone.

Tables 10A.5 through 10A.9 located in Annex 10A.2 present the underlying assumptions used for each region. Countries using a Tier 1 method to estimate methane emissions from manure management should review the regional variables in these tables to identify the region that most closely matches their animal operations, and use the default emission factors for that region.

Annual volatile solid excretion rates should be determined for each livestock category defined by the livestock population characterization. Country-specific rates may either be taken directly from documents or reports such as agricultural industry and scientific literature, or calculated based on estimates of dry matter intake (DMI), ash content and urinary energy (as explained below). In some situations, it may be appropriate to use excretion rates developed by other countries that have livestock with similar characteristics.

If country-specific data cannot be collected or derived, or appropriate data are not available from another country, the IPCC default volatile solid excretion rates presented in Table 10.13a can be used. These rates are presented in units of volatile solid excreted per 1000 kg of animal per day. These rates can be applied to livestock sub-categories of varying ages and growth stages using a typical average animal mass (TAM) for that population sub-category, as shown in Equation 10.22a for a Tier 1 calculation. The TAM should be consistent with median weight of the animal during its production stage. Typically, for animals used in meat production systems, this is the median weight of the animal during its growth period. Animals that are kept for the production of products (milk, eggs), draft or other uses would use the typical live weight of the animal herd.

Volatile solids should be calculated according to Equation 10.22a, either for the simple Tier 1 or the advanced Tier 1a, where parameters are split by their productivity class in the calculaton of volatile solid excretion. Note that if countries are mixing Tier 1 and Tier 2 methods and volatile solids are calculated through Equation 10.22A and are applied in Equation 10.23 (Tier 2), the constant of 365 should be removed from that equation.

EQUATION 10.22A (NEW)
ANNUAL VS EXCRETION RATES (TIER 1)

$$VS_{(T,P)} = \left(VS_{rate(T,P)} \bullet \frac{TAM_{T,P}}{1000} \right) \bullet 365$$

Where:

$VS_{(T,P)}$ = annual VS excretion for livestock category *T*, for productivity system *P* (when applicable), kg VS animal^{-1} yr^{-1}

$VS_{rate(T,P)}$ = default VS excretion rate, for productivity system *P* (when applicable), kg VS (1000 kg animal mass)$^{-1}$ day^{-1} (see Table 10.13a)

$TAM_{(T,P)}$ = typical animal mass for livestock category *T*, for productivity system *P* (when applicable), kg animal^{-1}

The calculation is a simple linear adjustment, so in the case of an animal that is 500 kg of weight, the VS emission rate will be half of the rate presented per 1000 kg live weight.

Default TAM values are provided in Table 10A.5 as well as in the Annexes of Chapter 10 of the *2006 IPCC Guidelines*. However, it is preferable to collect country-specific TAM values to be able to track changes in emissions with changes in productivity and animal size in certain animal categories. For example, market swine may vary from nursery pigs weighing less than 30 kilograms to finished pigs that weigh over 90 kilograms. By constructing animal population groups that reflect the various growth stages of market pigs, countries will be better able to estimate the total volatile solid excreted by their swine population.

Table 10.14 shows the default emission factors per kg of volatile solid excretion and year for all animal categories for each manure management system and climate zone. Emission factors are listed for the climate zone where the livestock manure is managed. It is *good practice* for countries to estimate the percentage of animal populations in different climate zones and compute a weighted average emission factor. Where this is not possible, an estimate should be made based on the proportion of area in each climate zone; however, this may not give an accurate estimate of emissions that are highly sensitive to temperature variations (e.g., liquid/slurry systems).

Separate emission factors are shown for high and low productivity systems in these t*ables, reflecting the general differences in feed intake and feed characteristics of the animals in regions that have highly differential production systems existing in the same country. Emission factors result from the MCFs in Table 10.17 and the B_0 in Table 10.16 and as a result, vary by animal category and manure management system, with liquid systems demonstrating higher emissions per unit VS. Lower emission factors associated with low productivity systems are representative of the lower B_0 values associated with lower quality feeds and manures with high C to N ratios.

TABLE 10.13A (NEW)
DEFAULT VALUES FOR VOLATILE SOLID EXCRETION RATE (KG VS (1000 KG ANIMAL MASS)$^{-1}$ DAY^{-1})

Category of animal	Region																		
	North America	Western Europe	Eastern Europe	Oceania[7]	Latin America			Africa[6]			Middle East[6]			Asia			India subcontinent		
					Mean	High PS[1]	Low PS[1]	Mean	High PS	Low PS	Mean	High PS	Low PS	Mean	High PS	Low PS	Mean	High PS	Low PS
Dairy cattle[4]	9.2	8.4	6.7	6.0	7.9	9.0	7.1	18.2	21.7	15.2	10.7	8.4	11.8	9.0	8.1	9.2	14.1	9.1	16.1
Other cattle[4]	7.6	5.7	7.6	8.7	8.5	8.1	8.6	12.1	10.2	12.7	12.3	9.3	14.5	9.8	6.8	10.8	12.2	13.5	12.0
Buffalo[4]	NA	7.7	6.2	NA	11.2	NE		12.9	NE		9.8	NE		13.5	NE		15.2	NE	
Swine[3]	3.3	4.5	4.0	4.0	5.0	3.3	8.3	7.2	4.3	8.7	4.3	3.9	7.2	5.8	4.3	7.1	7.7	5.5	8.7
Finishing	3.9	5.3	4.9	5.6	6.4	4.3	10.0	8.2	5.3	9.4	4.9	4.4	7.8	6.8	5.1	8.1	8.6	6.5	9.5
Breeding	1.8	2.4	2.0	2.1	2.7	1.7	4.8	4.4	2.4	6.0	2.5	2.3	4.6	3.4	2.3	4.3	4.6	3.0	5.5
Chicken[3]	14.5	12.3	12.6	15.4	13.5	13.3	15.7	12.6	12.3	13.0	14.2	14.1	16.5	11.2	10.6	14.3	14.9	14.3	15.7
Hens ±1 yr	9.4	8.6	9.4	8.6	10.1	9.3	14.7	10.2	8.0	11.6	9.0	8.4	15.8	9.3	8.5	12.8	13.2	11.6	14.6
Pullets	5.9	5.3	5.9	6.2	7.6	5.7	18.5	12.0	5.8	16.5	6.8	5.6	18.5	7.5	5.4	17.7	13.2	6.8	18.9
Broilers	16.8	16.1	16.0	18.3	15.6	15.5	17.8	15.9	16.0	15.4	17.7	17.7	17.9	15.7	15.6	17.1	17.7	17.6	18.2
Turkeys[8]	10.3																		
Ducks[8]	7.4																		
Sheep[3]	8.2				8.3														
Goats[5]	9				10.4														
Horses[8]	5.65				7.2														
Mules/ Asses[8]	7.2																		
Camels[8]	11.5																		

TABLE 10.13A (NEW) (CONTINUED)
DEFAULT VALUES FOR VOLATILE SOLID EXCRETION RATE (KG VS (1000 KG ANIMAL MASS)-1 DAY^{-1})

[1] High PS and Low PS refer to high and low productivity systems required for Tier 1a methodology.

[2] NE is reported when values are not estimated, due to their not being adequate differences between high and low productivity production systems and NA refers to situations in which these animal categories do not occur in these regions.

[3] Values are taken from FAO GLEAM databases (FAO 2017).

[4] Values are derived from diets used in the calculation of enteric fermentation Tier 1 emission factors.

[5] Calculations are detailed in Annex 10B.3.

[6] North African countries may wish to use values from the Middle East if their production systems are more similar.

[7] All data are weighted values, representative of Australia and New Zealand. For Pacific Island nations, GHG inventory compilers may refer to Asian values. GHG inventory compilers from the Island nations from Oceania may wish to use a Tier 1a approach. In this case, they could used values from Asia, or low productivity systems and high Tier 1a emission factor from Oceania, whichever is more representative to their production systems.

[8] Values are derived directly from the parameters reported in Table 10A-9 of the *2006 IPCC Guidelines*.

TABLE 10.14 (UPDATED)
METHANE EMISSION FACTORS BY ANIMAL CATEGORY, MANURE MANAGEMENT SYSTEM AND CLIMATE ZONE (G CH_4 KG VS^{-1}) [7]

Livestock species	Productivity Class	Manure Storage System[4]	Cool				Temperate		Warm			
			Cool Temp. Moist	Cool Temp. Dry	Boreal Moist	Boreal Dry	Warm Temp. Moist	Warm Temp. Dry	Tropical Montane	Tropical Wet	Tropical Moist	Tropical Dry
Dairy Cattle	High Productivity	Uncovered anaerobic lagoon	96.5	107.7	80.4	78.8	117.4	122.2	122.2	128.6	128.6	128.6
		Liquid/Slurry, Pit storage > 1 month [5]	33.8	41.8	22.5	22.5	59.5	65.9	94.9	122.2	117.4	119.0
		Solid storage	3.2				6.4		8.0			
		Dry lot	1.6				2.4		3.2			
		Daily spread	0.2				0.8		1.6			
		Anaerobic Digestion -Biogas[8]	3.2				3.7		3.7			
		Burned for fuel	16.1									
	Low Productivity[1]	Uncovered anaerobic lagoon	52.3	58.4	43.6	42.7	63.6	66.2	66.2	69.7	69.7	69.7
		Liquid/Slurry, Pit storage > 1 month [5]	18.3	22.6	12.2	12.2	32.2	35.7	51.4	66.2	63.6	64.5
		Solid storage	1.7				3.5		4.4			
		Dry lot	0.9				1.3		1.7			
		Daily spread	0.1				0.4		0.9			
		Anaerobic Digestion -Biogas[8]	9.2				9.5		9.5			
		Burned for fuel	8.7									

TABLE 10.14 (UPDATED) (CONTINUED)
METHANE EMISSION FACTORS BY ANIMAL CATEGORY, MANURE MANAGEMENT SYSTEM AND CLIMATE ZONE (G CH_4 KG VS^{-1}) [7]

Livestock species	Productivity Class	Manure Storage System[4]	Cool				Temperate		Warm			
			Cool Temp. Moist	Cool Temp. Dry	Boreal Moist	Boreal Dry	Warm Temp. Moist	Warm Temp. Dry	Tropical Montane	Tropical Wet	Tropical Moist	Tropical Dry
Non Dairy Cattle	High Productivity	Uncovered anaerobic lagoon	72.4	80.8	60.3	59.1	88.0	91.7	91.7	96.5	96.5	96.5
		Liquid/Slurry, Pit storage > 1 month[5]	25.3	31.4	16.9	16.9	44.6	49.4	71.2	91.7	88.0	89.2
		Solid storage	2.4				4.8		6.0			
		Dry lot	1.2				1.8		2.4			
		Daily spread	0.1				0.6		1.2			
		Anaerobic Digestion -Biogas[8]	2.4				2.7		2.8			
		Burned for fuel	12.1									
	Low Productivity[1,6]	Uncovered anaerobic lagoon	52.3	58.4	43.6	42.7	63.6	66.2	66.2	69.7	69.7	69.7
		Liquid/Slurry, Pit storage > 1 month[5]	18.3	22.6	12.2	12.2	32.2	35.7	51.4	66.2	63.6	64.5
		Solid storage	1.7				3.5		4.4			
		Dry lot	0.9				1.3		1.7			
		Daily spread	0.1				0.4		0.9			
		Anaerobic Digestion -Biogas[8]	9.2				9.5		9.5			
		Burned for fuel	8.7									

TABLE 10.14 (UPDATED) (CONTINUED)
METHANE EMISSION FACTORS BY ANIMAL CATEGORY, MANURE MANAGEMENT SYSTEM AND CLIMATE ZONE (G CH_4 KG VS^{-1}) [7]

Livestock species	Productivity Class	Manure Storage System[4]	Cool				Temperate		Warm			
			Cool Temp. Moist	Cool Temp. Dry	Boreal Moist	Boreal Dry	Warm Temp. Moist	Warm Temp. Dry	Tropical Montane	Tropical Wet	Tropical Moist	Tropical Dry
Growing and Breeding Swine	High Productivity	Uncovered anaerobic lagoon	180.9	202.0	150.8	147.7	220.1	229.1	229.1	241.2	241.2	241.2
		Liquid/Slurry, and Pit storage below animal confinements > 1 month[5]	63.3	78.4	42.2	42.2	111.6	123.6	177.9	229.1	220.1	223.1
		Liquid/Slurry, and Pit storage below animal confinements < 1 month[5]	18.1	24.1	12.1	12.1	39.2	45.2	75.4	114.6	108.5	126.6
		Solid storage	6.0				12.1		15.1			
		Dry lot	3.0				4.5		6.0			
		Daily spread	0.3				1.5		3.0			
		Anaerobic Digestion - Biogas[8]	6.0				6.8		7.0			
		Burned for fuel	30.2									
	Low Productivity[1]	Uncovered anaerobic lagoon	116.6	130.2	97.2	95.2	141.8	147.7	147.7	155.4	155.4	155.4
		Liquid/Slurry, and Pit storage below animal confinements > 1 month[5]	40.8	50.5	27.2	27.2	71.9	79.7	114.6	147.7	141.8	143.8
		Liquid/Slurry, and Pit storage below animal confinements < 1 month[5]	11.7	15.5	7.8	7.8	25.3	29.1	48.6	73.8	69.9	81.6
		Solid storage	3.9				7.8		9.7			
		Dry lot	1.9				2.9		3.9			
		Daily spread	0.2				1.0		1.9			
		Anaerobic Digestion - Biogas[8]	20.6				21.1		21.2			
		Burned for fuel	19.4									

TABLE 10.14 (UPDATED) (CONTINUED)
METHANE EMISSION FACTORS BY ANIMAL CATEGORY, MANURE MANAGEMENT SYSTEM AND CLIMATE ZONE (G CH_4 KG VS^{-1}) [7]

Livestock species	Productivity Class	Manure Storage System[4]	Cool				Temperate		Warm			
			Cool Temp. Moist	Cool Temp. Dry	Boreal Moist	Boreal Dry	Warm Temp. Moist	Warm Temp. Dry	Tropical Montane	Tropical Wet	Tropical Moist	Tropical Dry
Poultry	High productivity	Uncovered anaerobic lagoon	156.8	175.1	130.7	128.0	190.7	198.6	198.6	209.0	209.0	209.0
		Liquid/Slurry, and Pit storage below animal confinements > 1 month[5]	54.9	67.9	36.6	36.6	96.7	107.1	154.2	198.6	190.7	193.4
		Solid storage	5.2				10.5		13.1			
		Dry lot	2.6				3.9		5.2			
		Anaerobic Digestion - Biogas[8]	5.2				10.5		13.1			
		Burned for fuel	2.6									
	Low productivity[1]	All Systems	2.4									
Sheep	High productivity	Solid storage	2.5				5.1		6.4			
		Dry lot	1.3				1.9		2.5			
	Low productivity[1]	Solid storage	1.7				3.5		4.4			
		Dry lot	0.9				1.3		1.7			
Goats	High productivity	Solid storage	2.4				4.8		6.0			
		Dry lot	1.2				1.8		2.4			
	Low productivity[1]	Solid storage	1.7				3.5		4.4			
		Dry lot	0.9				1.3		1.7			

TABLE 10.14 (UPDATED) (CONTINUED)
METHANE EMISSION FACTORS BY ANIMAL CATEGORY, MANURE MANAGEMENT SYSTEM AND CLIMATE ZONE (G CH_4 KG VS^{-1}) [7]

Livestock species	Productivity Class	Manure Storage System[4]	Cool	Temperate	Warm
Camels	High productivity	Solid storage	3.5	7.0	8.7
		Dry lot	1.7	2.6	0.0
	Low productivity[1]	Solid storage	2.8	5.6	7.0
		Dry lot	1.4	2.1	2.8
Horses	High productivity	Solid storage	4.0	8.0	10.1
		Dry lot	2.0	3.0	4.0
	Low productivity[1]	Solid storage	3.5	7.0	8.7
		Dry lot	1.7	2.6	3.5
Mules/ Asses	High productivity	Solid storage	4.4	8.8	11.1
		Dry lot	2.2	3.3	4.4
	Low productivity[1]	Solid storage	3.5	7.0	8.7
		Dry lot	1.7	2.6	3.5
All Animals	High and Low Productivity	Pasture Range and Paddock	0.6		

All values are calculated based on MCFs and B_0s reported in Tables 10.17 and 10.16, respectively, using the equation MCF*B_0*0.67.

[1] For the application of Tier 1, for all regions other than North America, Europe and Oceania the Tier 1 default values are the low productivity EFs. Pasture range and paddock emission factor is based on observation in the updated version of Cai *et al*. (2017) database (see Annex 10B.6). No differences were observed for animal type, region or productivity class and are therefore reported as a constant for all animal and productivity categories.

[2] Temp. is an abbreviation for temperate.

[3] Composting is the biological oxidation of organic material.

[4] Definitions of manure management systems can be found in Table 10.18.

[5] Emissions for liquid systems are calculated from manure management systems with a 6 month retention time.

[6] Buffalo emission factors are equivalent to low productivity non dairy animals.

[7] Uncertainty is ±30% consisten with the *2006 IPCC Guidelines*.

[8] Anaerobic digestion biogas values: for high productivity are based on emission estimates from high quality gas-tight digesters and average MCFs for storage whereas, for low productivity are based on emission estimates from high digester leakage rates and average MCFs for storage leakage rates. Countries should consider the type and quality of digesters used in their individual countries in evaluating what emission factors they choose to employ as opposed to the level of productivity for anaerobic digesters only.

TABLE 10.15 (UPDATED)
MANURE MANAGEMENT METHANE EMISSION FACTORS FOR DEER, REINDEER, RABBITS, OSTRICH AND FUR-BEARING ANIMALS AND DERIVATION PARAMETERS APPLIED

Livestock	CH_4 emission factor (kg CH_4 $head^{-1}$ yr^{-1})	VS (kg VS day^{-1})[4]	B_0 (m^3 kg VS)[4]
Deer[1]	0.22	NR	NR
Reindeer[2]	0.36	0.39	0.19
Rabbits[3]	0.08	0.10	0.32
Fur-bearing animals (e.g., fox, mink)[2]	0.68	0.14	0.25
Ostrich	5.67	1.16	0.25

The uncertainty in these emission factors is ±30 %.

[1] Sneath *et al*. (1997).

[2] Estimations of Agricultural University of Norway, Institute of Chemistry and Biotechnology, Section for Microbiology.

[3] Judgement of the IPCC Expert Group.

[4] Table 10A-9 of the *2006 IPCC Guidelines*.

Tier 2

The Tier 2 method is applicable when Manure Management is a key source or when the data used to develop the default values do not correspond well with the country's livestock and manure management conditions. Because cattle, buffalo and swine characteristics and manure management systems can vary significantly by country, countries with large populations of these animals should consider using the Tier 2 method for estimating methane emissions.

The Tier 2 method relies on two primary types of inputs that affect the calculation of methane emission factors from manure:

Manure characteristics*:* Includes the amount of volatile solids (VS) produced in the manure and the maximum amount of methane able to be produced from that manure (B_0). Production of manure VS can be estimated based on feed intake and digestibility, which are the variables also used to develop the Tier 2 enteric fermentation emission factors. Alternatively, VS production rates can be based on laboratory measurements of livestock manure. B_0 varies by animal species and feed regime and is a theoretical methane yield based on the amount of VS in the manure. Bedding materials (straw, sawdust, chippings, etc.) are not included in the VS modelled under the Tier 2 method. The type and use of these materials is highly variable from country to country. Since they typically are associated with solid storage systems, their contribution would not add significantly to overall methane production. CH_4 emissions from co-digestion of on-farm organic resources (crop residues, energy crops) need to be reported under the source category '3.A2(k) – Co-digestates'.

Animal waste management system characteristics (AWMS)*:* Includes the types of systems used to manage manure and a system-specific methane conversion factor (MCF) that reflects the portion of B_o that is achieved. Regional assessments of manure management systems are used to estimate the portion of the manure that is handled with each manure management technique. A description of manure management systems is included in Table 10.18. The system MCF varies with the manner in which the manure is managed and the climate. Theoretically the value can range from 0 to 100 percent. Both temperature and retention time play an important role in the calculation of the MCF. Manure that is managed as a liquid under warm conditions for an extended period of time promotes methane formation. These manure management conditions can have high MCFs of 76 to 80 percent. Manure managed as dry material in cold climates does not readily produce methane, and consequently has an MCF of about 1 percent.

Development of Tier 2 emission factors involves determining a weighted average MCF using the estimates of the manure managed by each waste system within each climate region. The average MCF is then multiplied by the VS excretion rate and the B_o for the livestock categories. In equation form, the estimate is as follows:

EQUATION 10.23
CH_4 EMISSION FACTOR FROM MANURE MANAGEMENT[5]

$$EF_{(T)} = \left(VS_T \bullet 365\right)\left[B_{0(T)} \bullet 0.67 \bullet \sum_{S,k} \frac{MCF_{S,k}}{100} \bullet AWMS_{(T,S,k)}\right]$$

Where:

$EF_{(T)}$ = annual CH_4 emission factor for livestock category *T*, kg CH_4 animal^{-1} yr^{-1}

$VS_{(T)}$ = daily volatile solid excreted for livestock category *T*, kg dry matter animal^{-1} day^{-1}

365 = basis for calculating annual VS production, days yr^{-1}

$B_{0(T)}$ = maximum methane producing capacity for manure produced by livestock category *T*, m^3 CH_4 kg^{-1} of VS excreted

0.67 = conversion factor of m^3 CH_4 to kilograms CH_4

$MCF_{(S,k)}$ = methane conversion factors for each manure management system *S* by climate region *k*, percent

$AWMS_{(T,S,k)}$ = fraction of livestock category *T*'s manure handled using animal waste management system *S* in climate region *k*, dimensionless

Even when the level of detail presented in the Tier 2 method is not possible in some countries, country-specific data elements such as animal mass, VS excretion, and others can be used to improve emission estimates. If country-specific data are available for only a portion of these variables, countries are encouraged to calculate country-specific emission factors, using the data available in Annex 10A.1 and 10A.2 to fill gaps.There is no defined threshold to indicate how much country-specific information is required for a Tier 2 method, but it is understood that increased use of country-specific information improves emission estimates, by better representing local production characteristics.

Measurement programs can be used to improve the basis for making the estimates. In particular, measurements of emissions from manure management systems under field conditions are useful to verify MCFs. Also, measurements of B_0 from livestock in tropical regions and for varying diet regimens are needed to expand the representativeness of the default factors.

As emissions can vary significantly by region and livestock species/category, emission estimates should reflect as much as possible the diversity and range of animal populations and manure management practices between different regions within a country. This may require separate estimates to be developed for each region. Emission factors should be updated periodically to account for changes in manure characteristics and management practices. These revisions should be based on reliable scientifically reviewed data. Frequent monitoring is desirable to verify key model parameters and to track changing trends in the livestock industry.

VS excretion rates

Volatile solids (VS) are the organic material in livestock manure and consist of both biodegradable and non-biodegradable fractions. The value needed for the Equation 10.24 is the total VS (both degradable and non-biodegradable fractions) as excreted by each animal species since the B_o values are based on total VS entering the systems. The best way to obtain average daily VS excretion rates is to use data from nationally published sources. If average daily VS excretion rates are not available, country-specific VS excretion rates can be estimated from feed intake levels. Feed intake for cattle and buffalo can be estimated using the 'Enhanced' characterisation method described in Section 10.2. This will also ensure consistency in the data underlying the emissions estimates. For swine, country-specific swine production data may be required to estimate feed intake.

The VS content of manure equals the fraction of the diet consumed that is not digested and thus excreted as fecal material which, when combined with urinary excretions, constitutes manure. Countries should estimate gross

[5] When biogas is produced in on-farm plants, emissions from on-farm co-digestates can be calculated separately using a similar equation: $CH_{4(cdg)}=C_{cdg}$ *B0*0.67*(MCF/100) and added to methane totals, where C_{cdg} is the total kg dry matter of the co-digested material and other parameters are as defined in Equation 10.23

energy (GE) intake (Section 10.2, Equation 10.16) and its fractional digestibility, DE, in the process of estimating enteric methane emissions.

Once these are estimated, the VS excretion rate is estimated as:

EQUATION 10.24 (UPDATED)
VOLATILE SOLID EXCRETION RATES

$$VS = \left[GE \bullet \left(1 - \frac{DE}{100} \right) + \left(UE \bullet GE \right) \right] \bullet \left[\left(\frac{1 - ASH}{18.45} \right) \right]$$

Where:

VS	= volatile solid excretion per day on a dry-organic matter basis, kg VS day^{-1}
GE	= gross energy intake, MJ day^{-1}
DE	= digestibility of the feed in percent (e.g. 60 percent)
$(UE \bullet GE)$	= urinary energy expressed as fraction of GE. Typically 0.04GE can be considered urinary energy excretion by most ruminants (reduce to 0.02 for ruminants fed with 85 percent or more grain in the diet or for swine). Use country-specific values where available.
ASH	= the ash content of feed calculated as a fraction of the dry matter feed intake (e.g., 0.06 for sows: Dämmgen *et al*. 2011). Use country-specific values where available.
18.45	= conversion factor for dietary GE per kg of dry matter (MJ kg^{-1}). This value is relatively constant across a wide range of forage and grain-based feeds commonly consumed by livestock.

Representative DE percent values for various livestock categories are provided in Section 10.2, Table 10.2 of this report. The value for ash content fraction can range substantially between livestock types and should reflect national circumstances.

B_0 values

The maximum methane-producing capacity of the manure (B_0) varies by species and diet. The preferred method to obtain B_0 measurement values is to use data from country-specific published sources, measured with a standardised method. It is important to standardise the B_0 measurement, including the method of sampling, and to confirm if the value is based on total as-excreted VS or biodegradable VS, since the Tier 2 calculation is based on total as-excreted VS. If country-specific B_0 measurement values are not available, default values are provided in Table 10.16 where data is summarized from Table 10A-4 through 10A-9 of *2006 IPCC Guidelines*.

MCFs

MCFs are determined for a specific manure management system and represent the degree to which B_0 is achieved. Default methane conversion factors (MCFs) are provided in Table 10.17 for different manure management systems. The amount of methane generated by a specific manure management system is affected by the amount of volatile solids, the extent of anaerobic conditions present, the temperature of the system, and the retention time of organic material in the system. Default MCF values for liquid systems and lagoons presented in Table 10.17 include the effect of longer retention times.

Liquid-based systems are sensitive to temperature effects. Average annual MCF values for a specific system will largely be determined by the quantity of VS in the storage system during peak temperature periods (Balde *et al*. 2016). Emissions increase exponentially with increasing temperatures. For this reason, monthly temperature variations in combination with timing of storage and application times largely define annual MCFs rather than average annual temperatures.

Climate zones are used to differentiate variations in MCFs associated with ranges and annual monthly temperature variability. Detailed definitions of climate zones and a decision tree to determine in what climate zone a specific region falls, can be found in Annex 10A.2, Figure 10A.1. Inventory compilers should consult long-term averages from national meteorological statistics and evaluate the climate zones for each region of their country based on the criteria outlined in Annex 10A.2. It is *good practice* to assure consistency of the definition of climate zones for all sectors of the inventory that may be influenced by climate.

Manure removal statistics should be taken from farm practice surveys or from expert consultation. Compilers should develop an estimate of the average number of manure removals per year and the months of the highest

frequency of removals. If regional practices vary, compilers should develop MCFs that are representative of regional practice by entering consistent manure removal statistics with regional temperature profiles. If regional MCFs are calculated, the national MCF should be weighted based on the number of animals feeding into the regional manure management systems represented by the manure removal profile and the regional temperature profile.

In cases in which countries lie in multiple climate zones, it is *good practice* for compilers, if possible, to disaggregate livestock populations by climate zone. However, when it is not possible, compilers should select the dominant climate zone in their country or region.

Further, in cases that countries have information available on their manure spreading practices (number of times that manure storages are emptied per year) and have monthly temperature profiles it is *good practice* that they customize MCF calculations based on their monthly temperature profiles according to the example provided in Annex 10A.2. If regional MCFs are calculated, the national MCF should be weighted based on the number of animals feeding into the regional manure management systems represented by the manure removal profile and the regional temperature profile. Global temperature data can be downloaded from a number of sites such as the National Oceanic and Atmospheric Administration (NOAA) website, long-term monthly averages should be used for the development of MCFs.

Likewise, for cases in which manure is maintained in the animal housing, compilers may wish to calculate the MCF considering the temperature profile of the housing. An example of how to derive an MCF for a liquid system is provided in Annex 10A.3 and a simple spreadsheet model is available in the supplemental data supplied with this chapter. Please refer to "Raw data for cattle and buffalo spreadsheet".

For manure deposited by grazing animals onto pastures, ranges and paddocks, it is recommended to use a value that is consistent with the emission factor provided in Table 10.14. In this table, a single emission factor per unit of volatile solid excretion is provided, as an analysis of 45 data points showed that there was no significant difference between climatic zones nor were there differences per animal category (Annex 10B.6). Therefore, the MCF reported in Table 10.17 must be used in conjunction with a single B_0 value of 0.19 m^3 CH_4 kg^{-1} of VS excreted, derived from the experimental results described in Annex 10B.6. This single emission factor was judged by the expert panel to be more accurate than emission factors estimated from regionally based MCFs and animal category based B_0, considering the differences in processes that would result in methane production between excretion of VS on pasture, range and paddock relative to typical manure storage systems.

Anaerobic digestion is an important manure management technology that provides renewable energy through biogas production. There is a wide variety of digesters available of varyinig quality and use including industrial centralised biogas digester plants, and animal farm based biogas digesters. Some biogas digesters may co-digest energy crops and different types of organic waste in varying combinations. The quality of the digester and the pre- and post-storage of digester input and output (digestate) are the main factors in determining the methane that is lost to the atmosphere before, during and after digestion.

Default methane conversion factors (MCFs) of anaerobic digesters are provided in Table 10.17. Default values for biogas digesters presented include the estimated MCF from combinations of either high and low quality anaerobic digetsers with different types and qualities of storage systems. The approach to calculate these MCFs, based on Haenel *et al*. (2018) is outlined in Annex 10A.4. The main factors considered in differentiating between digester systems are the degree of leakage from the digester itself (varying between 1 and 10 percent of the methane production potential B_0) and the loss of CH_4 from the digeste storage system.

All manure management methane emission factors are based on experimental measurements that typically combine the VS and bedding. Based on current scientific literature, these two sources cannot be separated. More refined measurements of methane from manure storage and stages of storage are for further scientific development. These default values may not encompass the potentially wide variation within the defined categories of management systems. Therefore, country-specific MCFs that reflect the specific management systems used in particular countries or regions should be developed, if possible. This is particularly important for countries with large animal populations or with multiple climate regions. In such cases, and if possible, field measurements should be conducted for each climate region to replace the default MCF values. Measurements should include the following factors:

- Duration of storage and timing of application;
- Information on manure treatment and VS (including bedding) entering the storage system;
- Feed and animal characteristics at the measurement site (see Section 10.2 for the type of data that would be pertinent);
- Determination of the amount of manure left in the storage facility after emptying (methanogenic inoculum);

- Monthly temperature in the storage.

CH_4 emissions from multiple Manure Management systems

If manure is managed in multiple systems, by default, manure emission factors should be allocated to the dominant storage systems; but a country specific emission factor could be developed considering the emissions originating from all systems used in storage prior to field applicaton.

A number of combinations are possible and it is beyond the scope of these guidelines to provide guidance for all possibilities but common examples include: i.) manure flushed from a dairy freestall barn to an anaerobic lagoon that first pass through a solids separation unit where some of the manure nitrogen is removed and managed as a solid. In this case, the methodology must integrate an additional fraction to the AWMS system that tranfers those solids to a solid storage systems; ii.) pit storage that is flushed to a larger holding tank. In this case, the methodology must consider modifications to the B_0 that result from the initial storage period based on the length of the storage and the temperature dependant MCF. iii.) solid manure pack that is allowed to accumulate, and periodically transferred to heaps. Likewise in this case, the impact of the prestorage period to the B_0 of the manure in the secondary storage should be adjusted to consider the emissions that occurred during the initial storage.

In cases in which country-specific methodologies are used to estimate emissions from multiple systems rely on B_0s and MCFs as defined in Tables 10.16 and 10.17, these methodologies should assure that the total annual B_0 of the stored manure is not reduced or increased during the application of the methodology. Further, methodologies that require additional fractionation of manure must assure that calculated VS input is not reduced or increased.

TABLE 10.16A (UPDATED)
DEFAULT VALUES FOR MAXIMUM METHANE PRODUCING CAPACITY (B_0) (M^3 CH_4 KG^{-1} VS)

Category of animal [2]	Region					
	North America	Western Europe	Eastern Europe	Oceania	Other Regions[1]	
					High productivity systems	Low productivity systems
Dairy cattle	0.24				0.24	0.13
Non dairy cattle	0.19	0.18	0.17	0.17	0.18	0.13
Buffalo	0.10				0.10	0.10
Swine	0.48	0.45	0.45	0.45	0.45	0.29
Chicken-Layer	0.39				0.39	0.24
All other poultry	0.36				0.36	0.24
Sheep	0.19				0.19	0.13
Goats	0.18				0.18	0.13
Horses	0.30				0.30	0.26
Mules/ Asses	0.33				0.33	0.26
Camels	0.26				0.26	0.21
All Animals PRP	0.19					

Sources: All values are consistent with *2006 IPCC Guidelines* values from Annex 10A.2 with the exception of PRP, taken from the analysis described in Annex 10B.6.

[1] For other regions, low productivity is considered the default value for Tier 1 if not using the Tier 1a.

[2] Only presenting values for manure, compilers are recommended to consult scientific literature or develop country-specific B_0 values for the different codigestates that may be used in anaerobic digesters.

Uncertainty values are ±15 percent.

TABLE 10.17 (UPDATED)
METHANE CONVERSION FACTORS FOR MANURE MANAGEMENT SYSTEMS

System[4]		MCFs by climate zone									
		Cool				Temperate		Warm			
		Cool Temp. Moist	Cool Temp. Dry	Boreal Moist	Boreal Dry	Warm Temp. Moist	Warm Temp. Dry	Tropical Montane	Tropical Wet	Tropical Moist	Tropical Dry
Uncovered anaerobic lagoon[7]		60%	67%	50%	49%	73%	76%	76%	80%	80%	80%
Liquid/Slurry, and Pit storage below animal confinements[1]	1 Month	6%	8%	4%	4%	13%	15%	25%	38%	36%	42%
	3 Month[8]	12%	16%	8%	8%	24%	28%	43%	61%	57%	62%
	4 Month[9]	15%	19%	9%	9%	29%	32%	50%	67%	64%	68%
	6 Month[9]	21%	26%	14%	14%	37%	41%	59%	76%	73%	74%
	12 Month[9]	31%	42%	21%	20%	55%	64%	73%	80%	80%	80%
Cattle and Swine deep bedding[5]	> 1 month[10]	21%	26%	14%	14%	37%	41%	59%	76%	73%	74%
	< 1 month[11]	2.75%				6.50%		18%			
Solid storage[6,12]		2.00%				4.00%		5.00%			
Solid storage – Covered/compacted[6,13]		2.00%				4.00%		5.00%			
Solid storage – Bulking agent addition[6,14]		0.50%				1.00%		1.50%			
Solid storage – Additives[6,15]		1.00%				2.00%		2.50%			
Dry lot[16]		1.00%				1.50%		2.00%			
Daily spread[17]		0.10%				0.50%		1.00%			
Composting - In-vessel[4,18]		0.50%									
Composting - Static pile (Forced aeration)[4,6,19]		1.00%				2.00%		2.50%			
Composting - Intensive windrow[4,20]		0.50%				1.00%		1.5%			
Composting – Passive windrow (Unfrequent turning)[3,4,6,21]		1.00%				2.00%		2.50%			

TABLE 10.17 (UPDATED) (CONTINUED)
METHANE CONVERSION FACTORS FOR MANURE MANAGEMENT SYSTEMS

System[4]	MCFs by climate zone									
	Cool				Temperate		Warm			
	Cool Temp. Moist	Cool Temp. Dry	Boreal Moist	Boreal Dry	Warm Temp. Moist	Warm Temp. Dry	Tropical Montane	Tropical Wet	Tropical Moist	Tropical Dry
Pasture/Range/Paddock[2]	0.47%									
Poultry manure with and without litter[22]	1.50%									
Aerobic treatment[23]	0.00%									
Burned for fuel[24]	10.00%									
Anaerobic Digester[25], Low leakage, High quality gastight storage, best complete industrial technology	1.00%									
Anaerobic Digester[25], Low leakage, High quality industrial technology, low quality gastight storage technology	1.41%									
Anaerobic Digester[25], Low leakage, High quality industrial technology, open storage	3.55%				4.38%		4.59%			
Anaerobic Digester[25], High leakage, low quality technology, high quality gastight storage technology	9.59%									
Anaerobic Digester[25], High leakage, low quality technology, low quality gastight storage technology	10.00%									
Anaerobic Digester[25], High leakage, low quality technology, open storage	12.14%				12.97%		13.17%			

TABLE 10.17 (UPDATED) (CONTINUED)
METHANE CONVERSION FACTORS FOR MANURE MANAGEMENT SYSTEMS

[1] The initial judgement of IPCC Expert Group supported by additional new research. See Annex 10B.7 for additional details. Suggested default values are equivalent to liquid systems with 6 month retention time if retention times are unknown. A reduction of 40% due to crust cover may be applied only when a thick, dry, crust is present. Thick dry crusts occur in systems in which organic bedding is used in the barn and is allowed to be flushed into the liquid storage tank and solids are not separated from the manure stream and further the surface is not exposed to regular heavy precipitation that may disrupt the surface. Sources: Aguerre *et al*. (2012); Nielsen *et al*. (2013); VanderZaag *et al*. (2008).

New information suggests that a solid cover reduces CH_4 emissions by 25 to 50% (range: 0 to 90%). Sources: Amon *et al*. (2006), Amon *et al*. (2007); Clemens *et al*. (2006); Guarino *et al*. (2006), Matulaitis *et al*. (2015), Misselbrook *et al*. (2016), VanderZaag *et al*. (2009), Hou *et al*. (2015), VanderZaag *et al*. (2008).

[2] Pasture Range and Paddock MCFs must always be used in conjunction with a B_0 value of 0.19 m^3 CH_4 kg^{-1} of VS excreted to maintain consistency with the data in the updated version of Cai *et al*. (2017) database (see Annex 10B.6).

[3] Definitions for manure management systems are provided in Table 10.18.

[4] Composting is the biological oxidation of a solid waste including manure usually with bedding or another organic carbon source typically at thermophilic temperatures due to microbial heat production.

[5] Articles from which these values were derived were for cattle and swine, but for other animal production systems that use deep bedding these values are proposed to be used as surrogates. Suggested default values are equivalent to liquid systems with 6 month retention time.

[6] Sources and assumptions to calculate MCF values for *Solid storage categories and composting (static pile and passive windrows)* are detailed in Annex 10B.7.

[7] Judgement of IPCC Expert Group utilizing a 12 month retention time and the equations and parameters presented in Mangino *et al*. (2001). Solid-liquid separation that removes VS and diverts it to aerobic/solid management should be considered when calculating the VS loading rate into liquid systems.

[8] The avg °C for Cool Temperate Moist, Cool Temperate Dry, Warm Temperate Moist, Warm Temperate Dry, Tropical Montane, Tropical Wet, Tropical Moist, Tropical Dry were 4.6, 5.8, 13.9, 14.0, 21.5, 25.9, 25.2, 25.6 respectively.

[9] Solid-liquid separation that removes VS and diverts it to aerobic/solid management should be considered when calculating the VS loading rate into liquid systems.

[10] Judgement of IPCC 2006 Expert Group in combination with Mangino *et al*. (2001). Values are consistent with liquid systems. Values presented here are consistent with a 6 month retention time, however compilers should take into account country-specific retention time when possible.

[11] Judgement of IPCC 2006 Expert Group in combination with Moller *et al*. (2004). Expect emissions to be similar, and possibly greater, than pit storage, depending on organic content and moisture content.

[12] Expert judgement based on IPCC (2006) and update supported by Pardo *et al*. (2015). Emissions in temperate climate can be double relative to a cool climate.

[13] Expert judgement based on Pardo *et al*., (2015). Emissions in the same range than solid storage.

[14] Expert judgement based on Pardo *et al*. (2015). Estimated reduction of 75% due to bulking agent addition.

[15] Expert judgement based on Pardo *et al*. (2015). Estimated reduction of 50% due to additives addition.

[16] Judgement of IPCC 2006 Expert Group in combination with Hashimoto & Steed (1993).

[17] Hashimoto & Steed (1993).

[18] Judgement of IPCC 2006 Expert Group and Amon *et al*. (1998a). MCFs are less than half of solid storage. Not temperature dependant.

[19] Expert judgement updated based on Pardo *et al*. (2015). Estimated reduction of 50% compared to solid storage. Previously it was considered "Not temperature dependent" but now temperature influence has been considered.

[20] Judgement of IPCC Expert Group and Amon *et al*. (1998a). MCFs are slightly less than solid storage. Less temperature dependant.

[21] Expert judgement update based on Pardo *et al*. (2015). Estimated reduction of 50% compared to solid storage. Previous MCFs have been modified as they could underestimate CH_4 emissions.

[22] Judgement of 2006 IPCC Expert Group. MCFs are similar to solid storage or to dry lot but with generally constant warm temperatures.

[23] Judgement of 2006 IPCC Expert Group. MCFs are near zero. Aerobic treatment can result in the accumulation of sludge which may be treated in other systems. Sludge requires removal and has large VS values. It is important to identify the next management process for the sludge and estimate the emissions from that management process if significant.

[24] Judgement of IPCC 2006 Expert Group in combination with Safley *et al*. (1992).

[25] Calculations based on Haenel *et al*. (2018), outlined in Annex 10A.4.

10.4.3 Choice of activity data

There are two main types of activity data for estimating CH_4 emissions from manure management: (1) animal population data; and (2) manure management system usage data.

The animal population data should be obtained using the approach described in Section 10.2. As noted in Section 10.2, it is *good practice* to conduct a single livestock characterisation that will provide the activity data for all emissions sources relying on livestock population data. It is important to note, however, that the level of disaggregation in the livestock population data required to estimate emissions from manure management, may differ from those used for other sources, such as Enteric Fermentation. For example, for some livestock population species/categories, such as cattle, the enhanced characterisation required for the Tier 2 enteric fermentation estimate could be aggregated to broader categories that are sufficient for this source category. For other livestock species, such as swine, it may be preferable to have more disaggregation of weight categories for manure management calculations than for enteric fermentation. However, consistency in livestock categories should be retained throughout the inventory.

Inventory agencies in countries with varied climatic conditions are encouraged to obtain population data for each major climatic zone as defined in Volume 4, Chapter 3, Annex 3A.5, Figure 3A.5.1 or the version found in Annex 10A.2 of this Chapter. This will allow more specific selection of default factors or MCF values for those systems more sensitive to temperature changes. Ideally, the regional population breakdown can be obtained from published national livestock statistics, and the temperature data from national meteorological statistics. If regional data are not available, experts should be consulted regarding regional production (e.g., milk, meat, and wool) patterns or land distribution, which may provide the required information to estimate the regional animal distributions.

To implement the Tier 2 method, the portion of manure managed in each manure management system must also be collected for each representative animal species. Table 10.18 summarizes the main types of manure management systems. Quantitative data should be used to distinguish whether the system is judged to be a solid storage or liquid/slurry. The borderline between dry and liquid can be drawn at 15 percent dry matter content. Note that in some cases, manure may be managed in several types of manure management systems. For example, manure flushed from a dairy freestall barn to an anaerobic lagoon may first pass through a solids separation unit where some of the manure solids are removed and managed as a solid. Therefore, if manure is managed in multiple systems, it is *good practice* to report the respective CH_4 emissions from each system (see N_2O emissions from multiple Manure Management systems). Manure removal statistics should also be monitored where possible. It is recommended that agencies develop an estimate of the average number of manure removals per year and the months of the highest frequency of removals. If regional practices vary and also represent significant differences in temperature profiles, statistics that are representative of regional practice should be tracked combining the appropriate manure removal statistics together with regional temperature profiles.

The best means of obtaining manure management system distribution data is to consult regularly published national statistics. If such statistics are unavailable, the preferred alternative is to conduct an independent survey of manure management system usage. If the resources are not available to conduct a survey, experts should be consulted to obtain an opinion of the system distribution. Volume 1, Chapter 2 *Approaches to Data Collection* describes how to elicit expert judgement. Similar expert elicitation protocols can be used to obtain manure management system distribution data.

TABLE 10.18 (UPDATED)
DEFINITIONS OF MANURE MANAGEMENT SYSTEMS[3]

System		Definition
Pasture/Range/Paddock (PRP)		The manure from pasture and range grazing animals is allowed to lie as deposited, and is not managed.
Daily spread		Manure is routinely removed from a confinement facility and is applied to cropland or pasture within 24 hours of excretion.
Solid storage		The storage of manure, typically for a period of several months, in unconfined piles or stacks. Manure is able to be stacked due to the presence of a sufficient amount of bedding material or loss of moisture by evaporation. Solid stores can be covered or compacted. In some cases, bulking agent or additives are added.
Solid storage-Covered/compacted		Similar to solid storage, but the manure pile is a) covered with a plastic sheet to reduce the surface of manure exposed to air and/or b) compacted to increase the density and reduce the free air space within the material.
Solid storage - Bulking agent addition		Specific materials (bulking agents) are mixed with the manure to provide structural support. This allows the natural aeration of the pile, thus enhancing decomposition (e.g. sawdust, straw, coffee husks, maize stover).
Solid storage - Additives		The addition of specific substances to the pile in order to reduce gaseous emissions. Addition of certain compounds such as attapulgite, dicyandiamide or mature compost have shown to reduce N_2O emissions; while phosphogypsum reduces CH_4 emissions.
Dry lot		A paved or unpaved open confinement area without any significant vegetative cover. Dry lots do not require the addition of bedding to control moisture. Manure may be removed periodically and spread on fields.
Liquid/Slurry [1]		Manure is stored as excreted or with some minimal addition of water or bedding material in tanks or ponds outside the animal housing. Manure is removed and spread on fields once or more in a calendar year. Manure is agitated before removal from the tank/ponds to ensure that most of the VS are removed from the tank.
Uncovered anaerobic lagoon		A type of liquid storage system designed and operated to combine waste stabilization and storage. Lagoons have a lower depth and a much larger surface compared to liquid slurry stores. Anaerobic lagoons are designed with varying lengths of storage (up to a year or greater), depending on the climate region, the volatile solids loading rate, and other operational factors. The supernatant water from the lagoon may be recycled as flush water or used to irrigate and fertilise fields.
Pit storage below animal confinements		Collection and storage of manure usually with little or no added water typically below a slatted floor in an enclosed animal confinement facility, usually for periods less than one year. Manure may be pumped out of the storage to a secondary storage tank multiple times in one year, or stored and applied directly to fields. It is assumed that VS removal rates on tank emptying are >90%.
Anaerobic digester	Digesters of high quality and low leakage	Animal manure with and without straw is collected and anaerobically digested in a containment vessel. Co-digestion with other waste or energy crops may occur. Digesters are designed, constructed and operated according to industrial technology standard for waste stabilization by the microbial reduction of complex organic compounds to CO_2 and CH_4. Biogas is captured and used as a fuel. Digestate is stored either in open storage, in covered storage with no leakage control, or in gas tight storage with gas recovery or flaring.
	Digesters with high leakage	Animal manure with and without straw is collected and anaerobically digested in covered lagoon. Digesters are used for waste stabilization by the microbial reduction of complex organic compounds to CO_2 and CH_4. Biogas is captured and flared or used as a fuel. After anaerobic digestion, digestate is stored either openly, covered, or gas tightly.
Burned for fuel		The dung and urine are excreted on fields. The sun dried dung cakes are burned for fuel.

TABLE 10.18 (UPDATED) (CONTINUED)
DEFINITIONS OF MANURE MANAGEMENT SYSTEMS

System		Definition
Deep bedding		As manure accumulates, bedding is continually added to absorb moisture over a production cycle and possibly for as long as 6 to 12 months. This manure management system also is known as a bedded pack manure management system and may be combined with a dry lot or pasture. Manure may undergo periods where animals are present and are actively mixing the manure, or periods in which the pack is undisturbed.
Composting	In-vessel[2]	Composting, typically in an enclosed channel, with forced aeration and continuous mixing.
	Static pile	Composting in piles with forced aeration but no mixing, with runoff/leaching containment.
		Composting in piles with forced aeration but no mixing, without runoff/leaching containment.
	Intensive windrow[2]	Composting in windrows with regular (at least daily) turning for mixing and aeration, runoff/leaching containment.
		Composting in windrows with regular (at least daily) turning for mixing and aeration, no runoff/leaching containment.
	Composting - Passive windrow[2]	Composting in windrows with infrequent turning for mixing and aeration, with runoff/leaching.
		Composting in windrows with infrequent turning for mixing and aeration, no runoff/leaching.
Poultry manure with litter		Similar to cattle and swine deep bedding except usually not combined with a dry lot or pasture. Typically used for all poultry breeder flocks, for alternative systems for layers and for the production of meat type chickens (broilers) and other fowl. Litter and manure are left in place with added bedding during the poultry production cycle and cleaned between poultry cycles, typically 5 to 9 weeks in productive systems and greater in lower productivity systems.
Poultry manure without litter		May be similar to open pits in enclosed animal confinement facilities or may be designed and operated to dry the manure as it accumulates. The latter is known as a high-rise manure management system and is a form of passive windrow composting when designed and operated properly. Some intensive poultry farms installed the manure belt under the cage, where the manure is dried inside housing.
Aerobic treatment		The biological oxidation of manure collected as a liquid with either forced or natural aeration. Natural aeration is limited to aerobic and facultative ponds and wetland systems and is due primarily to photosynthesis. Hence, these systems typically become anoxic during periods without sunlight.

[1] Covers on manure management systems can impact emissions of direct N_2O, CH_4 and NH_3. With N_2O and CH_4 emission, the effect of the cover depends upon character of the cover material.

[2] Composting is the biological oxidation of a solid waste including manure usually with bedding or another organic carbon source typically at thermophilic temperatures produced by microbial heat production.

[3] Comparative definitions with the EMEP/EEA Air Pollutant Emission Inventory 2016 Guidebook can be found in Annex 10A.2, Table 10A.10.

10.4.4 Uncertainty assessment

No refinement.

10.4.5 Completeness, Time series, Quality assurance / Quality control and Reporting

No refinement.

10.5 N_2O EMISSIONS FROM MANURE MANAGEMENT

This section describes how to estimate the N_2O produced, directly and indirectly, during the storage and treatment of manure before it is applied to land or otherwise used for feed, fuel, or construction purposes. The approach is based on N excretion, emission factors for N_2O emissions, as well as volatilization and leaching factors. This section also details the principles of N flow and the connection between IPCC N_2O reporting and NH_3 and NO_x reporting required for UNECE countries.

The term 'manure' is used here collectively to include both dung and urine (i.e., the solids and the liquids) produced by livestock. The N_2O emissions generated by manure in the system 'pasture, range, and paddock' occur directly and indirectly from the soil, and are therefore reported under the category 'N_2O Emissions from Managed Soils' (see Chapter 11, Section 11.2). Direct and indirect N_2O emissions generated by manure managed in other systems and following its application to soils are also reported under the category 'N_2O Emissions from Managed Soils' (see Chapter 11, Section 11.2). The emissions associated with the burning of dung for fuel are to be reported under 'Fuel Combustion' (see Volume 2: Energy), or under 'Waste Combustion' (see Volume 5: Waste) if burned without energy recovery.

Direct N_2O emissions occur via combined nitrification and denitrification of nitrogen contained in the manure. The emission of N_2O from manure during storage and treatment depends on the nitrogen and carbon content of manure, and on the duration of the storage and type of treatment. Nitrification (the oxidation of ammonia nitrogen to nitrate nitrogen) is a necessary prerequisite for the emission of N_2O from stored animal manures. Nitrification is likely to occur in stored animal manures provided there is a sufficient supply of oxygen. Nitrification does not occur under anaerobic conditions. Nitrites and nitrates are transformed to N_2O and dinitrogen (N_2) during the naturally occurring process of denitrification, an anaerobic process. There is general agreement in the scientific literature that the ratio of N_2O to N_2 increases with increasing acidity, nitrate concentration, and reduced moisture. In summary, the production and emission of N_2O from managed manures requires the presence of either nitrites or nitrates in an anaerobic environment preceded by aerobic conditions necessary for the formation of these oxidized forms of nitrogen. In addition, conditions preventing reduction of N_2O to N_2, such as a low pH or limited moisture, must be present.

Indirect emissions result from volatile nitrogen losses that occur primarily in the forms of ammonia and NO_x. The fraction of excreted organic nitrogen that is mineralized to ammonium nitrogen during manure collection and storage depends primarily on oxygen supply, time, and on temperature. Simple forms of organic nitrogen such as urea (mammals) and uric acid (poultry) are rapidly mineralized to ammonium nitrogen, which is converted to ammonia under alkaline conditions. Ammonia is highly volatile and easily diffused into the surrounding air (Asman *et al*. 1998; Monteny & Erisman 1998). Nitrogen losses begin at the point of excretion in houses and other animal production areas (e.g., milk parlors) and continue through on-site management in storage and treatment systems (i.e., manure management systems). Nitrogen is also lost through runoff and leaching into soils from the solid storage of manure at outdoor areas, in feedlots and where animals are grazing in pastures. Emissions of nitrogen compounds from grazing livestock are considered separately in Chapter 11, Section 11.2, *N_2O Emissions from Managed Soils*.

In the case of co-digestion of animal manures with additional organic residues, energy crops, additional N enters the system. This additional N source also emits N_2O during the storage, and must be considered in the section "N_2O emissions from manure management".

Due to significant direct and indirect losses of manure nitrogen in management systems it is important to estimate the remaining amount of animal manure nitrogen available for application to soils or for use in feed, fuel, or construction purposes. This value is used for calculating N_2O emissions from managed soils (see Chapter 11, Section 11.2). The methodology to estimate manure nitrogen that is directly applied to soils, or available for use in feed, fuel, or construction purposes is described in this chapter under Section 10.5.4 "Coordination with reporting for N_2O emissions from managed soils".

10.5.1 Choice of method

The level of detail and methods chosen for estimating N_2O emissions from manure management systems will depend upon national circumstances and the decision tree in Figure 10.4 describes *good practice* in choosing a method accordingly. The following sections describe the different tiers referenced in the decision tree for calculating direct and indirect N_2O emissions from manure management systems.

Direct N_2O emissions from Manure Management

Tier 1

The Tier 1 method entails multiplying the total amount of N excretion (from all livestock species/categories) in each type of manure management system by an emission factor for that type of manure management system (see Equation 10.25). Emissions are then summed over all manure management systems. The Tier 1 method is applied using IPCC default N_2O emission factors, default nitrogen excretion data, and default manure management system data (see Annex 10A.2, Tables 10A.5 to 10A.9 for default animal weights and manure management system allocations). It is recommended to consult the methane and enteric fermentation sections to clarify how to implement the Tier 1a approach, if that is the approach selected.

Tier 2

A Tier 2 method follows the same calculation equation as Tier 1 but would include the use of country-specific data for some or all of these variables. For example, the use of country-specific nitrogen excretion rates for livestock categories would constitute a Tier 2 methodology.

Tier 3

A Tier 3 method utilizes alternative estimation procedures based on a country-specific methodology. For example, a process-based, mass balance approach which tracks nitrogen throughout the system in detail starting with feed input through final use/disposal could be utilized as a Tier 3 procedure. Tier 3 methods should be well documented to clearly describe estimation procedures.

To estimate emissions from manure management systems, the livestock population must first be divided into categories that reflect the varying amounts of manure produced per animal as well as the manner in which the manure is handled. This division of manure by type of system should be the same as that used to characterize methane emissions from manure management (see Section 10.4). For example, if Tier 1 default emission factors are used for calculating CH_4 emissions, then the manure management systems usage data from Tables 10A.5 to 10A.9 should be applied. Detailed information on how to characterise the livestock population for this source is provided in Section 10.2.

In the case of anaerobic digestion of animal manures with additional organic residues it is essential to estimate the additional N input from these organic residues and the respective N_2O emissions.

The following five steps are used to estimate direct N_2O emissions from Manure Management:

Step 1: Collect population data from the Livestock Population Characterisation;

Step 2: Use default values or develop the annual average nitrogen excretion rate per head ($Nex_{(T,P)}$) for each defined livestock species/category T, and productivity system P, when applicable;

Step 3: Use default values or determine the fraction of total annual nitrogen excretion for each livestock species/category T that is managed in each manure management system S ($AWMS_{(T,S,P)}$);

Step 4: Use default values or develop N_2O emission factors for each manure management system S ($EF_{3(S)}$); and

Step 5: For each manure management system type S, multiply its emission factor ($EF_{3(S)}$) by the total amount of nitrogen managed (from all livestock species/categories) in that system, to estimate N_2O emissions from that manure management system. Then sum over all manure management systems.

In some cases, manure nitrogen may be managed in several types of manure management systems. If manure is managed in multiple systems, it is *good practice* to estimate N_2O emissions from all systems.

The calculation of direct N_2O emissions from manure management is based on the following equation:

EQUATION 10.25 (UPDATED)
DIRECT N_2O EMISSIONS FROM MANURE MANAGEMENT

$$N_2O_{D(mm)} = \left[\sum_S \left[\sum_{T,P} \left(\left(N_{(T,P)} \bullet Nex_{(T,P)} \right) \bullet AWMS_{(T,S,P)} \right) + N_{cdg(s)} \right] \bullet EF_{3(S)} \right] \bullet \frac{44}{28}$$

Where:

$N_2O_{D(mm)}$ = direct N_2O emissions from Manure Management in the country, kg N_2O yr^{-1}

$N_{(T,P)}$ = number of head of livestock species/category *T* in the country, for productivity system *P*, when applicable

$Nex_{(T,P)}$ = annual average N excretion per head of species/category *T* in the country, for productivity system *P*, when applicable in kg N animal^{-1} yr^{-1}

$N_{cdg(s)}$ = annual nitrogen input via co-digestate in the country, kg N yr^{-1}, where the system (s) refers exclusively to anaerobic digestion

$AWMS_{(T,S,P)}$ = fraction of total annual nitrogen excretion for each livestock species/category *T* that is managed in manure management system *S* in the country, dimensionless; to consider productivity class *P*, if using a Tier 1a approach

$EF_{3(S)}$ = emission factor for direct N_2O emissions from manure management system *S* in the country, kg N_2O-N/kg N in manure management system *S*

S = manure management system

T = species/category of livestock

P = productivity class, high or low, to be considered if using the Tier 1a approach

44/28 = conversion of N_2O-$N_{(mm)}$ emissions to $N_2O_{(mm)}$ emissions

As is the case in the calculation of methane emission, countries may choose to consider if they have significantly different production systems in their country and apply a Tier 1a approach. In this case, compilers should consider the productivity class of their animal system as included in the calculation of CH_4 emissions.

There may be losses of nitrogen in other forms (e.g., ammonia and NO_x) as manure is managed on site. Nitrogen in the volatilized form of ammonia may be deposited at sites downwind from manure handling areas and contribute to indirect N_2O emissions (see below). Countries are encouraged to consider using a mass balance approach to track the manure nitrogen excreted, managed on site in manure management systems, and ultimately applied to managed soils. The estimation of the amount of manure nitrogen which is directly applied to managed soils or otherwise available for use as feed, fuel or construction purposes is described in the Section 10.5.4 Coordination with reporting for N_2O emissions from managed soils is required. See Chapter 11, Section 11.2 for procedures to calculate N_2O emissions from managed manure nitrogen applied to soils. Additional guidance on ensuring consistency in the mass balance approach and between emissions from manure in the source category N_2O Emissions from Manure Management and N_2O Emissions from Managed Soils is given in Section 10.5.6 in the subsection Consistency of nitrogen flows.

Indirect N_2O emissions from Manure Management

Tier 1

The Tier 1 calculation of N volatilisation in forms of NH_3 and NO_x from manure management systems is based on multiplication of the amount of nitrogen excreted (from all livestock categories) and managed in each manure management system by a fraction of volatilised nitrogen (see Equation 10.26). N losses are then summed over all manure management systems. The Tier 1 method is applied using default nitrogen excretion data, default manure management system data, animal weights (see Annex 10A.2, Tables 10A.5 to 10A.9) and default fractions of N loss from manure management systems (see Table 10.22):

EQUATION 10.26 (UPDATED)
N LOSSES DUE TO VOLATILISATION FROM MANURE MANAGEMENT

$$N_{volatilization-MMS} = \sum_{S}\left[\sum_{T,P}\left[\left(\left(N_{(T,P)} \bullet Nex_{(T,P)}\right) \bullet AWMS_{(T,S,P)}\right) + N_{cdg(s)}\right) \bullet Frac_{GasMS(T,S)}\right]\right]$$

Where:

$N_{volatilization-MMS}$ = amount of manure nitrogen that is lost due to volatilisation of NH_3 and NO_x, kg N yr^{-1}

$N_{(T,P)}$ = number of head of livestock species/category *T* in the country, for productivity system *P*, when applicable

$Nex_{(T,P)}$ = annual average N excretion per head of species/category *T* in the country, , for productivity system *P*, when applicable in kg N animal^{-1} yr^{-1}

$N_{cdg(s)}$ = amount of nitrogen from co-digestates added to biogas plants such as food wastes or purpose grown crops, kg N yr^{-1} where the system (s) refers exclusively to anaerobic digestion

P = productivity class, high or low, to be considered if using the Tier 1a approach

$AWMS_{(T,S,P)}$ = fraction of total annual nitrogen excretion for each livestock species/category T that is managed in manure management system S in the country, dimensionless. To consider productivity class P, if using a Tier 1a approach

$Frac_{gasMS(T,S)}$ = fraction of managed manure nitrogen for livestock category T that volatilises as NH_3 and NO_x in the manure management system S

The Tier 1 calculation of N leached and runoff from manure management systems is based on multiplication of the amount of nitrogen excreted (from all livestock categories) and managed in each manure management system by a fraction of nitrogen leached, in analogy to the approach to estimate nitrogen volatilsation (see Equation 10.26). There are limited measurement data on leaching and runoff losses from various manure management systems. The greatest N losses due to runoff and leaching typically occur where animals are on a drylot, pens, in over-wintering areas or feeding pens used during dormant growth periods for pastured animals and manure heaps or composting systems, uncovered and uncontained. In drier climates, runoff losses are smaller than in high rainfall areas and have been estimated in the range from 3 to 6 percent of N excreted (Eghball & Power 1994). Studies by Bierman *et al*. (1999) found nitrogen lost in runoff was 5 to 19 percent of N excreted and 10 to 16 percent leached into soil, while other data show relatively low loss of nitrogen through leaching in solid storage (less than 5 percent of N excreted); but greater loss could also occur (Rotz 2004). Table 10.22 contains leaching loss fractions that may be applied under very specific circumstances. Leaching can be estimated using these fractions in cases in which manure is uncovered on permeable soil, or where runoff may occur to permeable soil and runoff is not collected in a impermeable basin and redistributed to agricultural fields. Leaching losses are estimated only in cases in which manure nitrogen is being lost to the environment and not accounted for in any other N flows. Further research is needed in this area to improve the estimated losses and the conditions and practices under which such losses occur however an estimate may be provided.

EQUATION 10.27 (UPDATED)
N LOSSES DUE TO LEACHING FROM MANURE MANAGEMENT

$$N_{leaching-MMS} = \sum_{S}\left[\sum_{T,P}\left[\left(\left(N_{(T,P)} \bullet Nex_{(T,P)} \bullet AWMS_{(T,S,P)}\right) + N_{cdg(s)}\right) \bullet Frac_{LeachMS(T,S)}\right]\right]$$

Where:

$N_{leaching-MMS}$ = amount of manure nitrogen that is lost due to leaching, kg N yr^{-1}

$N_{(T,P)}$ = number of head of livestock species/category T in the country, for productivity system P, when applicable

$Nex_{(T,P)}$ = annual average N excretion per head of species/category T in the country, for productivity system P, when applicable in kg N $animal^{-1}$ yr^{-1}

$N_{cdg(s)}$ = amount of nitrogen from co-digestates added to biogas plants such as food wastes or purpose grown crops, kg N yr^{-1} where the system (s) refers exclusively to anaerobic digestion

P = productivity class, high or low, to be considered if using the Tier 1a approach

$AWMS_{(T,S,P)}$ = fraction of total annual nitrogen excretion for each livestock species/category T that is managed in manure management system S in the country, for productivity system P, when applicable, dimensionless

$Frac_{LeachMS(T,S)}$ = fraction of managed manure nitrogen for livestock category T that is leached from the manure management system S (from Table 10.22)

The indirect N_2O emissions from volatilisation of N in forms of NH_3 and NO_x ($N_2O_{G(mm)}$) are estimated using Equation 10.28:

EQUATION 10.28
INDIRECT N_2O EMISSIONS DUE TO VOLATILISATION OF N FROM MANURE MANAGEMENT

$$N_2O_{G(mm)} = \left(N_{volatilization-MMS} \bullet EF_4\right) \bullet \frac{44}{28}$$

Where:

$N_2O_{G(mm)}$ = indirect N_2O emissions due to volatilization of N from Manure Management in the country, kg N_2O yr^{-1}

EF_4 = emission factor for N_2O emissions from atmospheric deposition of nitrogen on soils and water surfaces, kg N_2O-N (kg NH_3-N + NO_x-N volatilised)$^{-1}$; given in Chapter 11, Table 11.3

The indirect N_2O emissions due to leaching and runoff from Manure Management ($N_2O_{L(mm)}$) are estimated using Equation 10.29:

EQUATION 10.29
INDIRECT N_2O EMISSIONS DUE TO LEACHING FROM MANURE MANAGEMENT

$$N_2O_{L(mm)} = (N_{leaching-MMS} \bullet EF_5) \bullet \frac{44}{28}$$

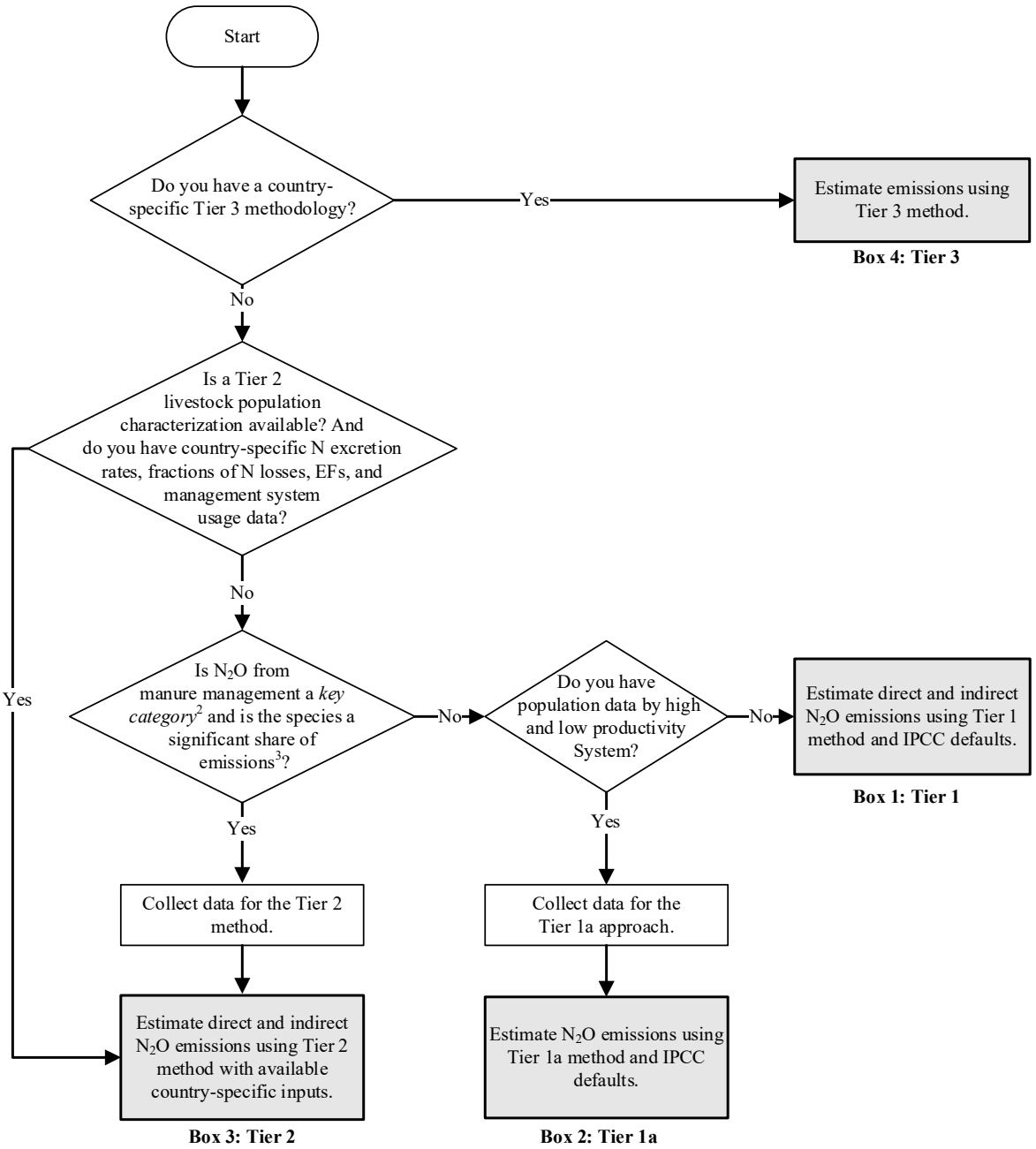
Where:

$N_2O_{L(mm)}$ = indirect N_2O emissions due to leaching and runoff from Manure Management in the country, kg N_2O yr^{-1}

$N_{leaching-MMS}$ = amount of manure nitrogen that is lost due to leaching, kg N yr^{-1}

EF_5 = emission factor for N_2O emissions from nitrogen leaching and runoff, kg N_2O-N/kg N leached and runoff, given in Chapter 11, Table 11.3

Figure 10.4 (Updated) Decision tree for N_2O emissions from Manure Management[(1)]



Note:
1: N_2O emissions from manure management systems include both direct and indirect sources.
2: See Volume 1 Chapter 4, "Methodological Choice and Identification of Key Categories"(noting Section 4.1.2 on limited resources), for discussion of key categories and use of decision trees.
3:As a rule of thumb, a livestock species would be significant if it accounts for 25-30% or more of emissions from the source category.

Tier 2

Countries may wish to develop a Tier 2 methodology for better consideration of national circumstances and to reduce uncertainty of estimates as much as possible. As for direct N_2O emission from manure management, a Tier 2 method would follow the same calculation equation as Tier 1 but include the use of country-specific data for some or all of variables. For example, the use of country-specific nitrogen excretion rates for livestock categories would constitute a Tier 2 method. Tier 2 method would require more detailed characterisation of the flow of nitrogen throughout the animal housing and manure management systems used in the country. It is *good practice* to check N balance in a Tier 2 approach. Double counting of emissions associated with the application of managed manure should be avoided, as well as manure associated with pasture and grazing operations as described in Section 10.5.6. National NH_3 emission inventories developed by some countries could be used for Tier 2

estimation of NH_3 volatilisation from manure management systems. For countries reporting emissions of NH_3 and NO_x to the UN-ECE Convention on Long-Range Transboundary Air Pollution (UN-ECE LRTAP) using a Tier 2 approach as described in the EEA (2016) emission inventory guidebook, it is *good practice* to report $N_{volatilization-MMS}$ in consistency to the NH_3 and NO_x emissions reported to the UN-ECE.

Tier 3

To reduce uncertainty of the estimates, a Tier 3 method could be developed using advanced or process-based models for volatilisation and nitrogen leaching and runoff based on actual measurements.

All losses of N through manure management systems (both direct and indirect) need to be subtracted from the amount of manure N that is available for application to soils and which is reported in Chapter 11, Section 11.2 N_2O Emissions from Managed Soils. Refer to Section 10.5.4, Coordination with reporting for N_2O emissions from managed soils, for guidance on calculating total N losses from manure management systems.

10.5.2 Choice of emission factors

Annual average nitrogen excretion rates, $Nex_{(T)}$

Tier 1

Annual nitrogen excretion rates should be determined for each livestock category defined by the livestock population characterization. Country-specific rates may either be taken directly from documents or reports such as agricultural industry and scientific literature or derived from information on animal nitrogen intake and retention (as explained below). In some situations, it may be appropriate to use excretion rates developed by other countries that have livestock with similar characteristics.

If country-specific data cannot be collected or derived, or appropriate data are not available from another country, the IPCC default nitrogen excretion rates presented in Table 10.19 can be used. These rates are presented in units of nitrogen excreted per 1000 kg of animal per day. These rates can be applied to livestock sub-categories of varying ages and growth stages using a typical average animal mass (TAM) for that population sub-category, as shown in Equation 10.30.

EQUATION 10.30 (UPDATED)
ANNUAL N EXCRETION RATES

$$Nex_{(T,P)} = N_{rate(T,P)} \bullet \frac{TAM_{(T,P)}}{1000} \bullet 365$$

Where:

$Nex_{(T,P)}$ = annual N excretion for livestock category *T*, kg N animal^{-1} yr^{-1} (production level *P* if using a Tier 1 approach

$N_{rate(T,P)}$ = default N excretion rate, kg N (1000 kg animal mass)$^{-1}$ day^{-1} for animal category *T* (and production level *P*, if using a Tier 1a (see Table 10.19))

$TAM_{(T,P)}$ = typical animal mass for livestock category *T*, kg animal^{-1}

P = productivity class, high or low, to be considered if using the Tier 1a approach

Default TAM values are provided in Annex 10A.1, Table 10A.5. However, it is preferable to collect country-specific TAM values due to the sensitivity of nitrogen excretion rates to different weight categories. For example, market swine may vary from nursery pigs weighing less than 30 kilograms to finished pigs that weigh over 90 kilograms. By constructing animal population groups that reflect the various growth stages of market pigs, countries will be better able to estimate the total nitrogen excreted by their swine population.

When estimating the $Nex_{(T)}$ for animals whose manure is classified in the manure management system *burned for fuel* (Table 10.21), it should be kept in mind that the dung is burned, and the urine stays in the field. Generally, 50 percent of the nitrogen excreted is in the dung and 50 percent is in the urine. If the burned dung is used as fuel, then emissions are reported under the IPCC category *Fuel Combustion* (Volume 2: Energy), whereas if the dung is burned without energy recovery the emissions should be reported under the IPCC category *Waste Incineration* (Volume 5: Waste).

Tier 2

The annual amount of N excreted by each livestock species/category depends on the total annual N intake and total annual N retention of the animal. Therefore, N excretion rates can be derived from N intake and N retention data. Annual N intake (i.e., the amount of N consumed by the animal annually) depends on the annual amount of feed digested by the animal, and the protein content of that feed. Total feed intake depends on the production level of the animal (e.g., growth rate, milk production, draft power). Annual N retention (i.e., the fraction of N intake that is retained by the animal for the production of meat, milk, or wool) is a measure of the animal's efficiency of production of animal protein from feed protein. Nitrogen intake and retention data for specific livestock species/categories may be available from national statistics or from animal nutrition specialists. Nitrogen intake can also be calculated from data on feed and crude protein intake developed in Section 10.2. Default N retention values are provided in Table 10.20, Default values for the fraction of nitrogen in feed taken in by animals that is retained by the different animal species/categories. Rates of annual N excretion for each livestock species/category ($Nex_{(T)}$) are derived as follows:

EQUATION 10.31
ANNUAL N EXCRETION RATES, OPTION 1 (TIER 2)

$$Nex_{(T)} = N_{intake(T)} \bullet \left(1 - N_{retention_frac(T)}\right) \bullet 365$$

Where:

$Nex_{(T)}$ = annual N excretion rates, kg N animal^{-1} yr^{-1}

$N_{intake(T)}$ = the daily N intake per head of animal of species/category *T*, kg N animal^{-1} day^{-1}

$N_{retention_frac(T)}$ = fraction of daily N intake that is retained by animal of species/category *T*, dimensionless

365 = Number of days in a year[6]

EQUATION 10.31A (NEW)
ANNUAL N EXCRETION RATES, OPTION 2 (TIER 2)

$$Nex_{(T)} = \left(N_{intake(T)} - N_{retention(T)}\right) \bullet 365$$

Where:

$Nex_{(T)}$ = annual N excretion rates, kg N animal^{-1} yr^{-1}

$N_{intake(T)}$ = the daily N intake per head of animal of species/category *T*, kg N animal^{-1} day^{-1}

$N_{retention(T)}$ = amount of daily N intake by head of animal of species / category *T*, that is retained by animal of species/category *T*, kg N animal^{-1} day^{-1}

365 = Number of days in a year[6]

nitrogen excretion may be calculated based on the same dietary assumptions used in modelling enteric fermentation emissions (see Section 10.2). The amount of nitrogen excreted by cattle can be estimated as the difference between the total nitrogen taken in by the animal and the total nitrogen retained for growth and milk production. Equations 10.32, 10.32A and 10.33, 10.33A, 10.33B, 10.33C, 10.33D and 10.33E can be used to calculate the variables for nitrogen intake and nitrogen retained for use in Equations 10.31 and 10.31a. The daily nitrogen intake rate is derived as follows:

[6] Consideration should be taken of periods between production cycles, particularly for animal categories that may have multiple annual growth cycles. For livestock species with a lifetime shorter than one year, the approach suggested by Haenel *et al*. (2018) (see chapters 3.1.2.2.1 to 3.1.2.2.3) and by Rösemann *et al*. (2017) can be considered.

EQUATION 10.32
N INTAKE RATES FOR CATTLE, SHEEP AND GOATS

$$N_{\text{int}ake(T)} = \frac{GE}{18.45} \bullet \left(\frac{\frac{CP\%}{100}}{6.25} \right)$$

EQUATION 10.32A (NEW)
N INTAKE RATES FOR SWINE AND POULTRY

$$N_{\text{int}ake(T,i)} = DMI_i \bullet \left(\frac{\frac{CP\%_i}{100}}{6.25} \right)$$

Where:

$N_{\text{int}ake(T,i)}$ =daily N consumed per animal of category *T*, kg N animal^{-1} day^{-1}, per growth stage^{-1} "*i*" when applicable

GE = gross energy intake of the animal, in enteric model, based on digestible energy, milk production, pregnancy, current weight, mature weight, rate of weight gain, and IPCC constants, MJ animal^{-1} day^{-1} (used in conjunction with Tier 2 gross energy calculation for cattle, sheep and goats)

18.45 = conversion factor for dietary GE per kg of dry matter, MJ kg^{-1}. This value is relatively constant across a wide range of forage and grain-based feeds commonly consumed by livestock

DMI_i = dry matter intake per day during a specific growth stage "*i*", (kg DMI animal day^{-1})

$CP\%_i$ = percent crude protein in dry matter for growth stage "*i*". (Table 10A.1, Table 10A.2 and Table 10A.3 present default CP% values for all regions)

6.25 = conversion from kg of dietary protein to kg of dietary N, kg feed protein (kg N)$^{-1}$

As an example, the intake of N for a growing pig between 32 to 60 kg of body weight with a daily intake of 1.67 kg of a diet containing 18 percent CP would be, applying the above equation, equivalent to 0.05 kg N day^{-1}.

The daily value can be converted to a total N input per year or per growth stage by multiplying either by 365 or by the length of the growth period of interest.

TABLE 10.19 (UPDATED)
DEFAULT VALUES FOR NITROGEN EXCRETION RATE (KG N (1000 KG ANIMAL MASS)$^{-1}$ DAY^{-1})

Category of animal	Region																		
	North America	Western Europe	Eastern Europe	Oceania	Latin America			Africa			Middle East			Asia			India subcontinent		
					Mean	High PS[1]	Low PS[1]	Mean	High PS	Low PS	Mean	High PS	Low PS	Mean	High PS	Low PS	Mean	High PS	Low PS
Dairy cattle[3]	0.59	0.54	0.42	0.72	0.39	0.60	0.28	0.44	0.41	0.45	0.50	0.49	0.51	0.44	0.55	0.41	0.65	0.51	0.70
Other cattle[3]	0.40	0.42	0.47	0.46	0.31	0.36	0.29	0.45	0.42	0.44	0.56	0.51	0.59	0.38	0.36	0.39	0.44	0.64	0.41
Buffalo[3]	NA	0.45	0.35	NA	0.41			0.42			0.39			0.44			0.58		
Swine[4]	0.39	0.65	0.63	0.54	0.59	0.55	0.67	0.44	0.33	0.49	0.66	0.67	0.56	0.61	0.54	0.67	0.68	0.63	0.71
Finishing	0.46	0.76	0.77	0.72	0.73	0.69	0.80	0.49	0.39	0.54	0.73	0.75	0.60	0.70	0.63	0.76	0.76	0.74	0.76
Breeding	0.24	0.38	0.36	0.31	0.35	0.32	0.43	0.29	0.21	0.35	0.40	0.41	0.37	0.37	0.32	0.43	0.43	0.37	0.47
Chicken[4]	1.45	0.99	0.96	1.42	1.20	1.13	2.14	1.29	1.16	1.44	1.29	1.27	1.79	1.10	1.00	1.62	1.62	1.48	1.83
Hens >/= 1 yr	1.13	0.87	0.81	1.04	1.17	1.02	2.01	1.20	0.99	1.34	1.11	1.06	1.70	1.00	0.89	1.50	1.65	1.60	1.70
Pullets	0.77	0.58	0.58	0.76	0.95	0.68	2.50	1.29	0.70	1.72	0.85	0.74	2.03	0.83	0.60	1.91	1.63	0.98	2.20
Broilers	1.59	1.14	1.12	1.59	1.23	1.21	2.39	1.40	1.34	1.58	1.43	1.42	1.95	1.35	1.31	1.84	1.58	1.47	2.11
Turkeys[12]	0.74																		
Ducks[12]	0.83																		
Sheep[4]	0.35	0.36	0.36	0.43	0.32														
Goats[5]	0.46	0.46	0.44	0.42	0.34														
Horses and mules and asses[12]	0.30	0.26	0.30	0.30	0.46														

TABLE 10.19 (UPDATED) (CONTINUED)
DEFAULT VALUES FOR NITROGEN EXCRETION RATE (KG N (1000 KG ANIMAL MASS)$^{-1}$ DAY^{-1})

	Region																	
	North America	Western Europe	Eastern Europe	Oceania	Latin America			Africa			Middle East			Asia			India sub-continent		
					Mean	High PS[1]	Low PS[1]	Mean	High PS	Low PS	Mean	High PS	Low PS	Mean	High PS	Low PS	Mean	High PS	Low PS
Camels[12]	0.38				0.46														
Ostrich[7,11]	0.36																		
Deer[8,11]	0.67																		
Reindeer[9,11]	0.23																		
Mink and Polecat (kg N head^{-1} yr^{-1})[6,11]	4.59																		
Rabbits (kg N head^{-1} yr^{-1})[10,11]	8.10																		
Fox and Racoon (kg N head^{-1} yr^{-1})[6,11]	12.09																		

[1] High PS and Low PS refer to high- and low productivity systems required for Tier 1a methodology.

[2] NA refers to situations in which these animal categories do not occur in these regions.

[3] Values are derived from diets used in the calculation of enteric fermentation Tier 1 emission factors (Annex 10A.1).

[4] Values are taken from FAO GLEAM databases (FAO 2017).

[5] Calculations are detailed in Annex 10B.3.

[6] Data of Hutchings *et al*. (2001) (as cited in *2006 IPCC Guidelines*).

[7] Nex rate for ostrich in kg N (1000 kg animal mass)$^{-1}$ day^{-1} was calculated taking into account an average value on weight of bird (120 kg) and a rate of nitrogen excretion per head per year (15.6 kgN/head/year). Sources: Velthof (2014); Reis & Oliveira (2008); du Toit *et al*. (2013).

[8] Nex rate for deer in kg N (1000 kg animal mass)$^{-1}$ day^{-1} was calculated taking into account an average value on weight of animal (120 kg) and a rate of nitrogen excretion per head per year (29.32 kgN/head/year). Sources: Danish NIR (Nielsen *et al*. 2018), New Zealand's NIR (Ministry for the Environment 2018).

[9] Nex rate for reindeer in kg N (1000 kg animal mass)$^{-1}$ day^{-1} was calculated taking into account an average value on weight of animal (120 kg) and a rate of nitrogen excretion per head per year (5.75 kgN/head/year).Sources: Danish NIR (Nielsen *et al*. 2018); New Zealand's NIR (Ministry for the Environment 2018).

[10] Nex rate per average doe, including young reproduction stock and males. Sources: Maertens *et al*. (2005); Xiccato *et al*. (2005); Gasco *et al*. (2014); Velthof *et al*. (2015).

[11] The IPCC expert group reviewed the national inventory submissions under the UNFCCC and concluded that common distribution of systems used to manage manure as follows: 80 percent of ostrich'manure is deposited in pasture and in range and 20 percent is managed in solid based systems; deer and reindeer manure deposited mainly in pasture and in range, manure of rabbits and fur-bearing animals is managed mostly in a solid based systems. Hence, countries may apply the same allocation of MMS in the calculation of N_2O emissions from manure stored in manure management systems. However, countries are encouraged to develop a country-specific dataset on MMS used to manage manure generated by these categories of animals.

[12] The values are taken from Table 10.19 of Chapter 10 of Volume 4 of the *2006 IPCC Guidelines*.

TABLE 10.20 (UPDATED)
DEFAULT VALUES FOR THE FRACTION OF NITROGEN IN FEED INTAKE OF LIVESTOCK THAT IS RETAINED BY THE DIFFERENT LIVESTOCK SPECIES/CATEGORIES (FRACTION N-INTAKE RETAINED BY THE ANIMAL) [1]

Livestock category	$N_{retention_frac(T)}$, (kg N retained/animal/day) (kg N intake/animal/day)$^{-1}$
Cattle and Buffalo	See values in Annex 10A.1
Sheep	0.10
Goats	0.10
Camels	0.07
Swine	0.30
Horses	0.07
Poultry	0.30

This N retention values apply to non-dairy sheep and goats. For dairy sheep and goats country-specific values are recommended. Values are applied in Equation 10.31, Option 1 for the calculation of annual N excretion.

The uncertainty in these estimates is ±50%.

Source: *2006 IPCC Guidelines*, Table 10.21.

Tier 2 method for estimating nitrogen excretion for cattle

The total nitrogen retained for cattle is derived as follows:

EQUATION 10.33
N RETENTION RATES FOR CATTLE

$$N_{retention(T)} = \left[\frac{Milk \bullet \left(\frac{Milk\ PR\%}{100}\right)}{6.38}\right] + \left[\frac{WG \bullet \left[268 - \left(\frac{7.03 \bullet NE_g}{WG}\right)\right]}{6.25}\right]$$

Where:

$N_{retention(T)}$ = daily N retained per animal of category *T*, kg N animal^{-1} day^{-1}

MILK = milk production, kg animal^{-1} day^{-1} (applicable to dairy cows only)

Milk PR% = percent of protein in milk, calculated as [1.9 + 0.4 ● %Fat], where %Fat is an input, assumed to be 4% (applicable to dairy cows only), or the values reported in Table 10A.1, Table 10A.2 and Table 10A.3 can be used

6.38 = conversion from milk protein to milk N, kg Protein (kg N)$^{-1}$

WG = weight gain, input for each livestock category, kg day^{-1}

268 and 7.03 = constants from Equation 3-8 in NRC (1996), g Protein kg^{-1} animal^{-1} and g Protein MJ^{-1} animal^{-1} respectively

1000 = conversion from g protein to kg protein

NE_g = net energy for growth, calculated in livestock characterisation, based on current weight, mature weight, rate of weight gain, and IPCC constants, MJ day^{-1}

6.25 = conversion from kg dietary protein to kg dietary N, kg Protein (kg N)$^{-1}$

Nitrogen excretion is calculated using Equation 10.31a, Option 2.

Tier 2 method for estimating nitrogen excretion for pigs

The nitrogen excretion rate depends on the balance between the animal's feed N intake and its N retention in tissue. Different categories of animals (e.g. adult females, adult males and growing pigs) can have quite different N

requirements depending on, for example, their growth rates, lactation rates and yields (MacLeod *et al*. 2013). Likewise, the N retention rates can be different among different animal categories. Thus, when following a Tier 2 approach for estimating nitrogen excretion for pigs, it is a *good practice* to include N excretion estimates for at least the pig categories listed in Table 10.1.

For breeding pigs, if inventory compilers have detailed information about feed, breeding statistics piglets born and weaned and proportions of sows entering the breeding herd (optional), N retention may be calculated as follows:

EQUATION 10.33A (NEW)
N RETENTION RATES FOR BREEDING SOWS

$$N_{retention} = N_{gain} + N_{weaned\ piglets}$$

Where:

$N_{retention}$ = amount of N retained by the animal (in kg N animal^{-1} year^{-1})

N_{gain} = amount of N retained in the sow (in kg N animal^{-1} year^{-1}), calculated as (0.025 *FR * Skg)

Where:

0.025 = fraction of N retained in BW, kg N·kg BW gain^{-1}

FR = fertility rate of sows, parturitions·year^{-1}

Skg = is the sum of live weight change of sows from parturition to parturition, kg·head^{-1} and can be calculated from the litter birth weight and number (LITSIZE * Ckg/0.806

Where:

LITSIZE = litter size, heads

Ckg = live weight of piglets at birth, kg·head^{-1}

0.806 = constant to correct for the higher kg N per kg BW gain^{-1} in piglets, fraction)

$N_{weaned\ piglets}$ = amount of N in piglets weaned calculated as in Equation 10.33b (in kg N animal^{-1} year^{-1})

EQUATION 10.33B (NEW)
N RETENTION RATES FOR PIGLETS

$$N_{weaned\ piglets} = 0.025 \bullet LITSIZE \bullet FR \bullet \frac{(Wkg - Ckg)}{0.98}$$

Where:

0.025 = fraction of N retained in BW, kg N·kg BW gain^{-1}

LITSIZE = litter size, heads

FR = fertility rate of sows, parturitions·year^{-1}

Wkg = live weight of piglet at weaning age, kg·head^{-1}

Ckg = live weight of piglets at birth, kg·head^{-1} and

0.98 = protein digestibility as fraction (FAO, 2017)

TABLE 10.20A (NEW)
CALCULATION OF N RETENTION IN BREEDING SWINE FROM DIFFERENT PRODUCTION SYSTEMS, AN EXAMPLE

System	Ckg	Wkg	FR	LITSIZE	Sows Ngain[a]	Piglets Ngain
	kg	kg		heads	kg N animal^{-1} year^{-1}	kg N animal^{-1} year^{-1}
Low Productivity	0.8	6.5	1.7	9.1	0.92	2.25
High Productivity	1.2	7.0	2.1	9.2	1.38	2.85

[a] For this example, a live weight change of young sows from parturition to parturition of 12.5 kg was assumed.

The value of Skg is derived from national statistics on the average litter size and birth weight of piglets, factors that vary based on national production systems. Further, gilts will typically be mated at 125 – 140 kg of body weight, and continue to grow over several reproductive cycles to a mature weight of approximately 200 kg of body weight. The N excretion by breeding sows (Equation 10.33B) should also take into account that the sow will gain between 10 to 15 kg of body weight during the first four or five reproductive cycles (Chiba 2009). Inventory compilers are advised to: (a) use data that best describe their country production practices and/or genetic stocks employed for estimates of litter size and birth weight; (b) estimate the proportion of the breeding animals that are not at mature weight and consider the growth of these animals in their estimate of Skg. The weight of the placenta and other products of conception are not included in Tier 2 calculations as they are discarded at parturition. Countries that are able to track nitrogen in conception products may choose to do so through country specific methods

The daily N retention can be calculated by dividing the result of equation 10.33a by the total number of days in the gestational and weaning periods to provide a daily N retention in kg N day^{-1}. Nitrogen excretion is calculated using Equation 10.31a, Option 2.

For estimating N retention by growing animals, the following approach may be followed:

EQUATION 10.33C (NEW)
N RETENTION RATES FOR GROWING PIGS

$$N_{retention} = \sum_{i} (BW_{Final\,(i)} - BW_{Initial\,(i)}) \bullet N_{gain\,(i)}$$

Where:

$N_{retention}$ = amount of N retained in animal (in kg N animal^{-1} year^{-1})

$BW_{Final_{(i)}}$ = Live weight of the animal at the end of the stage (kg) per defined growth stage (*i*)

$BW_{Initial_{(i)}}$ = Live weight of the animal at the beginning of the stage (kg) per defined growth stage (*i*)

$N_{gain_{(i)}}$ = fraction of N retained at a given BW per defined growth stage *(i)*, the fraction should be calculated for the final BW of the phase. For example a finishing hog that weighed 109 kg at slaughter would use a value of 0.021 kg N kg BW gain^{-1}

These should be summed over the different production stages[7]. Daily N retention is calculated by dividing the total N retention by the length of the production period from weaning to slaughter. Nitrogen excretion is calculated using Equation 10.31a, Option 2.

[7] It should be noted that factors other than physiological stage can affect nitrogen retention, including body weight (Pettey *et al*. 2015), sex and genetic line (Wiseman *et al*. 2007).

TABLE 10.20B (NEW)
DEFAULT VALUES FOR N_{GAIN} BY GROWTH STAGE

Phase	N_{gain} (kg N kg BW^{-1})
Nursery (4 to 7 kg)	0.031
Nursery (7 to 20 kg)	0.028
Grower (20 to 40 kg)	0.025
Grower (40 to 80 kg)	0.024
Finisher (80 to 120 kg)	0.021

N_{gain} was calculated for a given BW as N_{gain} = -0.004 ln(BW) + 0.0381. Based on Shields *et al*. (1983) and further adjusted based on data from Poulsen & Kristensen (1998) and FAO (2017).

The approach used for estimating N excretion from growing pigs can be followed for gilts and growing boars that will be used for breeding purposes and for nursery, growing and finishing market pigs.

Tier 2 method for estimating nitrogen excretion for poultry

In broiler production, chicks generally cannot digest and absorb all nutrients, especially in the case of nutritional imbalance or high concentration of nutrients in feed. Thus, the surplus nutrients are broken down, and carbon is used to produce energy whereas nitrogen is excreted in faeces (Boonsinchai *et al*. 2016). Different categories of animals (for meat or eggs) can have quite different N requirements and different N retention rates (Poulsen & Kristensen 1998; Williams 2013; Velthof *et al*. 2015). Thus, when following a Tier 2 approach for estimating nitrogen excretion for poultry, it is a *good practice* to include N excretion estimations for at least the poultry categories listed in Table 10.1.

In estimating nitrogen excretion, the nitrogen balance approach is also very useful, for which information on feed intake, feed N content and animal productivity (egg production, weight gain, lengths of production stages) is required.

A suitable approach to estimate annual nitrogen retention by layer type hens is as follows (Poulsen & Kristensen 1998):

EQUATION 10.33D (NEW)
N RETENTION RATES FOR LAYER TYPE HENS

$$N_{retention,c} = \left[N_{LW} \bullet WG_c + \left(\frac{N_{EGG} \bullet EGG}{1000} \right) \right]$$

Where:

$N_{retention,c}$ = daily nitrogen retention by animal in cohort c, kg N·head^{-1}day^{-1}

N_{LW} = average content of nitrogen in live weight, kg N·kg head^{-1}. Default value of 0.028 is used

WG_c = average daily weight gain for cohort c, kg·head^{-1}·day^{-1}

N_{EGG} = average content of nitrogen in eggs, kg N·kg egg^{-1}. Default value of 0.0185 is used

EGG = egg mass production, g egg·head^{-1} day^{-1}

A suitable approach to estimate annual nitrogen retention by pullets and broilers is as follows (Poulsen & Kristensen 1998):

EQUATION 10.33E (NEW)
DAILY N RETENTION RATES FOR PULLETS OR BROILERS

$$N_{retention} = \frac{(BW_{Final} - BW_{Initial}) \bullet N_{gain}}{production_period}$$

Where:

$N_{retention}$ = amount of N retained in animal (kg N head^{-1}) day^{-1}

BW_{Final} = Live weight of the animal at the end of the stage (kg)

$BW_{Initial}$ = Live weight of the animal at the beginning of the stage (kg)

N_{gain} = the fraction of N (kg) retained per kg BW gain

$production_period$ = length of time from chick to slaughter (days)

Default value for N_{gain} = 0.028 based on data from Poulsen & Kristensen (1998) and FAO (2017)

Nitrogen excretion is calculated using Equation 10.31a, Option 2.

Emission factors for direct N_2O emissions from Manure Management

The best estimate will be obtained using country-specific emission factors that have been fully documented in peer reviewed publications. It is *good practice* to use country-specific emission factors that reflect the actual duration of storage and type of treatment of animal manure in each management system that is used. *Good practice* in the derivation of country-specific emission factors involves the measurement of emissions (per unit of manure N) from different management systems, taking into account variability in duration of storage and types of treatment. When defining types of treatment, conditions such as aeration and temperature should be taken into account. If inventory agencies use country-specific emission factors, they are encouraged to provide justification for these values via peer-reviewed documentation.

If appropriate country-specific emission factors are unavailable, inventory agencies are encouraged to use the default emission factors presented in Table 10.21, Default emission factors for direct N_2O emissions from Manure Management. This table contains default emission factors by manure management system. Note that emissions from liquid/slurry systems without a natural crust cover and anaerobic lagoons are considered negligible based on the absence of oxidized forms of nitrogen entering these systems combined with the low potential for nitrification and denitrification to occur in the system.

Emission factors for indirect N_2O emissions from Manure Management

In order to estimate indirect N_2O emissions from Manure Management, two fractions of nitrogen losses (due to volatilization, $Frac_{GasMS}$, and leaching/runoff, $Frac_{LeachMS}$), and two indirect N_2O emissions factors associated with these losses (EF_4 and EF_5) are needed. Default values for volatilization N losses are presented in the Table 10.22 for single manure systems. Values represent the sum of the loss rates for N in the forms of NH_3 and NO_x, with most of the loss in the form of NH_3. Ranges reflect values that appear in the literature. The values represent conditions without any significant nitrogen control measures in place. Countries are encouraged to develop country-specific values, particularly related to ammonia losses where component emissions may be well characterized as part of larger air quality assessments and where emissions may be affected by nitrogen reduction strategies. For example, detailed methodologies for estimating NH_3 and other nitrogen losses using mass balance/mass flow procedures are described in the EMEP/CORINAIR air pollutant emission inventory guidebook, Chapter 3B (current version: EEA 2016).

The fraction of manure nitrogen that leaches from manure management systems ($Frac_{leachMS}$) is highly uncertain and should be developed as a country-specific value applied in Tier 2 method.

N_2O emissions from multiple Manure Management systems

Consistent with CH_4 manure management, if manure is managed in multiple systems, by default, manure emission factors should be allocated to the dominant storage systems; But a country specific emission factor could be developed considering the emissions originating from all other systems used in storage prior to field applicaton.

A number of combinations are possible and as was the case with methane emissions from manure management, it is beyond the scope of these guidelines to provide guidance for all possibilities but common examples include: i.) manure flushed from a dairy freestall barn to an anaerobic lagoon that first pass through a solids separation unit

where some of the manure nitrogen is removed and managed as a solid; ii.) pit storage that is flushed to a larger holding tank; iii.) solid manure pack that is allowed to accumulate, and periodically transferred to heaps.

In these cases, emissions could be calculated based on Tier 2 factors from the separate manure fractions and weighted based on the duration of storage in the different systems. Emission factors as developed and reported in these guidelines are assumed to be for a full year of N within a given manure management system. The application of a country-specific, staged emission factor would require estimates of sub-annual emissions based on manure residency times in each stage. Further, this type of approach should consider the application of a full mass balance approach and likewise consider N loss at each stage.

Default values for EF_4 (N volatilisation and re-deposition) and EF_5 (N leaching/runoff) are given in Chapter 11, Table 11.3 (Default emission, volatilisation and leaching factors for indirect soil N_2O emissions).

Consistency should be maintained for the treatment of nitrogen flows throughout all agricultural emission calculations, including managed soils as outlined in Section 10.5.4[8].

[8] As discussed in Section 10.5.4, N losses from housing and storage have to be subtracted before the calculation of N_2O emissions (direct and indirect) from agricultural soils.

TABLE 10.21 (UPDATED)
DEFAULT EMISSION FACTORS FOR DIRECT N_2O EMISSIONS FROM MANURE MANAGEMENT[24]

System	Definition		EF_3 [kg N_2O-N (kg nitrogen excreted)$^{-1}$]
Pasture/Range/ Paddock	The manure from pasture and range grazing animals is allowed to lie as is, and is not managed.		Direct and indirect N_2O emissions associated with the manure deposited on agricultural soils and pasture, range, paddock systems are treated in Chapter 11, Section 11.2, N_2O emissions from managed soils.
Daily spread[5]	Manure is routinely removed from a confinement facility and is applied to cropland or pasture within 24 hours of excretion. N_2O emissions during storage and treatment are assumed to be zero. N_2O emissions from land application are covered under the Agricultural Soils category.		0
Solid storage[2,4,6]	The storage of manure, typically for a period of several months, in unconfined piles or stacks. Manure is able to be stacked due to the presence of a sufficient amount of bedding material or loss of moisture by evaporation.		0.010
Solid storage-Covered/compacted[4,7]	Similar to solid storage, but the manure pile is a) covered with a plastic sheet to reduce the surface of manure exposed to air and/or b) compacted to increase the density and reduce the free air space within the material.		0.01
Solid storage-Bulking agent addition[4,8]	Specific materials (bulking agents) are mixed with the manure to provide structural support. This allows the natural aeration of the pile, thus enhancing decomposition. (e.g. sawdust, straw, coffee husks, maize stover).		0.005
Solid storage – Additives[4,8]	The addition of specific substances to the pile in order to reduce gaseous emissions. Addition of certain compounds such as attapulgite, dicyandiamide or mature compost have shown to reduce N_2O emissions; while phosphogypsum reduces CH_4 emissions.		0.005
Dry lot[9]	A paved or unpaved open confinement area without any significant vegetative cover where accumulating manure may be removed periodically. Dry lots are most typically found in dry climates but also are used in humid climates.		0.02
Liquid/Slurry	Manure is stored as excreted or with some minimal addition of water to facilitate handling and is stored in either tanks or earthen ponds.	With [9] natural crust cover	0.005
		Without [10] natural crust cover	0
		Cover[11]	0.005
Uncovered[12] anaerobic lagoon	Anaerobic lagoons are designed and operated to combine waste stabilization and storage. Lagoon supernatant is usually used to remove manure from the associated confinement facilities to the lagoon. Anaerobic lagoons are designed with varying lengths of storage (up to a year or greater), depending on the climate region, the volatile solids loading rate, and other operational factors. The water from the lagoon may be recycled as flush water or used to irrigate and fertilise fields.		0
Pit storage[13] below animal confinements	Collection and storage of manure usually with little or no added water typically below a slatted floor in an enclosed animal confinement facility.		0.002
Anaerobic[14] digester	Anaerobic digesters are designed and operated for waste stabilization by the microbial reduction of complex organic compounds to CH_4 and CO_2, which is captured and flared or used as a fuel.		0.0006

TABLE 10.21 (UPDATED) (CONTINUED)
DEFAULT EMISSION FACTORS FOR DIRECT N_2O EMISSIONS FROM MANURE MANAGEMENT[24]

System	Definition		EF_3 [kg N_2O-N (kg nitrogen excreted)$^{-1}$]
Burned for fuel or as waste	The dung is excreted on fields. The sun dried dung cakes are burned for fuel.		The emissions associated with the burning of the dung are to be reported under the IPCC category 'Fuel Combustion' if the dung is used as fuel and under the IPCC category 'Waste Incineration' if the dung is burned without energy recovery.
	Urine N deposited on pasture and paddock.		Direct and indirect N_2O emissions associated with the urine deposited on agricultural soils and pasture, range, paddock systems are treated in Chapter 11, Section 11.2, N_2O emissions from managed soils.
Cattle and swine deep bedding	As manure accumulates, bedding is continually added to absorb moisture over a production cycle and possibly for as long as 6 to 12 months. This manure management system also is known as a bedded pack manure management system and may be combined with a dry lot or pasture.	No mixing[15]	0.01
		Active mixing [16]	0.07
Composting - In-Vessel[3,17]	Composting, typically in an enclosed channel, with forced aeration and continuous mixing.		0.006
Composting - Static Pile[3] (Forced aeration)[4,18]	Composting in piles with forced aeration but no mixing.		0.010
Composting - Intensive Windrow[3,19] (Frequent turning)	Composting in windrows with regular turning for mixing and aeration.		0.005
Composting- Passive windrow (infrequent turning) [4, 20]	Composting in windrows with infrequent turning for mixing and aeration.		0.005
Poultry manure with litter[21]	Similar to deep bedding systems. Typically used for all poultry breeder flocks and for the production of meat type chickens (broilers) and other fowl.		0.001
Poultry manure without litter[21]	May be similar to open pits in enclosed animal confinement facilities or may be designed and operated to dry the manure as it accumulates. The latter is known as a high-rise manure management system and is a form of passive windrow composting when designed and operated properly.		0.001

TABLE 10.21 (UPDATED) (CONTINUED)
DEFAULT EMISSION FACTORS FOR DIRECT N_2O EMISSIONS FROM MANURE MANAGEMENT[24]

System	Definition		EF_3 [kg N_2O-N (kg nitrogen excreted)$^{-1}$]
Aerobic treatment	The biological oxidation of manure collected as a liquid with either forced or natural aeration. Natural aeration is limited to aerobic and facultative ponds and wetland systems and is due primarily to photosynthesis. Hence, these systems typically become anoxic during periods without sunlight.	Natural aeration systems[22]	0.01
		Forced aeration systems[23]	0.005

[1] Also see AFRC (1995) and Dustan (2002), which compiled information from some of the original references cited.

[2] Quantitative data should be used to distinguish whether the system is judged to be a solid storage or liquid/slurry. The borderline between dry and liquid can be drawn at 15% dry matter content.

[3] Composting is the biological oxidation of a solid waste including manure usually with bedding or another organic carbon source typically at thermophilic temperatures produced by microbial heat production.

[4] Sources and assumptions to calculate N_2O EF for Solid storage systems with/without treatments and composting (static pile and passive windrows) are detailed in Annex 10B.7.

[5] *2006 IPCC Guidelines*, Table 10.21.

[6] Expert judgement based on Pardo *et al*. (2015). Median of N_2O emissions from farm-scale collected studies.

[7] Expert judgement based on Pardo *et al*. (2015). Emissions in the same range than solid storage.

[8] Expert judgement based on Pardo *et al*. (2015). Estimated reduction of 50% N_2O emissions due to bulking agent addition.

[9] Judgement of IPCC Expert Group in combination with Kulling *et al*. (2003).

[10] Judgement of IPCC Expert Group in combination with the following studies: Harper *et al*. (2000), Lague *et al*. (2004), Monteny *et al*. (2001), and Wagner-Riddle & Marinier (2003). Emissions are believed negligible based on the absence of oxidized forms of nitrogen entering systems in combination with low potential for nitrification and denitrification in the system.

[11] A detailed literature review carried out during the *2019 Refinement* revealed only few new datasets on the measurement of N_2O emissions from manure stores. These datasets emcompass a large range of N_2O emissions from a 50% reduction to a 100 % increase in N_2O emissions when slurry stores are covered. The *2019 Refinement* therefore suggest to use the emission factor of natural crust cover.

[12] Judgement of IPCC Expert Group in combination with the following studies: Harper *et al*. (2000), Lague *et al*. (2004), Monteny *et al*. (2001), and Wagner-Riddle & Marinier (2003). Emissions are believed negligible based on the absence of oxidized forms of nitrogen entering systems in combination with low potential for nitrification and denitrification in the system.

[13] Judgement of IPCC Expert Group in combination with the following studies: Amon *et al*. (2001), Kulling *et al*. (2003), and Sneath *et al*. (1997).

[14] The emission mainly from storage of digestate.

[15] Judgement of IPCC Expert Group in combination with the following studies: Wang *et al*. (2016), Rodhe *et al*. (2015); Wang *et al*. (2014b); Wang *et al*. (2014a); Li (2016); Amon *et al*. (2006); Moitzi *et al*. (2007); Clemens *et al*. (2006). Average value based on Moller *et al*. (2000), Sommer & Møller (2000), Amon *et al*. (1998a); Amon *et al*. (1998b), and Nicks *et al*. (2003).

[16] Average value based on Nicks *et al*. (2003) and Moller *et al*. (2000). Some literature cites higher values to 20% for well maintained, active mixing, but those systems included treatment for ammonia which is not typical.

[17] Judgement of IPCC Expert Group. Expected to be similar to static piles.

[18] Expert judgement based on Pardo *et al*. (2015). Emissions in the same range than solid storage.

[19] Assuming similar range to passive windrow.

[20] Expert judgement based on Pardo *et al*. (2015). Median of N_2O emissions from farm-scale collected studies and estimated reduction of 50% due to bulking agent addition.

[21] Judgement of IPCC Expert Group based on the high loss of ammonia from these systems, which limits the availability of nitrogen for nitrification/denitrification.

[22] Judgement of IPCC Expert Group. Nitrification-denitrification is used widely for the removal of nitrogen in the biological treatment of municipal and industrial wastewaters with negligible N_2O emissions. Limited oxidation may increase emissions compared to forced aeration systems.

[23] Judgement of IPCC Expert Group. Nitrification-denitrification is used widely for the removal of nitrogen in the biological treatment of municipal and industrial wastewaters with negligible N_2O emissions.

[24] Uncertainties for emission factors are defined as varying by a factor of 2 (±100%).

10.5.3 Choice of activity data

No refinement.

10.5.4 Coordination with reporting for N_2O emissions from managed soils

Following storage or treatment in any system of manure management, nearly all the manure will be applied to land. The emissions that subsequently arise from the application of the manure to soil are to be reported under the category *N_2O emissions from managed soils*. The methods for estimating these emissions are discussed in Chapter 11, Section 11.2. In estimating N_2O emissions from managed soils, the amount of animal manure nitrogen that is directly applied to soils, or available for use in feed, fuel, or construction purposes, are considered.

A significant proportion of the total nitrogen excreted by animals in managed systems (i.e., all livestock except those in pasture and grazing conditions) is lost prior to final application to managed soils or use as feed, fuel, or for construction purposes. In order to estimate the amount of animal manure nitrogen that is directly applied to soils, or available for use in feed, fuel, or construction purposes (i.e., the value which is used in Chapter 11, Equation 11.1 or 11.2), it is necessary to reduce the total amount of nitrogen excreted by animals in managed systems by the losses of N through volatilisation of reactive nitrogen gases (i.e., NH_3 and NO_x) or through leaching and runoff (both leading to indirect emissions of N_2O), direct conversion to N_2O, or losses as inert molecular nitrogen (N_2).

nitrogen in manure is present both as organic nitrogen (Norg) and mineral nitrogen, of which the majority consists of 'Total Ammoniacal nitrogen' (TAN). The sum of Norg and TAN gives the total nitrogen available (Ntot). Volatilization of NH_3 and other forms of gaseous N arise from the mineral fraction of nitrogen in manure, TAN. Organic nitrogen in manure needs first to be converted to TAN before NH_3 volatilization can happen. The EMEP/EEA air pollutant emission inventory Guidebook 2016 (EEA 2016, Chapter 3B) therefore distinguishes the flow of TAN and Norg and the transitions between the two forms in agricultural systems. The values for the volatilisation fraction $Frac_{GASMS}$ listed in Table 10.22 attempt to account for typical TAN contents in manure for the MMS considered. However, different excretion ratios of TAN vs. total N as a consequence of changes in livestock diets are not reflected. Also, information on the TAN content in manure available for application, N_{MMS_Avb}, is not kept if using Equation 10.34. Farming practices that reduce the escape of NH_3 from MMS but not the amount of TAN available are likely to lead to higher NH_3 volatilization rates once the manure is applied to soils or used for feed, fuel, or for construction purposes.

Where organic forms of bedding material (straw, sawdust, chippings, etc.) are used, the additional nitrogen from the bedding material should also be considered as part of the managed manure N applied to soils. The same applies to additional N input from co-digestates during anaerobic digestion. Bedding is typically collected with the remaining manure and applied to soils. It should be noted, however, that since mineralization of nitrogen compounds in beddings occurs more slowly compared to manure and the concentration of ammonia fraction in organic beddings is negligible, both volatilization and leaching losses during storage of bedding are assumed to be zero. If bedding material comes from crop residues, the amount of nitrogen needs to be considered when calculating N_2O emissions from crop residues from managed soils by accounting for this quantity in $Frac_{Remove(T)}$ in Equation 11.6 of Chapter 11. Further codigestates in the production of biogas may include food waste as well as purpose grown crops. Differences in N loss that might occur with crop residue being digested or being returned directly to the fields should be considered in this case.

The estimate of managed manure nitrogen available for application to managed soils, or available for use in feed, fuel, or construction purposes is based on the following equation:

EQUATION 10.34 (UPDATED)
MANAGED MANURE N AVAILABLE FOR APPLICATION TO MANAGED SOILS, FEED, FUEL OR CONSTRUCTION USES

$$N_{MMS_{Avb}} = \sum_{S}\left\{\sum_{(T)}\left[\begin{array}{l}\left[\left(N_{(T)} \bullet Nex_{(T)} \bullet AWMS_{(T,S)} + N_{cdg}\right) \bullet \left(1 - Frac_{LossMS_{(T,S)}}\right)\right] + \\ + \left[N_{(T)} \bullet AWMS_{(T,S)} \bullet N_{beddingMS_{(T,S)}}\right]\end{array}\right]\right\}$$

Where:

$N_{MMS_{Avb}}$ = amount of managed manure nitrogen available for application to managed soils or for feed, fuel, or construction purposes, kg N yr^{-1}

$N_{(T)}$ = number of head of livestock species/category *T* in the country

$Nex_{(T)}$ = annual average N excretion per animal of species/category *T* in the country, kg N $animal^{-1}$ yr^{-1}

$AWMS_{(T,S)}$ = fraction of total annual nitrogen excretion for each livestock species/category *T* that is managed in manure management system *S* in the country, dimensionless

$Frac_{LossMS_{(T,S)}}$ = total fraction of managed manure nitrogen for livestock category *T* that is lost in the manure management system *S* in the country, dimensionless. $Frac_{LossMS}$ is calculated according to Equation 10.34a

$N_{beddingMS_{(T,S)}}$ = amount of nitrogen from bedding (to be applied for solid storage and deep bedding MMS if known organic bedding usage), kg N $animal^{-1}$ yr^{-1}

N_{cdg} = amount of nitrogen from co-digestates added to biogas plants such as food wastes or purpose grown crops, kg N yr^{-1}

S = manure management system

T = species/category of livestock

EQUATION 10.34A (NEW)
FRACTION OF MANAGED MANURE N LOST PRIOR TO APPLICATION TO MANAGED SOILS FOR THE PRODUCTION OF FEED, FUEL OR FOR CONSTRUCTION USES

$$FRAC_{LOSS_{MS_{(T,S)}}} = FRAC_{GAS_{MS_{(T,S)}}} + FRAC_{LEACHS_{MS_{(T,S)}}} + FRAC_{N_2MS_{(S)}} + EF_{3_{(S)}}$$

Where:

$FRAC_{LOSS_{MS_{(T,S)}}}$ = total fraction of managed manure nitrogen for livestock category *T* that is lost in the manure management system *S*

$FRAC_{GAS_{MS_{(T,S)}}}$ = fraction of managed manure nitrogen for livestock category *T* that is lost by volatilisation in the manure management system *S* as NH_3 or NO_X (see Table 10.22)

$FRAC_{LEACHS_{MS_{(T,S)}}}$ = fraction of managed manure nitrogen for livestock category *T* that is lost in the manure management system *S* by leaching or run-off (see Table 10.22)

$FRAC_{N_2MS_{(S)}}$ = fraction of managed manure nitrogen that is lost in the manure management system *S* as N_2 (see Equation 10.34b)

$EF_{3_{(S)}}$ = emission factor for direct N_2O emissions from manure management system *S*; in this case considered dimensionless (see Table 10.21)

The amount of managed nitrogen that is lost by denitrification to N_2 can be obtained as a ratio of N_2:N_2O emissions. Webb & Misselbrook (2004) reviewed available data and concluded that as first approximation, emissions of N_2 might be 3-times those of N_2O. $Frac_{N2MS}$ can thus be calculated according to Equation 10.34B.

EQUATION 10.34B (NEW)
ESTIMATION OF $FRAC_{N2MS}$

$$Frac_{N_2MS_{(S)}} = R_{N_2(N_2O)} \bullet EF_{3(S)}$$

Where:

$FRAC_{N_2MS_{(S)}}$ = fraction of managed manure nitrogen for livestock category *T* that is lost as N_2 in the manure management system *S*,

$EF_{3_{(S)}}$ = emission factor for direct N_2O emissions from manure management system *S* in the country, kg N_2O-N (kg N)$^{-1}$ in manure management system *S*

$R_{N_2(N_2O)}$ = Ratio of N_2 : N_2O emissions. The default value of $R_{N2(N2O)}$ is 3 kg N_2-N (kg N_2O-N)$^{-1}$ (see Table 10.23)

Bedding materials vary greatly and inventory compilers should develop values for $N_{beddingMS}$ based on the characteristics of bedding material used in their livestock industries. Limited data from scientific literature indicates the amount of nitrogen contained in organic bedding material applied for dairy cows and heifers is usually around 7 kg N animal^{-1} yr^{-1}, for other cattle is 4 kg N animal^{-1} yr^{-1}, for market and breeding swine is around 0.8 and 5.5 kg N animal^{-1} yr^{-1}, respectively. For deep bedding systems, the amount of N in litter is approximately double these amounts (Webb 2001; Döhler *et al*. 2002).

As regards $N_{beddingMS}$ a cross check with the categories "3.C.4 - Direct N_2O emissions from managed soils" (F_{CR} - volume 11, chapter 11, section 11.2.1.3), "3.C.1 - Biomass burning" (volume 4, chapter 5, section 5.2.4 Non-CO_2 greenhouse gas emissions from biomass burning) and "4.C.2 - Open burning of waste" (volume 5, chapter 5, section 5.3.2 Amount of waste open-burned) relative to the amount of agricultural residues that is removed for other purposes (i.e. bedding) other than the amount of agricultural residues returned to soils or burnt should be done. This is important to eliminate the possibility of double counting.

nitrogen content of co-digestates should be consistent in quantity and definition with the co-digests defined information in guidance on the use of co-digestates in “Energy” found in Volume 2, Chapter 2, Section 2.3.3.4 and “Waste”, Volume 5, Chapters 2 and 3, Sections 2.3.2 and 3.2.

Table 10.22 presents default values for nitrogen loss due to volatilisation of NH_3 and NO_x and N leaching and run-off of nitrogen from manure management.

Table 10.23 presents default values for total losses of N_2 from manure management systems relative to emissions of N_2O. This ratio is used in combination with Equation 10.34b to calculate default N_2 emission factors. These default values include losses that occur from the point of excretion, including animal housing losses, manure storage losses, and losses from leaching and runoff at the manure storage system where applicable.

Countries may wish to develop an alternative approach for better consideration of national circumstances and to reduce the uncertainty of estimates as much as possible. This approach would entail more detailed characterisation of the flow of nitrogen through the components of the animal housing and manure management systems used in the country, accounting for any mitigation activity (e.g., the use of covers over slurry tanks), and consideration of local practices, such as type of bedding material used. For Tier 2 or Tier 3 approaches it is *good practice* to account for the TAN fraction in total manure N along the different stages of manure management. Additional details are available in the EMEP/EEA air pollutant emission inventory Guidebook 2016 (EEA 2016, Chapter 3B and 3.D and Annex A1.4).

TABLE 10.22 (UPDATED)
DEFAULT VALUES FOR NITROGEN LOSS FRACTIONS DUE TO VOLATILISATION OF NH_3 AND NO_X AND LEACHING OF NITROGEN FROM MANURE MANAGEMENT

System	Applicable System Variation	Swine		Dairy Cow		Poultry		Other Cattle		Other animals	
		[1]$Frac_{Gas_MS}$	[2,5]$Frac_{leach_MS}$	$Frac_{Gas_MS}$	[2,5]$Frac_{leach_MS}$	$Frac_{Gas_MS}$	[2,5]$Frac_{leach_MS}$	$Frac_{Gas_MS}$	[2,5]$Frac_{leach_MS}$	$Frac_{Gas_MS}$	[2,5]$Frac_{leach_MS}$
Uncovered anaerobic lagoon		0.40 (0.25 – 0.75)	0	0.35 (0.20 – 0.80)	0	0.40 (0.25 – 0.75)	0	0.35 (0.20 – 0.80)	0	0.35 (0.20 – 0.80)	0
Liquid/Slurry	With natural crust cover	0.30 (0.09 – 0.36)	0	0.30 (0.09 – 0.36)	0	no data	0	0.30 (0.09 – 0.36)	0	0.09	0
	Without natural crust cover	0.48 (0.15 – 0.60)	0	0.48 (0.15 – 0.60)	0	0.40 (0.25 – 0.75)	0	0.48 (0.15 – 0.60	0	0.15	0
	With cover	0.10 (0.03 – 0.12)	0	0.10 (0.03 – 0.12)	0	0.08 (0.05-0.15)	0	0.10 (0.03 – 0.12)	0	0.03	0
Pit storage below animal confinements		0.25 (0.15 – 0.30)	0	0.28 (0.10 – 0.40)	0	0.28 (0.10 – 0.40)	0	0.25 (0.15 – 0.30)	0	0.25 (0.15 – 0.30)	0
Daily spread		0.07 (0.05 – 0.60)	0	0.07 (0.05 – 0.60)	0	0.07 (0.05 – 0.60)	0	0.07 (0.05 – 0.60)	0	0.07 (0.05 – 0.60)	0
[7]Solid storage	Covered/compacted	0.22 (0.04 – 0.26)	0	0.14 (0.02 – 0.17)	0	0.20 (0.04 – 0.24)	0	0.22 (0.03 – 0.26)	0	0.05 (0 – 0.07)	0
	Bulking agent addition	0.58 (0.11 – 0.70)	0.02	0.38 (0.06 – 0.46)	0.02	0.54 (0.10 – 0.65)	0.02	0.58 (0.08 – 0.70)	0.02	0.15 (0.06 – 0.18)	0.02
	Additives	0.17 (0.03 – 0.21)	0.02	0.11 (0.01 – 0.14)	0.02	0.16 (0.03 – 0.20)	0.02	0.17 (0.02 – 0.21)	0.02	0.04 (0.01 – 0.05)	0.02
	-	0.45 (0.10 – 0.65)	0.02	0.30 (0.10 – 0.40)	0.02	0.40 (0.12 – 0.60)	0.02	0.45 (0.10 – 0.65)	0.02	0.12 (0.05 – 0.20)	0.02
[4]Dry lot		0.45 (0.10 – 0.65)	0.035 (0 – 0.07)	0.30 (0.20 – 0.50)	0.035 (0 – 0.07)	NA	NA	0.30 (0.20 – 0.50)	0.035 (0 – 0.07)	0.30 (0.20 – 0.50)	0.035
[3]Anaerobic digester		0.05 – 0.50	0	0.05 – 0.50	0	0.05 – 0.50	0	0.05 – 0.50	0	0.05 – 0.50	0

TABLE 10.22 (UPDATED) (CONTINUED)
DEFAULT VALUES FOR NITROGEN LOSS FRACTIONS DUE TO VOLATILISATION OF NH_3 AND NO_X AND LEACHING OF NITROGEN FROM MANURE MANAGEMENT

System	Applicable System Variation	Swine		Dairy Cow		Poultry		Other Cattle		Other animals	
		[1]$Frac_{Gas_MS}$	[2,5]$Frac_{leach_MS}$	$Frac_{Gas_MS}$	[2,5]$Frac_{leach_MS}$	$Frac_{Gas_MS}$	[2,5]$Frac_{leach_MS}$	$Frac_{Gas_MS}$	[2,5]$Frac_{leach_MS}$	$Frac_{Gas_MS}$	[2,5]$Frac_{leach_MS}$
Burned for fuel or as waste		NA									
Cattle and swine deep bedding		0.40 (0.10 – 0.60)	0.035	0.25 (0.10 – 0.30)	0.035	NA		0.25 (0.10 – 0.30)	0.035	NA	
[7]Composting	In-Vessel	0.60 (0.12-0.65)	0	0.45 (0.07-0.54)	0	0.60 (0.12-0.65)	0	0.60 (0.12-0.65)	0	0.18 (0.04-0.21)	0
	Static Pile	0.65 (0.14-0.70)	0.06	0.50 (0.07-0.60)	0.06	0.65 (0.14-0.70)	0.06	0.65 (0.14-0.70)	0.06	0.20 (0.05-0.24)	0.06
	Intensive Windrow	0.65 (0.14-0.70)	0.06	0.50 (0.07-0.60)	0.06	0.65 (0.14-0.70)	0.06	0.65 (0.14-0.70)	0.06	0.20 (0.05-0.24)	0.06
	Passive Windrow	0.60 (0.12-0.65)	0.04	0.45 (0.07-0.54)	0.04	0.60 (0.12-0.65)	0.04	0.60 (0.12-0.65)	0.04	0.18 (0.04-0.21)	0.04
Poultry manure	with litter	NA				0.40 (0.10 – 0.60)	0	NA			
	without litter	NA				0.48 (0.15 – 0.60)	0	NA			
[3]Aerobic treatment	Natural aeration systems	no data[6]	0	no data[6]	0	no data[6]	0	no data[6]	0	no data[6]	0
	Forced aeration systems	0.85 (0.27 – 1)	0	0.85 (0.27 – 1)	0	no data[6]	0	0.85 (0.27 – 1)	0	0.27	0

Source: The values are mainly from *2006 IPCC Guidelines* but other sources and analyses are discussed in Annex B.7. Values in italics are not derived specifically from literature but are taken from the most likely surrogate among the existing values and are for that reason prone to greater uncertainty.

[1] N loss due to volatilisation of NH_3+NO_x fraction of total N excreted.

[2] N loss due to leaching, fraction of total N excreted.

[3] Nitrogen losses from digestate storage strongly depend on the digestate composition and on the storage cover. Digestate with a low dry matter content and no cover can loose up to 0.5 of nitrogen. The lower range of 0.05 losses is valid for digestate with a high dry matter content and a cover. The ranges indicated also apply to co-digestates. It is advised to use the liquid slurry without cover for uncovered digestate.

[4] Uncertainty range is 0 to 0.07. Leaching values are dependant on annual rainfall. Country-specific data should be developed if leaching is observed to be a significant source based on default values and in humid climates should use the upper bound.

[5] Leaching is only included in the case of uncovered manure without confinement of runoff in which N is lost to the environment and therefore lost from the overall reactive N balance.

[6] No data indicates that no literature values were found, nor was there adequate certainty in providing a surrogate value. Country specific values should be used, or a surrogate should be selected from the table and justified based on consideration of factors controlling rates of volatilisation in the management system.

[7] Sources and assumptions to calculate NH_3 volatilization and N leaching/run-off for Solid storage and composting (static pile and passive windrows) systems are detailed in Annex 10B.7.

TABLE 10.23 (NEW)
DEFAULT VALUE FOR MOLECULAR NITROGEN (N_2) LOSS FROM MANURE MANAGEMENT

Factor	Unit	Value	Range
$R_{N_2(N_2O)}$	kg N_2-N (kg N_2O-N)$^{-1}$	3[1]	1-10

[1] Webb & Misselbrook (2004)

10.5.5 Uncertainty assessment

No refinement.

10.5.6 Completeness, Time series, Quality assurance/Quality control and Reporting

A complete inventory should estimate N_2O emissions from all systems of manure management for all livestock species/categories. Additional N input from organic residues and/or energy crops used for co-digestion in biogas plants must also be considered. Countries are encouraged to use manure management system definitions that are consistent with those presented in Table 10.18. Population data should be cross-checked between main reporting mechanisms (such as FAO and national agricultural statistics databases) to ensure that information used in the inventory is complete and consistent. Because of the widespread availability of the FAO database of livestock information, most countries should be able to prepare, at a minimum, Tier 1 estimates for the major livestock categories. For more information regarding the completeness of livestock characterisation, see Section 10.2.

Developing a consistent time series of emission estimates for this source category requires, at a minimum, the collection of an internally consistent time series of livestock population statistics. General guidance on the development of a consistent time series is addressed in Volume 1, Chapter 5 of this report.

In most countries, the other two activity data sets required for this source category (i.e., N excretion rates and manure management system usage data), as well as the manure management emission factors, will be kept constant for the entire time series. However, in some cases, there may be reasons to modify these values over time. For example, farmers may alter livestock feeding practices which could affect nitrogen excretion rates. A particular system of manure management may change due to operational practices or new technologies such that a revised emission factor is warranted. These changes in practices may be due to the implementation of explicit greenhouse gas mitigation measures, or may be due to changing agricultural practices without regard to greenhouse gases. Regardless of the driver of change, the parameters and emission factors used to estimate emissions must reflect the change. The inventory text should thoroughly explain how the change in farm practices or implementation of mitigation measures has affected the time series of activity data or emission factors.

It is *good practice* to implement general quality control checks as outlined in Volume 1, Chapter 6, Quality Assurance/Quality Control and Verification, and expert review of the emission estimates. Additional quality control checks and quality assurance procedures may also be applicable, particularly if higher tier methods are used to determine emissions from this source. The general QA/QC related to data processing, handling, and reporting should be supplemented with procedures discussed below:

Activity data check

The inventory agency should review livestock data collection methods, in particular checking that livestock subspecies data were collected and aggregated correctly with consideration for the duration of production cycles. The data should be cross-checked with previous years to ensure the data are reasonable and consistent with the expected trend. Inventory agencies should document data collection methods, identify potential areas of bias, and evaluate the representativeness of the data.

Manure management system allocation should be reviewed on a regular basis to determine if changes in the livestock industry are being captured. Conversion from one type of management system to another, and technical modifications to system configuration and performance, should be captured in the system modelling for the affected livestock.

National agricultural policy and regulations may have an effect on parameters that are used to calculate manure emissions, and should be reviewed regularly to determine what impact they may have. For example, guidelines to reduce manure runoff into water bodies may cause a change in management practices, and thus affect the N distribution for a particular livestock category. Consistency should be maintained between the inventory and ongoing changes in agricultural practices.

If using country-specific data for $Nex_{(T)}$ and $MS_{(T,S)}$, the inventory agency should compare these values to the IPCC default values. Significant differences, data sources, and methods of data derivation, should be documented.

The nitrogen excretion rates, whether default or country-specific values, should be consistent with feed intake data as determined through animal nutrition analyses.

Review of emission factors

The inventory agency should evaluate how well the implied N_2O emission factors and nitrogen excretion rates compare with alternative national data sources and with data from other countries with similar livestock practices. Significant differences should be investigated.

If using country-specific emission factors, the inventory agency should compare them to the default factors and note differences. The development of country-specific emission factors should be explained and documented, and the results peer-reviewed by independent experts.

Whenever possible, available measurement data, even if they represent only a small sample of systems, should be reviewed relative to assumptions for N_2O emission estimates. Representative measurement data may provide insights into how well current assumptions predict N_2O production from manure management systems in the inventory area, and how certain factors (e.g., feed intake, system configuration, retention time) are affecting emissions. Because of the relatively small amount of measurement data available for these systems worldwide, any new results can improve the understanding of these emissions and possibly their prediction.

External review

The inventory agency should utilise experts in manure management and animal nutrition to conduct expert peer review of the methods and data used. While these experts may not be familiar with greenhouse gas emissions, their knowledge of key input parameters to the emission calculation can aid in the overall verification of the emissions. For example, animal nutritionists can evaluate N production rates to see if they are consistent with feed utilization research for certain livestock species. Practicing farmers can provide insights into actual manure management techniques, such as storage times and mixed-system usage. Wherever possible, these experts should be completely independent of the inventory process in order to allow a true external review.

It is *good practice* to document and archive all information required to produce the national emissions inventory estimates as outlined in Volume 1, Chapter 6, Quality Assurance/Quality Control and Verification. When country-specific emission factors, fractions of N losses, N excretion rates, or manure management system usage data have been used, the derivation of or references for these data should be clearly documented and reported along with the inventory results under the appropriate IPCC source category.

N_2O emissions from different types of manure management systems have to be reported according to categories in Table 10.18. N_2O emissions from all types of manure management systems are to be reported under Manure Management, with two exceptions:

- Emissions from the manure management system for pasture, range, and paddock are to be reported under the IPCC source category N_2O emissions from managed soils because this manure is deposited directly on soils by the livestock.
- Emissions from the manure management system burned for fuel, are to be reported under the IPCC category Fuel Combustion if the dung is used as fuel and under the IPCC category Waste Incineration if the dung is burned without energy recovery. It should be noted, however, if the urine nitrogen is not collected for burning it must be reported under N_2O emissions from pasture, range, and paddock animal if deposited by grazing animals, or under manure management if collected in housed systems.

Consistency of nitrogen flows:

As discussed in Section 10.5.4, most of the manure excreted by livestock is finally applied to land or deposited to land by grazing animals, causing direct and indirect N_2O emissions from managed soils. On its way from the animal to uptake by crops or the release of N_2O, losses of nitrogen happen at all stages and in different forms. With anaerobic digestion, additional N might enter the system through co-digestates (e.g. organic residues, energy crops). The equations given in Chapters 10 and 11 follow a nitrogen balance approach, but are not capturing all effects on direct and indirect N_2O emissions that might occur as a consequence of 'upstream' changes of nitrogen flow, such as manure covers, changes in animal feeding, or nitrogen application technique, some of which are discussed in Section 10.5.4. It is also important to consider total N_2O emissions (see Equation 10.A4-1) when making a key source assessment.

The inventory agency should consult with experts to make sure that any potential effects on N_2O emissions are reflected in the total N_2O emission estimates. Annex 10A.5 lists a set of equations derived from relevant equations in Chapter 10 and 11, allowing the calculation of all direct and indirect N_2O emissions per livestock species/category. These equations can help identifying emissions estimates that might become inaccurate when

national methodologies for upstream flows are used. For example, Equation 10A.13-10A.16 and Equations 11.2-11.4 show that direct N_2O emissions from soils depend on the amount of manure N available for application, not considering any NH_3 losses that might change the amount of N available for N_2O formation. So any application technique that reduces or increases losses of NH_3, modifies the ratio of inorganic to organic N and increases or decreases the availability of N that can be transformed to N_2O must be carefully evaluated (see also Chapter 11, Sections 11.2.1.1 and 11.2.2.1). In this case, methodologies may want to consider, a correction factor that is consistent with the national method for NH_3 emissions and takes into account the forms of nitrogen that are stored, transferred and lost during these processes.

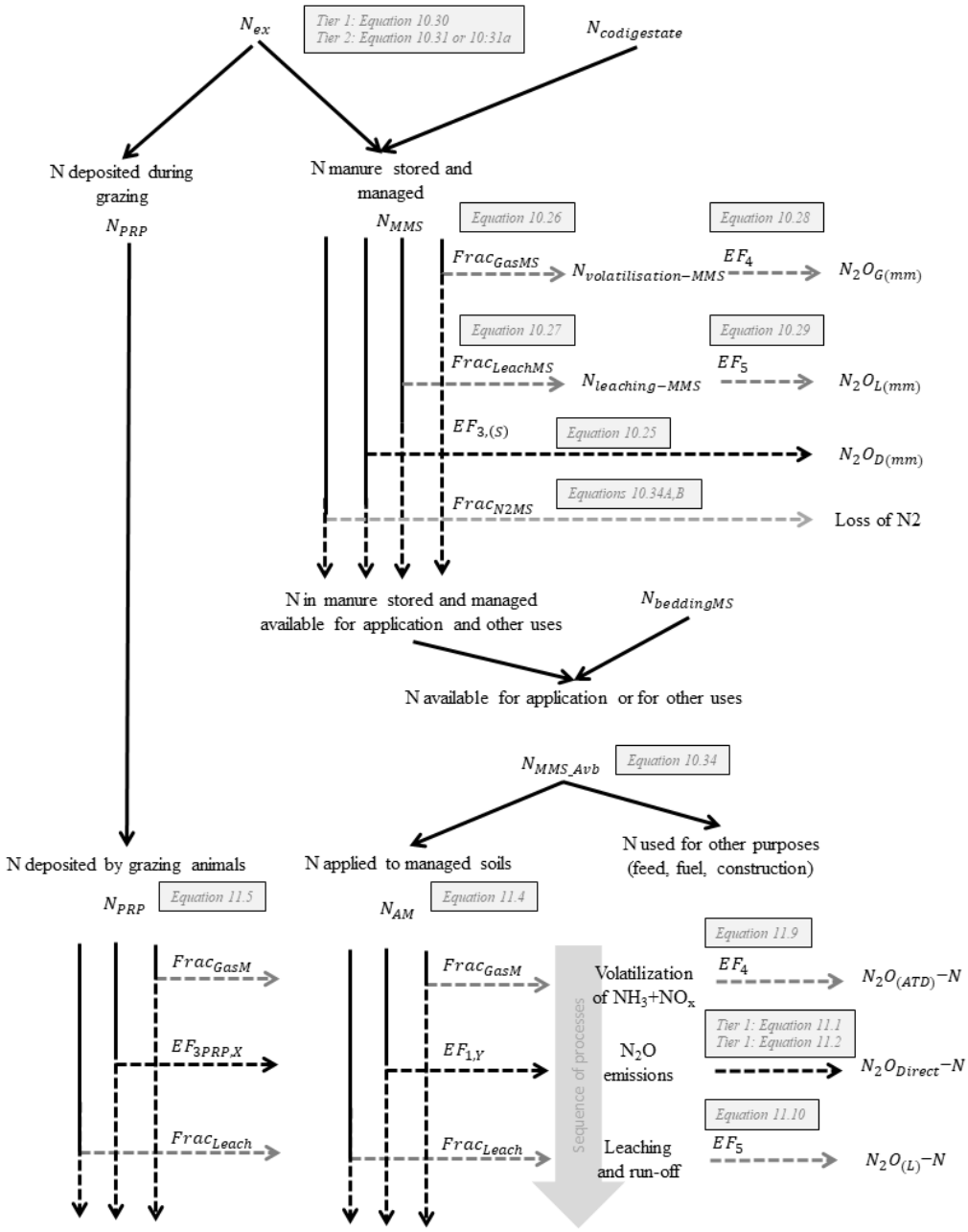
An illustration of N flows through animal and crop production systems is given in Figure 10.5. The figure follows the flow of nitrogen, starting from excretion of nitrogen by animals through livestock and crop production systems down to direct or indirect emissions of N_2O. For each flow shown in Figure 10.5, reference is made to the respective equation in Chapter 10 Emissions from livestock and manure management and Chapter 11 N_2O emissions from managed soils, and CO_2 emissions from lime and urea application. Losses to the environment are shown with broken arrows and indicate the emission factor or loss fraction to be used. Nitrogen input from bedding material and co-digestates enter the system and become part of the N available for application or for other uses.

Symbols are defined under the equations in Chapter 10 and 11 and in Annex 10A.5 of Chapter 10. In this Figure all flows denoted with N are averaged annual N flows per head of livestock species/category [kg N animal^{-1} yr^{-1}] or annual N input via co-digestates [kg N yr^{-1}]; symbols denoted with Frac are fractions in [kg N (kg N)$^{-1}$]; symbols denoted with EF are N_2O emission factors in [kg N_2O –N (kg N)$^{-1}$]. X: different EF_3 are used for cattle, pig and poultry (X=CPP) and for sheep and other animals (X=SO). Y: different EF_1 are used for flooded rice fields (Y=FR) and for other fields (no index Y used).

Broken arrows indicate flows that are split into an emission pathway and a flow of N in the agricultural system.

Note that for N deposited by grazing animals or N applied to managed soils, the flow of N is a sequence of processes with first volatilization of NH_3+NO_x and only thereafter emissions of N_2O and N leaching. This is not reflected in the equations proposed for Tier 1 methodology.

Figure 10.5 (New) Processes leading to the emission of gaseous N species from manure



10.5.7 Use of worksheets

No refinement.

Annex 10A.1 Data underlying methane default emission factors for enteric fermentation, volatile solids and nitrogen excretion and retention fractions for Cattle and Buffalo

This annex presents the data used to develop the default emission factors for methane emissions from Enteric Fermentation and Manure Management, Volatile solid and nitrogen excretion rates, and nitrogen retention fraction. The Tier 2 method was implemented with these data to estimate the default Tier 1 emission factors and rates for cattle and buffalo.

This annex also presents the data used to develop the volatile solid estimates used for methane emissions from manure management methane and for nitrogen excretion rates for cattle and buffaloes. The Tier 2 method was implemented with these data.

The literature source for these values are presented in Annex 10B.1 and spreadsheets with raw data for cattle and buffalo compiled for this refinement is available as supplemental material.

TABLE 10A.1 (NEW)
DATA FOR ESTIMATING TIER 1 AND TIER 1A ENTERIC FERMENTATION CH_4 EMISSION FACTORS, VOLATILE SOLID EXCRETION AND N EXCRETION RATES, AND N RETENTION FRACTION RATES FOR DAIRY CATTLE

Regions[7]	Weight, kg	Weight gain, kg/day	Feeding situation	Milk yield[1], kg/day	Fat content of milk, %	Protein content of milk, %	Work, hrs/day	% Pregnant	Digestibility of Feed, %	CP in diet, %	CH_4 conversion, %[2]	Day weighted population mix, %	Enteric fermentation EF, kg CH_4/head/year	kg VS (1000 kg animal mass^{-1}) day^{-1}	kg Nex (1000 kg animal mass^{-1}) day^{-1}	Nretention fraction, (kg N retained/animal/day) (kg N intake/animal/day)$^{-1}$
North America	650	0	Stall Fed	28.0	3.7	3.2	0	90	71	16.7	5.8[6]	100	138	9.2	0.59	0.27
Western Europe	600	0	Stall Fed	20.3	4.2	3.2	0	90	71	16.1	6.3	100	126	8.4	0.54	0.24
Eastern Europe	550	0	Stall Fed	10.9	3.9	3.2	0	85	70	15.1	6.5	100	93	6.7	0.42	0.19
Oceania[3]	488	0	Pasture/Range	12.1	4.8	3.7	0	92	77	22.3	6.5	100	93	6.0	0.72	0.17
Latin America	508	0	Pasture/Range	5.6	4.0	3.2	0	70	65	12.7	6.5	100	87	7.9	0.39	0.12
High productivity systems	520	0	Pasture/Range	9.3	4.0	3.1	0	72	65	17.0	6.5	38	103	9.0	0.60	0.13
Low productivity systems	500	0	Pasture/Range	3.4	4.0	3.2	0	68	65	10.0	6.5	62	78	7.1	0.28	0.11
Asia	386	0	Stall Fed	8.9	3.9	3.2	0	70	66	13.5	6.5	100	78	9.0	0.44	0.20
High productivity systems	485	0	Stall Fed	13.8	4.1	3.1	0	80	70	16.5	6.3	24	96	8.1	0.55	0.20
Low productivity systems	355	0	Stall Fed	7.3	3.9	3.2	0	67	65	12.6	6.5	76	71	9.2	0.41	0.20
Africa	260	0	Stall Fed[5]	3.5	4.3	3.6	0	54	51	8.7	6.5	100	76	18.2	0.44	0.15
High productivity systems	250	0	Stall Fed	5.8	4.3	3.6	0	57	50	7.8	6.5	49	86	21.7	0.41	0.24
Low productivity systems	270	0	Pasture/Range	1.2	4.3	3.6	0	52	51	9.6	6.5	51	66	15.2	0.45	0.05
Middle East	349	0	Stall Fed[5]	5.9	4.1	3.5	0	52	62	13.6	6.5	100	76	10.7	0.50	0.16
High productivity systems	510	0	Stall Fed	10.6	3.5	3.2	0	55	65	15.8	6.5	33	94	8.4	0.49	0.18
Low productivity systems	270	0	Pasture/Range	3.6	4.5	3.7	0	50	60	12.5	6.5	67	62	11.8	0.51	0.13

TABLE 10A.1 (NEW) (CONTINUED)
DATA FOR ESTIMATING TIER 1 AND TIER 1A ENTERIC FERMENTATION CH_4 EMISSION FACTORS, VOLATILE SOLID EXCRETION AND N EXCRETION RATES, AND N RETENTION FRACTION RATES FOR DAIRY CATTLE

Regions[7]	Weight, kg	Weight gain, kg/day	Feedingi situation	Milk yield[1], kg/day	Fat content of milk, %	Protein content of milk, %	Work, hrs/day	% Pregnant	Digestibility of Feed, %	CP in diet, %	CH_4 conversion, %[2]	Day weighted population mix, %	Enteric fermentation EF, kg CH_4/head/year	kg VS (1000 kg animal mass^{-1}) day^{-1}	kg Nex (1000 kg animal mass^{-1}) day^{-1}	Nretention fraction, (kg N retained/animal/day) (kg N intake/animal/day)$^{-1}$
Indian subcontinent	285	0	Pasture/Range[5]	5.2	4.2	3.7	0	42	57	14.3	6.5	100	73	14.1	0.65	0.14
High productivity systems	350	0	Stall Fed	7.1	4.0	3.6	0	50	65	15.5	6.5	23	70	9.1	0.51	0.18
Low productivity systems	265	0	Pasture/Range	4.6	4.2	3.7	0	40	55	14.0	6.5	77	74	16.1	0.70	0.13

[1] The value represent milk yield in kg per day during the whole year.

[2] Y_m values are consist with those reported in Table 10.12.

[3] All data are weighted values, representative of Australia and New Zealand. For Pacific Island nations, may refer to Asia values.

[4] Data of Latin America, Asia, Africa, Middle East and Indian subcontinent were estimated as weighted average by taken into account parameter values related to low- and high-production systems and livestock population structure of low and high productivity systems.

[5] As Feeding Situation corresponding to high productivity systems is defined as Stall Fed, but for low productivity systems as Pasture/Range, a weigted activitiy coefficient was applied to estimate Net energy for activity.

[6] Y_m is a weighted annual value using the high productivity value of 5.7 from Table 10.12 for the lactating period of 305 days and the value of 6.3 for the dry period (60 days).

[7] Scientific articles and reports consulted to derive peformance parameters of dairy and non-dairy cattle are listed in Annex 10B.1.

TABLE 10A.2 (NEW)
DATA FOR ESTIMATING TIER 1 ENTERIC FERMENTATION CH_4 EMISSION FACTORS, VOLATILE SOLID AND NITROGEN EXCRETION RATES, AND N RETENTION FRACTION FOR OTHER CATTLE

Regions[4,5]	Weight, kg	Weight gain, kg/day	Feeding Situation	Milk yield, kg/day[1]	Fat content of milk, %	Protein content of milk, %	Work, hrs/day	Pregnant, %	Digestibility of feed, %	CP in diet, %	CH_4 Conversion, %[2]	Day weighted population mix, %	Enteric fermentation EF, CH_4 kg/head/yr	kg VS (1000 kg animal mass^{-1}) day^{-1}	kg Nex (1000 kg animal mass^{-1}) day^{-1}	Nretention fraction, (kg N retained/animal/day) (kg N intake/animal/day)$^{-1}$
North America																
Mature Females	580		Pasture/Range	3.0	4.0	3.5		80	62	12.0	7.0	35	98	7.7	0.35	0.07
Mature Males	820		Pasture/Range						62	12.0	7.0	2	98	5.4	0.27	0.00
Calves on milk	125	1.0	Pasture/Range						95	16.0	0.0	16	0	1.9	0.35	0.42
Calves on forage	215	1.0	Pasture/Range						65	13.0	6.3	8	59	12.8	0.63	0.16
Growing heifers/steers	300	0.9	Pasture/Range						62	12.0	6.3	17	67	11.3	0.48	0.14
Replacement/growing	400	0.5	Pasture/Range						62	12.0	7.0	11	73	8.3	0.39	0.07
Feedlot cattle	500	1.4	Stall Fed						75	14.0	3.0	11	37	5.4	0.39	0.13
Western Europe																
Mature Males	600		Pasture/Range						60	14.7	7.0	22	81	6.5	0.38	0.00
Replacement/growing	400	0.4	Pasture/Range						65	16.5	6.3	55	57	6.7	0.47	0.04
Calves on milk	230	0.3	Stall fed						95	17.1	0.0	15	0	0.9	0.28	0.10
Calves on forage	230	0.3	Pasture/Range						73	16.5	6.3	8	32	5.2	0.45	0.06
Eastern Europe																
Mature Females	500		Pasture/Range	3.0	4.2	3.7		80	70	15.1	6.3	39	67	5.5	0.39	0.08
Mature Males	600		Pasture/Range						65	14.2	6.3	9	65	5.1	0.32	0.00
Replacement/growing	350	0.4	Pasture/Range						65	14.2	6.3	27	53	7.2	0.43	0.05
Calves on forage	180	0.7	Pasture/Range						65	14.3	6.3	25	46	12.1	0.68	0.12

TABLE 10A.2 (NEW) (CONTINUED)
DATA FOR ESTIMATING TIER 1 ENTERIC FERMENTATION CH_4 EMISSION FACTORS, VOLATILE SOLID AND NITROGEN EXCRETION RATES, AND N RETENTION FRACTION FOR OTHER CATTLE

Regions[4,5]	Weight, kg	Weight gain, kg/day	Feeding Situation	Milk yield, kg/day[1]	Fat content of milk, %	Protein content of milk, %	Work, hrs/day	Pregnant, %	Digestibility of feed, %	CP in diet, %	CH_4 Conversion, %[2]	Day weighted population mix, %	Enteric fermentation EF, CH_4 kg/head/yr	kg VS (1000 kg animal mass^{-1}) day^{-1}	kg Nex (1000 kg animal mass^{-1}) day^{-1}	Nretention fraction, (kg N retained/animal/day) (kg N intake/animal/day)$^{-1}$
Oceania[3]																
Mature Females	416		Pasture/ Range	1.7	4.8	3.7		81	61	14.0	7.0	45	76	8.5	0.46	0.05
Mature Males	467		Pasture/ Range						62	14.0	7.0	25	64	6.3	0.36	0.00
Young	185	0.41	Pasture/ Range						61	14.0	7.0	30	43	10.9	0.55	0.10
Latin America																
Mature Females	435		Pasture/Range	2.0	4.3	3.5		63	59	9.5	7.0	36	81	9.0	0.31	0.07
Mature Males	582		Pasture/Range						59	9.8	7.0	2	81	6.8	0.26	0.00
Growing heifers/steers	240	0.35	Pasture/Range						61	9.8	7.0	22	47	9.3	0.33	0.11
Replacement/growing	302	0.34	Pasture/Range						60	9.6	7.0	18	57	9.0	0.32	0.08
Calves on milk	66	0.35	Pasture/Range						95	9.5	0.0	10	0	1.8	0.16	0.50
Calves on forage	160	0.35	Pasture/Range						61	10.0	7.0	10	39	11.5	0.40	0.13
Feedlot cattle	460	0.90	Stall Fed						74	14.0	4.0	1	39	4.8	0.35	0.10
Asia																
Mature Females	376		Stall Fed	1.5	4.7	3.3	1.1	50	61	10.6	7.0	27	65	8.0	0.33	0.06
Mature Females - grazing	305		Pasture/Range	1.4	4.7	3.3		65	59	10.0	7.0	9	54	10.0	0.36	0.06
Mature Males	501		Stall Fed				1.1		57	10.1	7.0	15	72	7.3	0.27	0.00
Mature Males - grazing	430		Pasture/Range						57	10.0	7.0	6	68	8.1	0.30	0.00
Growing/Replacement[6]	207	0.28	Pasture/Range						61	10.5	7.0	25	44	10.1	0.39	0.07
Calves on forage6	90	0.36	Pasture/Range						62	10.7	6.3	18	26	15.0	0.56	0.16

TABLE 10A.2 (NEW) (CONTINUED)
DATA FOR ESTIMATING TIER 1 ENTERIC FERMENTATION CH_4 EMISSION FACTORS, VOLATILE SOLID AND NITROGEN EXCRETION RATES, AND N RETENTION FRACTION FOR OTHER CATTLE

Regions[4,5]	Weight, kg	Weight gain, kg/day	Feeding Situation	Milk yield, kg/day[1]	Fat content of milk, %	Protein content of milk, %	Work, hrs/day	Pregnant, %	Digestibility of feed, %	CP in diet, %	CH_4 Conversion, %[2]	Day weighted population mix, %	Enteric fermentation EF, CH_4 kg/head/yr	kg VS (1000 kg animal mass^{-1}) day^{-1}	kg Nex (1000 kg animal mass^{-1}) day^{-1}	Nretention fraction, (kg N retained/animal/day) (kg N intake/animal/day)$^{-1}$
Africa																
Mature Females	356		Pasture/Range	2.4	4.0	3.5	0.55[7]	62	60	11.3	7.0	17	74	9.9	0.41	0.08
Mature Females - grazing	275		Large Areas	1.2	4.1	3.6		54	58	10.0	7.0	11	67	12.1	0.43	0.05
Mature Males	540		Pasture/Range						58	11.2	7.0	2	79	7.3	0.31	0.00
Draft Bullocks[8]	340		Stall Fed				1.1		58	10.0	7.0	4	46	7.8	0.29	0.00
Bulls - Grazing	340		Large Areas						58	10.0	7.0	8	67	9.6	0.36	0.00
Growing/Replacement	204	0.24	Pasture/Range						59	10.4	7.0	42	46	11.0	0.41	0.06
Calves on forage	82	0.33	Pasture/Range						59	10.3	7.0	18	31	18.9	0.65	0.14
Middle East																
Mature Females	372		Pasture/Range	2.4	3.7	3.2		51	61	12.5	7.0	27	71	8.8	0.42	0.07
Mature Males	519		Pasture/Range				0.55		59	12.9	7.0	9	75	7.2	0.35	0.00
Replacement/growing	250	0.33	Pasture/Range						58	12.7	7.0	42	57	11.5	0.52	0.06
Calves on forage	115	0.51	Pasture/Range						58	12.8	7.0	23	46	19.8	0.85	0.12
Indian subcontinent																
Mature Females	253		Pasture/Range	1.7	4.6	3.2		40	55	10.2	7.0	22	62	13.0	0.44	0.07
Mature Males	309		Pasture/Range						57	11.4	7.0	3	53	8.7	0.37	0.00
Draft bullocks[8]	290		Stall Fed				1.7		55	10.0	7.0	43	47	8.6	0.31	0.00
Replacement/growing	152	0.20	Pasture/Range						57	10.9	7.0	16	40	13.4	0.51	0.06
Calves on forage	72	0.26	Pasture/Range						57	11.2	7.0	16	29	20.2	0.75	0.11

TABLE 10A.2 (NEW) (CONTINUED)
DATA FOR ESTIMATING TIER 1 ENTERIC FERMENTATION CH_4 EMISSION FACTORS, VOLATILE SOLID AND NITROGEN EXCRETION RATES, AND N RETENTION FRACTION FOR OTHER CATTLE

[1] The value represent milk yield in kg per day during the whole year.

[2] Y_m values are consist with those reported in Table 10.12.

[3] All data are weighted values, representative of Australia and New Zealand. For Pacific Island nations, may refer to Asia values.

[4] Data of Latin America, Asia, Africa, Middle East and Indian subcontinent were estimated as weighted average by taken into account parameter values related to low production systems and high production systems and livestock population structure of low and high productivity systems. The values were estimated based on the data reported in Table 10A.3.

[5] Scientific articles and reports consulted to derive peformance parameters of dairy and non-dairy cattle are presented in Annex 10B.1.

[6] As Feeding Situation corresponding to high productivity systems is defined as Stall Fed, but for low productivity systems as Pasture/Range, a weigted activitiy coefficient was applied to estimate Net energy for activity.

[7] It was assumed that the whole population of stall fed mature females is not used for draught on the regional scale in Africa.

[8] Draft bullocks were all assumed to be castrates and CF_i values were adjusted accordingly.

TABLE 10A.3 (NEW)
DATA FOR ESTIMATING TIER 1A ENTERIC FERMENTATION CH_4 EMISSION FACTORS, VOLATILE SOLID AND NITROGEN EXCRETION RATES AND N RETENTION FRACTION FOR OTHER CATTLE

Regions[4]	Weight, kg	Weight gain, kg/day	Feeding Situation	Milk yield, kg/day[1]	Fat content of milk, %	Protein content of milk, %	Work, hrs/day	Pregnant, %	Digestibility of feed, %	CP in diet, %	CH_4 Conversion, %[2]	Day weighted population mix, %[3]	Enteric fermentation EF, CH_4 kg/head/yr	kg VS (1000 kg animal mass^{-1}) day^{-1}	kg Nex (1000 kg animal mass^{-1}) day^{-1}	Nretention fraction, (kg N retained/animal/day) (kg N intake/animal/day)$^{-1}$
Latin America																
High productivity systems												23[3]				
Mature Females	490		Pasture/Range	2.7	4.2	3.2		78	61	11.2	7.0	33	89	8.4	0.35	0.07
Mature Males	595		Pasture/Range						61	11.2	7.0	1	79	6.2	0.28	0.00
Growing heifers/steers	240	0.50	Pasture/Range						63	11.8	6.3	22	45	9.2	0.40	0.13
Replacement/growing	350	0.50	Pasture/Range						61	11.0	7.0	16	70	9.3	0.38	0.08
Calves on milk	82	0.50	Pasture/Range						95	9.5	0.0	12	0	1.9	0.18	0.49
Calves on forage	200	0.50	Pasture/Range						63	12.3	7.0	12	44	10.8	0.50	0.11
Feedlot cattle	460	0.90	Stall Fed						74	14.0	4.0	4	39	4.8	0.35	0.10
Low productivity systems												77[3]				
Mature Females	420		Pasture/Range	1.8	4.3	3.2		59	59	9.1	7.0	37	79	9.2	0.30	0.07
Mature Males	580		Pasture/Range						59	9.6	7.0	2	81	6.8	0.25	0.00
Growing heifers/steers	240	0.30	Pasture/Range						60	9.2	7.0	22	47	9.3	0.30	0.10
Replacement/growing	290	0.30	Pasture/Range						60	9.3	7.0	19	54	8.9	0.30	0.08
Calves on milk	60	0.30	Pasture/Range						95	9.5	0.0	10	0	1.7	0.16	0.50
Calves on forage	145	0.30	Pasture/Range						60	9.2	7.0	10	35	11.7	0.37	0.14

TABLE 10A.3 (NEW) (CONTINUED)
DATA FOR ESTIMATING TIER 1A ENTERIC FERMENTATION CH_4 EMISSION FACTORS, VOLATILE SOLID AND NITROGEN EXCRETION RATES AND N RETENTION FRACTION FOR OTHER CATTLE

Regions[4]	Weight, kg	Weight gain, kg/day	Feeding Situation	Milk yield, kg/day[1]	Fat content of milk, %	Protein content of milk, %	Work, hrs/day	Pregnant, %	Digestibility of feed, %	CP in diet, %	CH_4 Conversion, %[2]	Day weighted population mix, %[3]	Enteric fermentation EF, CH_4 kg/head/yr	kg VS (1000 kg animal mass^{-1}) day^{-1}	kg Nex (1000 kg animal mass^{-1}) day^{-1}	Nretention fraction, (kg N retained/animal/day) (kg N intake/animal/day)$^{-1}$
Asia																
High productivity systems												17[3]				
Mature Females	450		Stall Fed	1.9	4.7	3.3		80	68	12.5	6.3	41	55	5.3	0.30	0.07
Mature Males	550		Stall Fed						68	12.5	6.3	2	49	3.9	0.23	0.00
Growing/Replacement	285	0.40	Stall Fed						68	12.5	6.3	27	41	6.3	0.35	0.07
Calves on forage	125	0.50	Stall Fed						68	12.5	6.3	30	28	9.6	0.47	0.18
Low productivity systems												83[3]				
Mature Females-Farming	350		Stall Fed	1.4	4.7	3.3	1.1	40	59	10.0	7.0	25	64	9.0	0.33	0.06
Mature Females-Grazing	305		Pasture/Range	1.4	4.7	3.3		65	59	10.0	7.0	11	63	10.0	0.36	0.06
Mature Males-Farming	500		Stall Fed				1.1		57	10.0	7.0	18	73	7.4	0.27	0.00
Mature Males-Grazing	430		Pasture/Range						57	10.0	7.0	8	68	8.1	0.30	0.00
Growing/Replacement	190	0.25	Pasture/Range						59	10.0	7.0	25	44	11.3	0.41	0.07
Calves on forage	75	0.30	Pasture/Range						59	10.0	7.0	15	28	18.5	0.61	0.14
Africa																
High productivity systems												30[3]				
Mature Females	390		Pasture/Range	2.9	3.9	3.5		65	61	11.8	7.0	39	76	9.1	0.40	0.09
Mature Males	540		Pasture/Range						58	11.2	7.0	6	79	7.3	0.31	0.00
Growing/Replacement	250	0.34	Pasture/Range						60	11.2	7.0	41	50	9.6	0.39	0.09
Calves on forage	105	0.43	Pasture/Range						61	11.4	7.0	14	36	16.1	0.64	0.14

TABLE 10A.3 (NEW) (CONTINUED)
DATA FOR ESTIMATING TIER 1A ENTERIC FERMENTATION CH_4 EMISSION FACTORS, VOLATILE SOLID AND NITROGEN EXCRETION RATES AND N RETENTION FRACTION FOR OTHER CATTLE

Regions[4]	Weight, kg	Weight gain, kg/day	Feeding Situation	Milk yield, kg/day[1]	Fat content of milk, %	Protein content of milk, %	Work, hrs/day	Pregnant, %	Digestibility of feed, %	CP in diet, %	CH_4 Conversion, %[2]	Day weighted population mix, %[3]	Enteric fermentation EF, CH_4 kg/head/yr	kg VS (1000 kg animal mass^{-1}) day^{-1}	kg Nex (1000 kg animal mass^{-1}) day^{-1}	Nretention fraction, (kg N retained/animal/day) (kg N intake/animal/day)$^{-1}$
Low productivity systems												70[3]				
Mature Females	275		Pasture/Range	1.2	4.1	3.6	0.55	54	58	10.0	7.0	7	60	11.0	0.39	0.06
Mature Females-Grazing	275		Large Areas	1.2	4.1	3.6		54	58	10.0	7.0	15	67	12.1	0.43	0.05
Draft Bullocks[5]	340		Stall Fed				1.1		58	10.0	7.0	5	53	7.8	0.29	0.00
Bulls - Grazing	340		Large Areas						58	10.0	7.0	11	65	9.6	0.36	0.00
Growing/Replacement	185	0.20	Pasture/Range						58	10.0	7.0	42	42	11.2	0.40	0.06
Calves on forage	75	0.30	Pasture/Range						58	10.0	7.0	20	30	19.9	0.65	0.13
Middle East																
High productivity systems												33[3]				
Mature Females	500		Pasture/Range	2.8	3.5	3.3		55	65	14.0	6.3	20	72	6.8	0.39	0.07
Mature Males	600		Pasture/Range						63	14.0	6.3	12	68	5.6	0.33	0.00
Replacement/growing	350	0.50	Pasture/Range						63	14.0	6.3	42	61	8.6	0.48	0.06
Calves on forage	165	0.70	Pasture/Range						63	14.0	6.3	26	47	14.2	0.74	0.13
Low productivity systems												67[3]				
Mature Females	330		Pasture/Range	2.3	3.8	3.2		50	60	12.0	7.0	30	67	9.7	0.43	0.08
Mature Males	450		Pasture/Range				0.55		55	12.0	7.0	7	79	9.3	0.40	0.00
Replacement/growing	200	0.25	Pasture/Range						55	12.0	7.0	42	50	13.4	0.54	0.05
Calves on forage	85	0.40	Pasture/Range						55	12.0	7.0	21	40	25.3	0.96	0.11

TABLE 10A.3 (NEW) (CONTINUED)
DATA FOR ESTIMATING TIER 1A ENTERIC FERMENTATION CH4 EMISSION FACTORS, VOLATILE SOLID AND NITROGEN EXCRETION RATES AND N RETENTION FRACTION FOR OTHER CATTLE

Regions[4]	Weight, kg	Weight gain, kg/day	Feeding Situation	Milk yield, kg/day[1]	Fat content of milk, %	Protein content of milk, %	Work, hrs/day	Pregnant, %	Digestibility of feed, %	CP in diet, %	CH_4 Conversion, %[2]	Day weighted population mix, %[3]	Enteric fermentation EF, CH_4 kg/head/yr	kg VS (1000 kg animal mass^{-1}) day^{-1}	kg Nex (1000 kg animal mass^{-1}) day^{-1}	Nretention fraction, (kg N retained/animal/day) (kg N intake/animal/day)$^{-1}$
Indian subcontinent																
High productivity systems												14[3]				
Mature Females	300		Pasture/Range	2.5	4.0	3.6		40	60	13.0	7.0	9	64	10.2	0.48	0.09
Mature Males	330		Pasture/Range						60	13.0	7.0	11	52	7.5	0.39	0.00
Replacement/growing	180	0.33	Pasture/Range						60	13.0	7.0	35	45	12.0	0.58	0.07
Calves on forage	90	0.33	Pasture/Range						60	13.0	7.0	45	31	16.7	0.77	0.11
Low productivity systems												86[3]				
Mature Females	250		Pasture/Range	1.7	4.6	3.7		40	55	10.0	7.0	24	62	13.2	0.43	0.08
Mature Males	290		Pasture/Range						55	10.0	7.0	2	54	9.9	0.35	0.00
Draft bullocks[5]	290		Stall Fed				1.7		55	10.0	7.0	50	47	8.6	0.31	0.00
Replacement/growing	140	0.15	Pasture/Range						55	10.0	7.0	13	37	13.9	0.47	0.05
Calves on forage	60	0.22	Pasture/Range						55	10.0	7.0	11	26	23.2	0.73	0.11

[1] The value represent milk yield in kg per day during the whole year.

[2] Ym values are consist with those reported in Table 10.12.

[3] A share of low- and high-productivity animals from the total livestock population of a region.

[4] Scientific articles and reports consulted to derive peformance parameters of dairy and non-dairy cattle are presented in Annex 10B.1.

[5] Draft bullocks were all assumed to be castrates and CF_i values were adjusted accordingly.

TABLE 10A.4 (NEW)
DATA FOR ESTIMATING TIER 1 ENTERIC FERMENTATION CH_4 EMISSION FACTORS, VOLATILE SOLID AND NITROGEN EXCRETION RATES, AND N RETENTION FRACTION RATES FOR BUFFALO

Regions[3]	Weight, kg	Weight gain, kg/day	Feeding Situation	Milk yield, kg/day[1]	Fat content of milk, %	Protein content of milk, %	Work, hrs/day	% Pregnant	Digestibility of feed, %	CP in diet, %	CH_4 Conversion, %[2]	Day weighted population mix, %	Enteric fermentation EF, CH_4 kg/head/yr	kg VS (1000 kg animal mass^{-1}) day^{-1}	kg Nex (1000 kg animal mass^{-1}) day^{-1}	Nretention fraction, (kg N retained/animal/day) (kg N intake/animal/day)$^{-1}$
Western Europe																
Mature Males	700		Stall Fed						65	14.0	6.3	3	59	4.4	0.27	0.00
Mature Females	615		Stall Fed	3.0	8.0	4.6		87	65	15.0	6.3	59	81	6.2	0.36	0.15
Growing/Replacement	420	0.53	Stall Fed						65	14.0	6.3	25	59	6.6	0.39	0.06
Calves	170	0.68	Stall Fed						65	14.0	6.3	13	42	11.7	0.64	0.13
Eastern Europe																
Mature Males	650		Pasture/Paddock						71	13.0	6.3	8	61	3.7	0.26	0.00
Mature Females	550		Pasture/Paddock	4.0	7.5	4.3		85	71	13.0	6.3	62	80	5.8	0.31	0.22
Growing/Replacement	350	0.55	Pasture/Paddock						71	13.0	6.3	14	53	6.0	0.38	0.08
Calves	155	0.66	Pasture/Paddock						71	13.0	6.3	16	37	9.4	0.54	0.16
Latin America																
Adult Males	650		Pasture/Range						60	11.0	7.0	4	86	6.3	0.28	0.00
Adult Females	500		Pasture/Range	4.2	7.1	4.3		62	60	11.0	7.0	40	106	10.1	0.35	0.21
Growing/Replacement	200	0.40	Pasture/Range						60	11.0	7.0	26	47	10.7	0.42	0.09
Calves	90	0.28	Pasture/Range						60	11.0	7.0	30	26	13.9	0.51	0.15
Asia																
Mature Males	490		Pasture/Paddock				1.1		55	10.0	7.0	20	88	9.5	0.34	0.00
Mature Females	420		Pasture/Paddock	1.6	9.1	5.2	1.1	45	55	10.0	7.0	40	99	12.5	0.39	0.12
Growing/Replacement	225	0.26	Pasture/Paddock						55	10.0	7.0	25	56	13.1	0.44	0.05
Calves	90	0.32	Pasture/Paddock						55	10.0	7.0	15	37	22.0	0.69	0.11

TABLE 10A.4 (NEW) (CONTINUED)
DATA FOR ESTIMATING TIER 1 ENTERIC FERMENTATION CH_4 EMISSION FACTORS, VOLATILE SOLID AND NITROGEN EXCRETION RATES, AND N RETENTION FRACTION RATES FOR BUFFALO

Regions[3]	Weight, kg	Weight gain, kg/day	Feeding Situation	Milk yield, kg/day[1]	Fat content of milk, %	Protein content of milk, %	Work, hrs/day	% Pregnant	Digestibility of feed, %	CP in diet, %	CH_4 Conversion, %[2]	Day weighted population mix, %	Enteric fermentation EF, CH_4 kg/head/yr	kg VS (1000 kg animal mass^{-1}) day^{-1}	kg Nex (1000 kg animal mass^{-1}) day^{-1}	Nretention fraction, (kg N retained/animal/day) (kg N intake/animal/day)$^{-1}$
Africa																
Mature Males	590		Pasture/Paddock				1.37		58	10.0	7.0	6	94	8.0	0.30	0.00
Mature Females	440		Pasture/Paddock	4.3	7.2	3.7	0.55	44	58	10.0	7.0	42	107	12.2	0.35	0.24
Growing/Replacement	300	0.40	Pasture/Paddock						58	10.0	7.0	32	68	11.3	0.40	0.07
Calves	115	0.45	Pasture/Paddock						58	10.0	7.0	20	43	18.7	0.61	0.14
Middle East																
Mature Males	650		Pasture/Paddock				1.37		60	11.0	7.0	5	96	7.1	0.31	0.00
Mature Females	520		Pasture/Paddock	3.0	7.0	4.2	0.55	65	65	11.0	6.3	52	83	7.5	0.30	0.17
Growing/Replacement	255	0.39	Pasture/Paddock						61	11.0	7.0	22	54	9.9	0.40	0.08
Calves	105	0.41	Pasture/Paddock						61	11.0	7.0	21	36	16.0	0.61	0.14
Indian subcontinent																
Breeding males	560		Pasture/Paddock						55	12.0	7.0	1	88	8.4	0.36	0.00
Working males[4]	560	8	Pasture/Paddock				1.37		55	12.0	7.0	4	86	8.2	0.35	0.00
Mature Females	480		Pasture/Paddock	4.8	7.3	3.5	0.55	50	55	12.0	7.0	48	127	14.1	0.54	0.09
Growing/Replacement	195	0.31	Pasture/Paddock						59	12.0	7.0	21	45	11.2	0.48	0.08
Calves	85	0.31	Pasture/Paddock						56	12.0	7.0	26	35	21.2	0.83	0.10

[1] The value represent milk yield in kg per day during the whole year.

[2] Ym values are consist with those reported in Table 10.12.

[3] Scientific articles and reports consulted to derive pefromance parameters of buffalo are listed in Annex 10B.1.

[4] Draft bullocks were all assumed to be castrates and CF_i values were adjusted accordingly.

Annex 10A.2 Additional data and information for the calculation of methane and nitrous oxide from Manure Management

This annex presents the required default data to implement the Tier 1 method for estimation of methane and nitrous oxide emissions from manure management. Data required in both methods include animal weight data required for the calculation of average VS and N excretion per animal category as well as AWMS information for regions in the country and improved definitional data, relating IPCC AWMS and definitions used in the EMEP/EEA air pollutant emission inventory guidebook. The information is a combination of the consistent data collection for cattle and buffalo that is compiled in Annex 10A.1 and data compiled by the FAO for use in their modelling system GLEAM (FAO 2017; MacLeod *et al*. 2017). More specific information can be found, sometimes at the country level at http://www.fao.org/gleam/resources/en/. Furthermore, information is supplied on IPCC climate zones.

TABLE 10A.5 (NEW)
DEFAULT VALUES FOR LIVE WEIGHTS FOR ANIMAL CATEGORIES (KG)

Category of animal	Region																		
	North America	Western Europe	Eastern Europe	Oceania	Latin America			Africa			Middle East			Asia			India subcontinent		
					Mean	High PS[1]	Low PS[1]	Mean	High PS	Low PS	Mean	High PS	Low PS	Mean	High PS	Low PS	Mean	High PS	Low PS
Dairy cattle[2]	650	600	550	488	508	520	500	260	250	270	349	510	270	386	485	355	285	350	265
Other cattle[2]	407	405	389	359	303	329	295	236	302	208	275	362	232	299	310	296	226	167	236
Buffalo[2]	NA	509	467	NA	315			339			381			336			321		
Swine[3]	77	76	77	61	65	81	59	49	72	37	59	70	53	58	69	52	59	68	53
Finishing	61	61	59	41	51	59	47	41	54	33	52	60	48	49	56	44	51	55	48
Breeding	184	190	204	163	143	205	121	100	200	61	118	157	99	122	160	102	121	162	99
Chicken[3]	1.4	1.4	1.3	1.3	1.1	1.3	0.9	0.9	1	0.8	0.9	1.2	0.7	1.2	1.4	1	1.0	1.2	0.8
Hens >/= 1 yr	1.5	1.9	1.9	2	1.4	1.6	1.3	1.4	1.9	1.1	1.2	1.7	1	1.5	1.9	1.3	1.3	1.5	1.1
Pullets	1.2	1.5	1.3	1.4	0.7	1.3	0.5	0.7	1.4	0.5	0.6	1.2	0.4	0.8	1.5	0.6	0.6	1.3	0.4
Broilers	1.4	1.2	1.1	1.2	0.9	1.2	0.7	0.8	0.8	0.7	0.7	1	0.5	0.8	1	0.7	0.8	1	0.6
Turkeys[4]	6.8																		
Ducks[4]	2.7																		
Sheep[3]	40				31														
Goats[5]	41	40	36	33	24														
Horses[4]	377				238														
Mules and asses[4]	130																		
Camels[4]	217																		
Ostrich[5]	120																		

TABLE 10A.5 (NEW) (CONTINUED)
DEFAULT VALUES FOR LIVE WEIGHTS FOR ANIMAL CATEGORIES (KG)

Category of animal	Region																			
	North America	Western Europe	Eastern Europe	Oceania	Latin America			Africa			Middle East			Asia			India sub-continent		
					Mean	High PS[1]	Low PS[1]	Mean	High PS	Mean	High PS[1]	Low PS[1]	Mean	High PS	Mean	High PS[1]	Low PS[1]	Mean	High PS
Deer[5]	120																			
Reindeer[5]	120																			

[1] High PS and Low PS refer to high- and low productivity systems required for Tier 1a methodology.

[2] Values are derived from diets used in the calculation of enteric fermentation Tier 1 and Tier 1a emission factors (Table 10A.1 – Table 10A.4).

[3] Values are taken from FAO GLEAM databases (FAO 2017). High and low estimates are simplified extracts from the model database.

[4] Values are taken from Table 10A-9 of the *2006 IPCC Guidelines*.

[5] For more information see Table 10.10 and Table 10.19 of the *2019 Refinement*.

TABLE 10A.6 (NEW)
ANIMAL WASTE MANAGEMENT SYSTEM (AWMS) REGIONAL AVERAGES FOR CATTLE AND BUFFALO

Animal Category	Region[1]	AWMS (%)								
		Lagoon	Liquid /Slurry	Solid storage	Drylot	Pasture/ Range/ Paddock	Daily spread	Digester	Burned for fuel	Other
Dairy Cattle	North America	26	24	24	no data	15	11	no data	no data	no data
	Western Europe	no data	43	29	no data	26	2	no data	no data	no data
	Eastern Europe	no data	5	74	no data	20	1	no data	no data	no data
	Oceania	5	no data	no data	no data	94	1	no data	no data	no data
	East Asia and South-East Asia (Asia)	no data	1	21	29	38	no data	no data	11	no data
	South Asia (Indian subcontinent)	no data	no data	1	49	30	no data	no data	20	no data
	Latin America and the Caribbean	no data	no data	5	38	57	no data	no data	no data	no data
	Near East (Middle East) and North Africa	no data	no data	14	35	46	no data	no data	5	no data
	Sub-Saharan Africat	no data	no data	20	29	45	no data	no data	6	no data
non-Dairy Cattle	North America	no data	1	43	14	42	no data	no data	no data	no data
	Western Europe	no data	22	26	no data	48	4	no data	no data	no data
	Eastern Europe	no data	64	5	no data	31	no data	no data	no data	no data
	Oceania	no data	no data	no data	no data	100	no data	no data	no data	no data
	East Asia and South-East Asia (Asia)	no data	no data	29	28	36	no data	no data	7	no data
	South Asia (Indian subcontinent)	no data	no data	1	49	30	no data	no data	20	no data
	Latin America and the Caribbean	no data	no data	3	5	92	no data	no data	no data	no data
	Near East (Middle East) and North Africa	no data	no data	5	46	42	no data	no data	7	no data
	Sub-Saharan Africa	no data	no data	15	30	50	no data	no data	5	no data

TABLE 10A.6 (NEW) (CONTINUED)
ANIMAL WASTE MANAGEMENT SYSTEM (AWMS) REGIONAL AVERAGES FOR CATTLE AND BUFFALO

Animal Category	Region	AWMS (%)								
		Lagoon	Liquid /Slurry	Solid storage	Drylot	Pasture/ Range/ Paddock	Daily spread	Digester	Burned for fuel	Other
Buffalo Dairy	North America	no data	43	40	no data	17	no data	no data	no data	no data
	Western Europe	no data	34	63	no data	3	no data	no data	no data	no data
	Eastern Europe	no data	18	68	no data	13	1	no data	no data	no data
	East Asia and South-East Asia (Asia)	no data	no data	10	58	29	no data	no data	3	no data
	South Asia (Indian subcontinent)	no data	no data	1	41	38	no data	no data	20	no data
	Latin America and the Caribbean	no data	no data	2	48	50	no data	no data	no data	no data
	Near East (Middle East) and North Africa	no data	no data	18	35	46	no data	no data	1	no data
Buffalo non-Dairy	Eastern Europe (including Russia)	no data	9	64	no data	27	no data	no data	no data	no data
	East Asia and South-East Asia (Asia)	no data	no data	6	64	28	no data	no data	2	no data
	South Asia (Indian subcontinent)	no data	no data	1	40	39	no data	no data	20	no data
	Latin America and the Caribbean	no data	no data	2	5	93	no data	no data	no data	no data
	Near East (Middle East) and North Africa	no data	no data	16	12	57	no data	no data	15	no data

TABLE 10A.7 (NEW)
ANIMAL WASTE MANAGEMENT SYSTEM (AWMS) REGIONAL AVERAGES FOR SWINE (%)

Animal Category	Productivity class	Region	Lagoon	Liquid/ Slurry	Solid storage	Drylot	Pit < 1	Pit > 1	Daily spread	Digester	Pasture
Growing Swine	High Productivity	North America	28	31	4	3	no data	34	no data	no data	no data
		Western Europe	6	51	14	no data	2	26	1	no data	no data
		Eastern Europe	5	31	55	1	4	4	no data	no data	no data
		Russian Federation	no data	24	76	no data	no data	no data	no data	no data	no data
		Oceania	91	no data	1	8	no data	no data	no data	no data	no data
		East Asia and South East Asia	35	21	no data	2	35	no data	no data	7	no data
		Indian subcontinent	12	23	13	35	2	no data	7	8	no data
		Latin America and the Caribbean	11	34	12	41	no data	no data	2	no data	no data
		Near East (Middle East) and North Africa	10	29	no data	54	no data	no data	no data	7	no data
		Sub-saharan Africa	no data	7	6	86	1	no data	no data	no data	no data
	Low Productivity	East Asia and South East Asia	5	27	18	14	14	5	6	5	6
		Indian subcontinent	5	30	15	15	15	5	5	5	5
		Latin America and the Caribbean	5	30	15	15	15	5	5	5	5
		Near East (Middle East) and North Africa	5	30	15	15	15	5	5	5	5
		Sub-saharan Africa	5	30	15	15	15	5	5	5	5

TABLE 10A.7 (NEW) (CONTINUED)
ANIMAL WASTE MANAGEMENT SYSTEM (AWMS) REGIONAL AVERAGES FOR SWINE (%)

Animal Category	Productivity class	Region	Lagoon	Liquid/ Slurry	Solid storage	Drylot	Pit < 1	Pit > 1	Daily spread	Digester	Pasture
Breeding Swine	High Productivity	North America	28	31	4	3	no data	34	no data	no data	no data
		Western Europe	6	51	15	no data	2	25	1	no data	no data
		Eastern Europe	5	31	55	1	4	4	no data	no data	no data
		Russian Federation	no data	24	76	no data	no data	no data	no data	no data	no data
		Oceania	91	no data	1	8	no data	no data	no data	no data	no data
		East Asia and South East Asia	35	21	no data	2	35	no data	no data	7	no data
		Indian subcontinent	12	23	14	32	3	no data	8	8	no data
		Latin America and the Caribbean	11	34	12	41	no data	no data	2	no data	no data
		Near East (Middle East) and North Africa	10	29	no data	54	no data	no data	no data	7	no data
		Sub-saharan Africa	no data	7	6	86	1	no data	no data	no data	no data
	Low Productivity	East Asia and South East Asia	4	28	22	13	13	4	6	4	6
		Indian subcontinent	5	30	15	15	15	5	5	5	5
		Latin America and the Caribbean	5	30	15	15	15	5	5	5	5
		Near East (Middle East) and North Africa	5	30	15	15	15	5	5	5	5
		Sub-saharan Africa	5	30	15	15	15	5	5	5	5

TABLE 10A.8 (NEW)
ANIMAL WASTE MANAGEMENT SYSTEM (AWMS) REGIONAL AVERAGES FOR SHEEP AND GOATS

Animal Category	Region[1]	AWMS (%)								
		Lagoon	Liquid/ Slurry	Solid storage	Drylot	Pasture/ Range/ Paddock	Daily spread	Digester	Burned for fuel	Other
Sheep - Meat	North America	no data	no data	54	no data	46	no data	no data	no data	no data
	Western Europe	no data	no data	13	no data	87	no data	no data	no data	no data
	Eastern Europe	no data	no data	54	no data	46	no data	no data	no data	no data
	Near East (Middle East) and North Africa	no data	no data	no data	50	50	no data	no data	no data	no data
	East Asia and South-East Asia	no data	no data	17	3	80	no data	no data	no data	no data
	Oceania	no data	no data	no data	no data	100	no data	no data	no data	no data
	South Asia (Indian subcontinent)	no data	no data	17	3	80	no data	no data	no data	no data
	Latin America and the Caribbean	no data	no data	17	3	80	no data	no data	no data	no data
	Sub-Saharan Africa	no data	no data	17	3	80	no data	no data	no data	no data
Sheep - Dairy	Western Europe	no data	no data	22	no data	78	no data	no data	no data	no data
	Eastern Europe	no data	no data	42	no data	58	no data	no data	no data	no data
	Near East (Middle East) and North Africa	no data	no data	no data	50	50	no data	no data	no data	no data
	East Asia and South-East Asia	no data	no data	17	3	80	no data	no data	no data	no data
	South Asia (Indian subcontinent)	no data	no data	17	3	80	no data	no data	no data	no data
	Latin America and the Caribbean	no data	no data	17	3	80	no data	no data	no data	no data
	Sub-Saharan Africa	no data	no data	17	3	80	no data	no data	no data	no data

TABLE 10A.8 (NEW) (CONTINUED)
ANIMAL WASTE MANAGEMENT SYSTEM (AWMS) REGIONAL AVERAGES FOR SHEEP AND GOATS

Animal Category	Region[1]	AWMS (%)								
		Lagoon	Liquid/ Slurry	Solid storage	Drylot	Pasture/ Range/ Paddock	Daily spread	Digester	Burned for fuel	Other
Goats	North America	no data	no data	50	no data	50	no data	no data	no data	no data
	Russian Federation	no data	no data	82	no data	18	no data	no data	no data	no data
	Western Europe	no data	no data	28	no data	72	no data	no data	no data	no data
	Eastern Europe	no data	no data	9	no data	91	no data	no data	no data	no data
	Near East (Middle East) and North Africa	no data	no data	no data	50	50	no data	no data	no data	no data
	East Asia and South-East Asia	no data	no data	50	no data	50	no data	no data	no data	no data
	Oceania	no data	no data	no data	no data	100	no data	no data	no data	no data
	South Asia (Indian subcontinent)	no data	no data	50	no data	50	no data	no data	no data	no data
	Latin America and the Caribbean	no data	no data	17	3	80	no data	no data	no data	no data
	Sub-Saharan Africa	no data	no data	17	3	80	no data	no data	no data	no data

TABLE 10A.9 (NEW)
ANIMAL WASTE MANAGEMENT SYSTEM (AWMS) REGIONAL AVERAGES FOR POULTRY AND OTHER[1] ANIMALS

Animal Category	Region	AWMS (%)								
		Lagoon	Liquid/ Slurry	Solid storage	Drylot	Pasture/ Range/ Paddock	Pit >1 month	Daily spread	Digester	Other (Poultry manure with litter)
Chicken-Layer	North America	1	29	70	no data	no data	no data	no data	no data	no data
	Russian Federation	no data	no data	no data	no data	no data	100	no data	no data	no data
	Western Europe	no data	1	20	21	no data	43	1	no data	14
	Eastern Europe	no data	no data	no data	47	no data	34	no data	no data	19
	Near East (Middle East) and North Africa	11	7	11	no data	no data	67	no data	no data	4
	East Asia and South-East Asia	no data	4	no data	no data	1	94	1	no data	no data
	Oceania	no data	no data	no data	no data	23	77	no data	no data	no data
	South Asia (Indian subcontinent)	no data	no data	100	no data	no data	no data	no data	no data	no data
	Latin America and the Caribbean	no data	58	42	no data	no data	no data	no data	no data	no data
	Sub-Saharan Africa	no data	no data	no data	no data	no data	90	no data	no data	10
Chicken-Broiler	North America	no data	no data	no data	no data	no data	no data	no data	no data	100
	Russian Federation	no data	no data	no data	no data	no data	no data	no data	no data	100
	Western Europe	no data	no data	no data	no data	no data	no data	no data	no data	100
	Eastern Europe	no data	no data	no data	no data	no data	no data	no data	no data	100
	Near East (Middle East) and North Africa	no data	no data	no data	no data	no data	no data	no data	no data	100
	East Asia and South-East Asia	no data	no data	no data	no data	no data	no data	no data	no data	100
	Oceania	no data	no data	no data	no data	no data	no data	no data	no data	100
	South Asia (Indian subcontinent)	no data	no data	no data	no data	no data	no data	no data	no data	100
	Latin America and the Caribbean	no data	no data	no data	no data	no data	no data	no data	no data	100
	Sub-Saharan Africa	no data	no data	no data	no data	no data	no data	no data	no data	100

TABLE 10A.9 (NEW) (CONTINUED)
ANIMAL WASTE MANAGEMENT SYSTEM (AWMS) REGIONAL AVERAGES FOR POULTRY AND OTHER[1] ANIMALS

Animal Category	Region[1]	AWMS (%)								
		Lagoon	Liquid/ Slurry	Solid storage	Drylot	Pasture/ Range/ Paddock	Pit >1 month	Daily spread	Digester	Other (Poultry manure with litter)
Low productivity	North America	no data	no data	no data	no data	50	no data	50	no data	no data
	Russian Federation	no data	no data	no data	no data	50	no data	50	no data	no data
	Western Europe	no data	no data	no data	no data	50	no data	50	no data	no data
	Eastern Europe	no data	no data	no data	no data	50	no data	50	no data	no data
	Near East (Middle East) and North Africa	no data	no data	no data	no data	50	no data	50	no data	no data
	East Asia and South-East Asia	no data	no data	no data	no data	50	no data	50	no data	no data
	Oceania	no data	no data	no data	no data	50	no data	50	no data	no data
	South Asia (Indian subcontinent)	no data	no data	no data	no data	50	no data	50	no data	no data
	Latin America and the Caribbean	no data	no data	no data	no data	50	no data	50	no data	no data
	Sub-Saharan Africa	no data	no data	no data	no data	50	no data	50	no data	no data

[1] For Other animal, the IPCC expert group reviewed the national inventory submissions as well as guidance in the *2006 IPCC Guidelines* under the UNFCCC and concluded that common distribution of systems used to manage manure as follows:

Horses, camelelids, mules and asses, and other grazing animals; should use the data supplied for goats as a proxy;

American bison should use the same manure management fractions as beef cattle in North America;

Deer and reindeer manure deposited at 100% in PRP;

Ostrich (Emu) manure is 80% in PRP and 20 percent managed in solid based systems;

Manure of rabbits and fur-bearing animals is 100% managed in a solid based system.

Hence, countries may apply the same allocation of MMS in the calculation of N_2O emissions from manure stored in manure management systems. However, countries are encouraged to develop a country-specific dataset on MMS used to manage manure generated by these categories of animals.

Information required to determine climate zones according to Chapter 3 of Volume 4 Current Guideline

Outlined below are the conditions required to determine the climate zone required for the selection of a country's MCF, according to the IPCC climate zone determination as defined in Volume 4, Chapter 3, Annex 3A.5, Figure 3A.5.2. Where possible, if countries span multiple climate zones, efforts should be made to disaggregate animal populations into climate zones. If this is not possible, partys are advised to select the climate zone covering the greatest surface area of their country or regions of their country for which they have distinct animal populations.

Briefly, all data is drawn from "The Climate Reseach Unit (CRU) or the CGIAR-Consortium for Spatial Information (CSI) 1985-2015." Climate zones are differentiated based on the factors of mean annual temperature, elevation, mean annual precipitation and the ratio of mean annual precipitation to precipitation for this 30 year average annual weather data compilation.

Therefore, as identified in Volume 4, Chapter 3, of these guidelines climate zones are defined:

Tropical Montane: has > 18°C mean annual temperature and at an elevation greater than 1000m;

Tropical Wet: has > 18°C mean annual temperature and mean annual precipitation >2000mm;

Tropical Moist: has > 18°C mean annual temperature and mean annual precipitation >1000mm;

Tropical Dry: has > 18°C mean annual temperature and mean annual precipitation < 1000mm;

Tropical Moist: has > 18°C mean annual temperature and mean annual precipitation >1000mm;

Warm temperate moist: has > 10°C mean annual temperature and a ratio of potential evapotranspiration to precipitation > 1;

Warm temperate dry: has > 10°C mean annual temperature and a ratio of potential evapotranspiration to precipitation < 1;

Cool temperate moist: has > 0°C mean annual temperature and a ratio of potential evapotranspiration to precipitation > 1;

Cool temperate dry: has > 0°C mean annual temperature and a ratio of potential evapotranspiration to precipitation < 1;

Boreal moist: has < 0°C mean annual temperature but some monthly temperatures > 10°C and a ratio of potential evapotranspiration > 1;

Boreal dry: has < 0°C mean annual temperature but some monthly temperatures > 10°C and a ratio of potential evapotranspiration to precipitation < 1;

Polar moist: has < 0°C mean annual temperature but all monthly temperatures < 10°C and a ratio of potential evapotranspiration > 1;

Polar dry: has < 0°C mean annual temperature but all monthly temperatures < 10°C and a ratio of potential evapotranspiration to precipitation < 1.

Figure 10A.1 (New) Mapping of IPCC climate zones (taken from Volume 4, Chapter 3, Annex 3A.5)

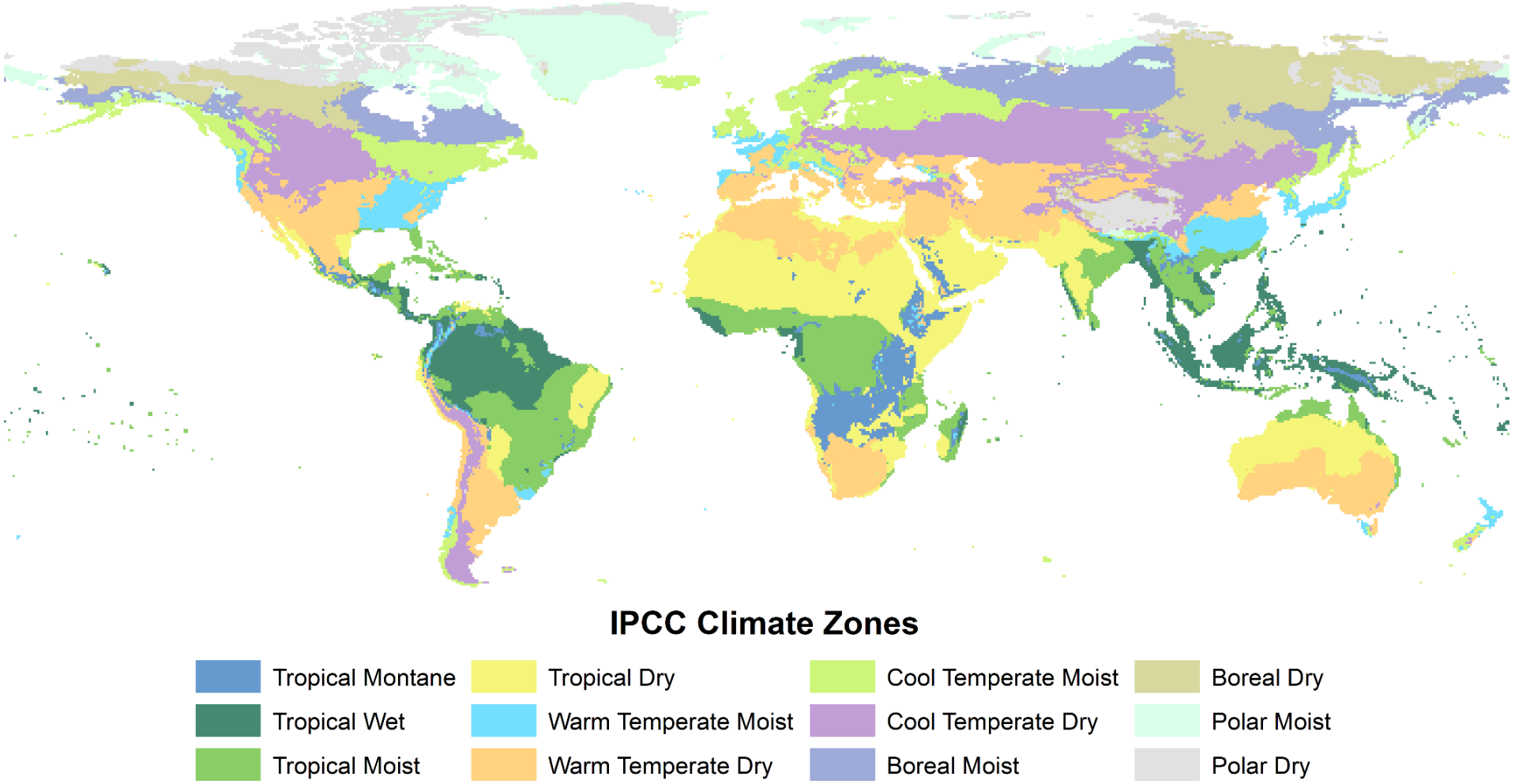


TABLE 10A.10 (NEW)
COMPARISON OF MANURE STORAGE TYPE DEFINITIONS USED BY THE IPCC AND BY THE EMEP/EEA AIR POLLUTANT EMISSION INVENTORY GUIDEBOOK 2016 (HTTPS://WWW.EEA.EUROPA.EU/PUBLICATIONS/EMEP-EEA-GUIDEBOOK-2016)

System IPCC	System EMEP / EEA	Definition
Pasture/Range/Paddock (PRP)	Grazing	The manure from pasture and range grazing animals is allowed to lie as deposited, and is not managed.
Daily spread	No definition given	Manure is routinely removed from a confinement facility and is applied to cropland or pasture within 24 hours of excretion.
Solid storage	Heaps	The storage of manure, typically for a period of several months, in unconfined piles or stacks. Manure is able to be stacked because of the presence of a sufficient amount of bedding material or loss of moisture by evaporation
Dry lot	No definition given	A paved or unpaved open confinement area without any significant vegetative cover. Dry lots do not require the addition of bedding to control moisture. Manure may be removed periodically and spread on fields.
Liquid/Slurry	Tanks	Manure is stored as excreted or with some minimal addition of water in either tanks or earthen ponds outside the livestock building, usually for periods of less than 1 year; Storage with a low surface area to depth ratio; normally steel or concrete cylinders
Liquid/Slurry, With natural crust cover	Crust	Natural or artificial layer on the surface of slurry which reduces the diffusion of gasses to the atmosphere
Liquid/Slurry, cover	Cover	Rigid or flexible structure that covers the manure and is impermeable to water and gasses
Uncovered anaerobic lagoon	Lagoons	Storage with a large surface area to depth ratio; normally shallow excavations in the soil
Pit storage below animal confinements	In-house slurry pit	Mixture of excreta and washing water, stored within the livestock building, usually below the confined animals
Anaerobic digester	Biogas treatment	Anaerobic fermentation of slurry and/or solid
Burned for fuel	No definition given	The dung and urine are excreted on fields. The sun dried dung cakes are burned for fuel.
Deep bedding	In-house deep litter	Mixture of excreta and bedding, accumulated on the floor of the livestock building

TABLE 10A.10 (NEW) (CONTINUED)
COMPARISON OF MANURE STORAGE TYPE DEFINITIONS USED BY THE IPCC AND BY THE EMEP/EEA AIR POLLUTANT EMISSION INVENTORY GUIDEBOOK 2016 (HTTPS://WWW.EEA.EUROPA.EU/PUBLICATIONS/EMEP-EEA-GUIDEBOOK-2016)

System IPCC		System EMEP / EEA	Definition
Composting	In-vessel	Forced-aeration composting	Aerobic decomposition of manure with forced ventilation
	Static pile	Composting, passive windrow	Aerobic decomposition of manure without forced ventilation
	Intensive windrow	No EMEP equivalent	
	Composting - Passive windrow	No EMEP equivalent	
Poultry manure with litter		Laying hens – solid Broilers – litter Other poultry - litter	Similar to cattle and swine deep bedding except usually not combined with a dry lot or pasture. Typically used for all poultry breeder flocks, for alternative systems for layers and for the production of meat type chickens (broilers) and other fowl. Litter and manure are left in place with added bedding during the poultry production cycle and cleaned between poultry cycles, typically 5 to 9 weeks in productive systems.
Poultry manure without litter		Laying hens – slurry	May be similar to open pits in enclosed animal confinement facilities or may be designed and operated to dry the manure as it accumulates. The latter is known as a high-rise manure management system and is a form of passive windrow composting when designed and operated properly. Some intensive poultry farms installed the manure belt under the cage, where the manure is dried inside housing.
Aerobic treatment		No EMEP equivalent	The biological oxidation of manure collected as a liquid with either forced or natural aeration. Natural aeration is limited to aerobic and facultative ponds and wetland systems and is due primarily to photosynthesis. Hence, these systems typically become anoxic during periods without sunlight.
No definition given		Slurry separation	The separation of the solid and liquid components of slurry
No definition given		Acidification	The addition of strong acid to reduce manure pH

Annex 10A.3 Spreadsheet example for the calculation of a country or regions specific MCF

MCF CALCULATIONS AND EXAMPLE SPREADSHEET

This Annex was developed to explain how MCFs in the guidelines have been derived and to provide a detailed step by step protocol for inventory compilers to calculate country or region specific MCFs. Application of the model at the national scale requires national or regional monthly air temperature profiles as well as the average number and timing of the emptying of manure storages. Temperature data can be downloaded from various agencies such as the National Oceanic and Atmospheric Administration (NOAA) or the European Environmental Agency. Manure removal statistics may be taken from farm practice surveys or from expert consultation. Compilers should develop an estimate of the average number of manure removals per year and the months of the highest frequency of removals. If regional practices vary within a country, compilers should develop MCFs that are representative of regional practice by entering consistent manure removal statistics with regional temperature profiles. If regional MCFs are calculated, the national MCF should be weighted based on the number of animals feeding into the regional manure management systems represented by the manure removal profile and the regional temperature profile.

Further, to support the *2019 Refinement*, a spreadsheet was created to enable users to calculate a site-specific Methane Conversion Factor (MCF). The spreadsheet uses the same calculations that were used to calculate the MCF Table in the guidance document, but has been designed for use by inventory compilers to do calculations for their country-specific circumstances. The spreadsheed is available in the supplemental data supplied with this Chapter, identified as Supplemental Information Chapter 10, Volume IV, *2019 Refinement*, and available on the IPCC TFI website.

The calculation procedure outlined in the spreadsheet contains three main sections:

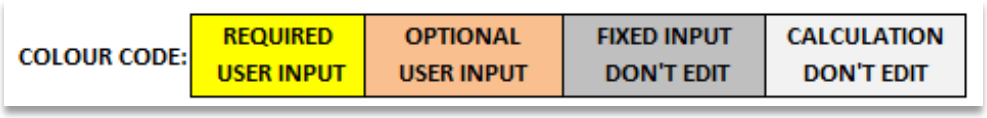
Inputs to the model;

Model calculations;

Results from the model.

As an explanation of procedures, within each section, cells are colour coded. Compilers are required to develop input data for anything that is indicated by yellow highlighted cells, and have the option of editing the orange highlighted cells if needed, but only if country-specific information is available for those parameters. Other cells are not meant to be edited by the user.

Figure 10A.2 (New) Colour code for cells in the example spreadsheet



MODEL INPUT

Temperature

The Input required to run the model at a national scale and recreate the spreadsheet is shown below (Figures 10A.3(New) and 10A.4(New)). In this section, the compiler should input 12 months of temperature data (degrees C) in cells D9:D20, based on average monthly temperatures for the region for which they wish to develop the MCF.

If the compiler has estimates of national or regional manure temperature, "Manure" should be selected in cell D6. As a result, the spreadsheet will copy the user-input temperature into cells E9:E20, for further use in the analysis.

If the compiler is using national or regional air temperature (not manure temperature), "Air" should be selected in cell D6. As a result, the spreadsheet will generate an estimate for manure temperature in cells E9:E20. The estimates are based on the following logic:

- Manure temperature lags 1-month behind air temperature.
  - e.g., Tmanure in June = Tair in May.
- The minimum manure temperature will be used (1 degree C by default; user adjustable).
  - e.g., for Tair = -9 C, Tmanure = 1 C.

If and only if the storage is emptied once per year, manure temperature will be reduced by a dampening factor (3 degrees C by default; user adjustable).

i.e. Tman = Tair – damping factor; e.g., 12 = 15 – 3

The logic equation is implemented in Excel as follows, for example, in cell E9: =IF($D$6="Manure",D9,IF($F$21>1,MAX(D20,f_Tmin),MAX(D20-f_T2damping,f_Tmin)))

Broken into steps:

If $D$6="Manure" then the result in E9 will equal D9

If $D$6 is not "Manure" (i.e. it is “Air”) then the second IF statement is operated

IF $F$21>1 (i.e. multiple removals per year), then no damping is applied

Manure temperature is selected as air temperature from the previous month, and it is always greater or equal to the minimum temperature,
i.e. E9 will equal MAX(D20,f_Tmin). In this case, D20 (-6.7) is less than the minimum, so the result in E9 is the minimum (1.0).

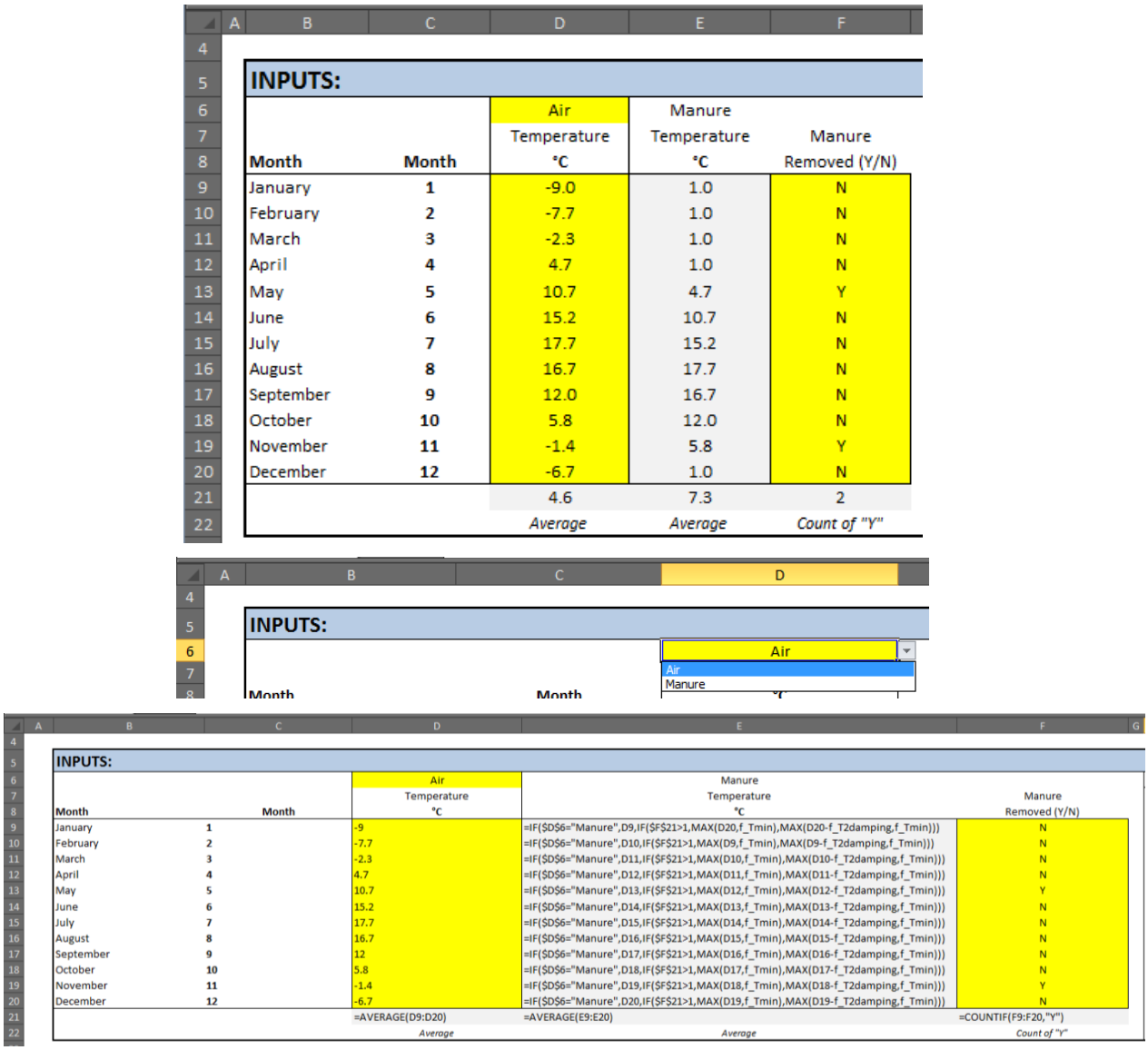
IF $F$21=1 then damping is applied

Damping is applied by subtracting the damping factor: D20-f_T2damping

The temperature is always greater or equal to the minimum temperature, using the MAX() function.

The compiler should then identify the months when manure is removed from the storage in column F (F9:F20). This can be indicated by a “Y” indicating months when manure was removed, and an “N” for months when manure is not removed. The number of months when manure was removed is counted and displayed in cell F21.

Figure 10A.3 (New) Temperature and manure removal inputs to the model



INPUTS:				
Month	Month	Air Temperature °C	Manure Temperature °C	Manure Removed (Y/N)
January	1	-9.0	1.0	N
February	2	-7.7	1.0	N
March	3	-2.3	1.0	N
April	4	4.7	1.0	N
May	5	10.7	4.7	Y
June	6	15.2	10.7	N
July	7	17.7	15.2	N
August	8	16.7	17.7	N
September	9	12.0	16.7	N
October	10	5.8	12.0	N
November	11	-1.4	5.8	Y
December	12	-6.7	1.0	N
		4.6	7.3	2
		Average	*Average*	*Count of "Y"*

INPUTS:				
Month	Month	Air Temperature °C	Manure Temperature °C	Manure Removed (Y/N)
January	1	-9	=IF($D$6="Manure",D9,IF($F$21>1,MAX(D20,f_Tmin),MAX(D20-f_T2damping,f_Tmin)))	N
February	2	-7.7	=IF($D$6="Manure",D10,IF($F$21>1,MAX(D9,f_Tmin),MAX(D9-f_T2damping,f_Tmin)))	N
March	3	-2.3	=IF($D$6="Manure",D11,IF($F$21>1,MAX(D10,f_Tmin),MAX(D10-f_T2damping,f_Tmin)))	N
April	4	4.7	=IF($D$6="Manure",D12,IF($F$21>1,MAX(D11,f_Tmin),MAX(D11-f_T2damping,f_Tmin)))	N
May	5	10.7	=IF($D$6="Manure",D13,IF($F$21>1,MAX(D12,f_Tmin),MAX(D12-f_T2damping,f_Tmin)))	Y
June	6	15.2	=IF($D$6="Manure",D14,IF($F$21>1,MAX(D13,f_Tmin),MAX(D13-f_T2damping,f_Tmin)))	N
July	7	17.7	=IF($D$6="Manure",D15,IF($F$21>1,MAX(D14,f_Tmin),MAX(D14-f_T2damping,f_Tmin)))	N
August	8	16.7	=IF($D$6="Manure",D16,IF($F$21>1,MAX(D15,f_Tmin),MAX(D15-f_T2damping,f_Tmin)))	N
September	9	12	=IF($D$6="Manure",D17,IF($F$21>1,MAX(D16,f_Tmin),MAX(D16-f_T2damping,f_Tmin)))	N
October	10	5.8	=IF($D$6="Manure",D18,IF($F$21>1,MAX(D17,f_Tmin),MAX(D17-f_T2damping,f_Tmin)))	N
November	11	-1.4	=IF($D$6="Manure",D19,IF($F$21>1,MAX(D18,f_Tmin),MAX(D18-f_T2damping,f_Tmin)))	Y
December	12	-6.7	=IF($D$6="Manure",D20,IF($F$21>1,MAX(D19,f_Tmin),MAX(D19-f_T2damping,f_Tmin)))	N
		=AVERAGE(D9:D20)	=AVERAGE(E9:E20)	=COUNTIF(F9:F20,"Y")
		Average	*Average*	*Count of "Y"*

Note. Top panel: alphanumeric values in each cell. Middle panel: dropdown menu to select "Air" or "Manure". Bottom panel: all formulae are visible.

Constants and Other Input Parameters

The inventory compiler is required to provide several other inputs in the section shown below (Figure 10A.4(New)). The name of each parameter is provided in column H, the numeric value of the parameter is in column I, the units are in column J, the source of each value is given in column K, additional notes are in columns L and M, default values are in column N. To make equations more easily understood, the Microsoft Excel feature of "Named Cells" has been used to name the cells in column I, and the name of each cell is shown in column O for convenience. For example, cell I7 is given the name "VS_PROD_YR". See Figure 10A.4(New) for a full list of named cells.

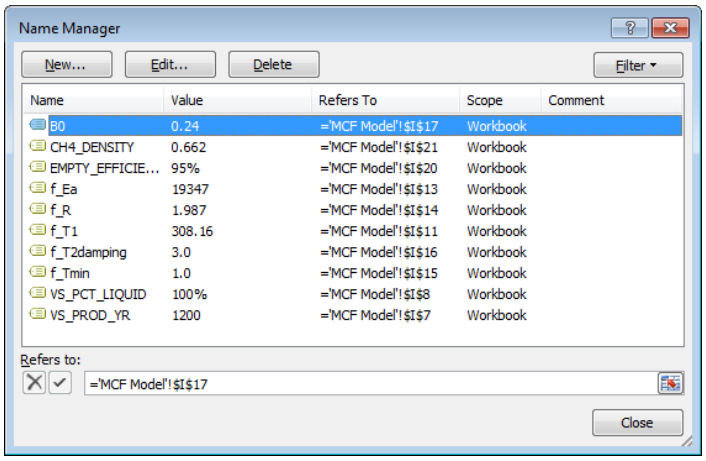
Additional information about the input parameters:

- VS Excretion – based on IPCC guidance.
- VS% liquid storage – this indicates what percentage of excreted VS is handled as a liquid. For example. 100 percent indicates that all excreted VS enters the liquid storage;
- A lower number (say, 75 percent) could indicate that a portion of the solids is separated by a screwpress and handled as a solid (25 percent) while the remaining 75 percent is handled as liquid;
- The compiler must provide a B_0 value for the manure. Refer to IPCC guidance;

- The compiler may, optionally, adjust the minimum temperature (and temperature damping factors);
- The compiler also has the option to adjust the emptying efficiency, which indicates the percentage of manure removed from storage at each removal. By default this is set to 95 percent, indicating that 5 percent of the VS remain in storage after emptying. Set this value to 100 percent for complete removal.

Figure 10A.4 (New) Constants and other input parameters for the model

Parameter:	Value	Units	Source:	Notes	Default Value:	Named Cell
VS Excretion:	1200	kg/year	user input	based on VS excretion, and manure handling	n/a	VS_PROD_YR
VS % liquid storage:	100%	%	user input	% going to liquid storage (e.g. solid-liquid separat	100%	VS_PCT_LIQUID
				note emissions from solid must be handled separately		
f equation:	f = EXP((Ea*(T2-T1))/(R*T2*303.16))					
T1	308.16	K	Temperature of B0 assays		308.16	f_T1
T2	monthly input	K	user input	Enter in Column D (D9:D20)	n/a	n/a
Ea	19347	cal/mol	Petersen et al. PLoS One	(compare: 15175 from Mangino et al. 2001)	19347	f_Ea
R	1.987	cal/K.mol	Mangino et al. 2001		1.987	f_R
Minimum T2	1.0	C	Judgement.	converted to K in calculation	1.0	f_Tmin
Damping T2	3.0	C	Judgement (Rennie et al. 2017.)	applied only when manure removed once per year		f_T2damping
B0	0.24	m3/kg VS added	user input	refer to IPCC guidance for default B0 values	n/a	B0
MDP	1.0	unitless	MDP is not used (i.e. =1.0). Adjust VS % liquid storage or excretion instead.		1.0	
emptying efficiency	95%	%	Judgement. Default 95%	Percent of manure removed (1-residual)	95%	EMPTY_EFFICIENCY
CH4 density	0.662	kg/m3	IPCC guidance		0.662	CH4_DENSITY



Note. Constants and other input parameters for the model are shown in the top panel. Named Cells in column I are shown in column O, and in the Name Manager dialog box (bottom panel). No formulae exist in this part of the spreadsheet.

MODEL CALCULATIONS

The model calculations are run for three years, in order to ensure VS available has stabilized on an annual basis. For example, in Figure 10A.5(New), we see that VS Available (column J) increases substantially from the first year to the second year (J64 vs J65), and then stabilizes in the third year (J66). This is because the first year begins from a perfectly empty storage, whereas the second year is emptied according to the Emptying Efficiency parameter (95 percent removed / 5 percent remaining; Figure 10A.4(New)).

The model approach is as follows:

Column B: Month of year, over 3 years. These month numbers are used to extract input data shown in Figure 10A.3(New).

Column C: Average manure temperature in each month. This is extracted from cells E9:E20 (Figure 10A.3(New)) using a VLOOKUP function (Figure 10A.6(New)).

Column D: temperature is converted from Celsius to Kelvin, using Excel's CONVERT function 10A.6(New) .

Column E: the temperature-dependent *f* parameter is calculated using the van't Hoff-Arrhenius equation (Mangino *et al*. 2001; IPCC 2006), with updated input parameters shown in Figure 10A.4(New).

Column F: monthly VS excreted is calculated by dividing the annual VS input parameter by 12.

Column G: monthly VS loaded is calculated by multiplying VS excreted by the percentage stored as liquid. In this example, the two are equal because VS_PCT_LIQUID is 100 percent (Figure 10A.4(New)).

Column H: monthly manure emptying is extracted from cells F9:F20 (Figure 10A.3(New)) using a VLOOKUP function (Figure 10A.6(New)).

Column I: the quantity of VS emptied is calculated. The logic is as follows: if emptying occurred, then calculate the mass of VS available to be removed using the mass of VS available in the previous month minus the mass of VS consumed in the previous month. Then, multiply the result by the EMPTY_EFFICIENCY parameter (Figures 10A.4(New) and 10A.6(New)).

Column J: the mass of VS available for producing methane is calculated. In the first month of the first year this is equal to the mass of VS loaded. In all other months, this is calculated as the VS loaded in the current month + VS available in the previous month – VS consumed in the previous month – VS emptied in the current month.

Column K: the mass of VS consumed is calculated by multiplying VS available by *f*.

Column L: the volume of CH_4 produced is calculated by multiplying VS consumed by B_0.

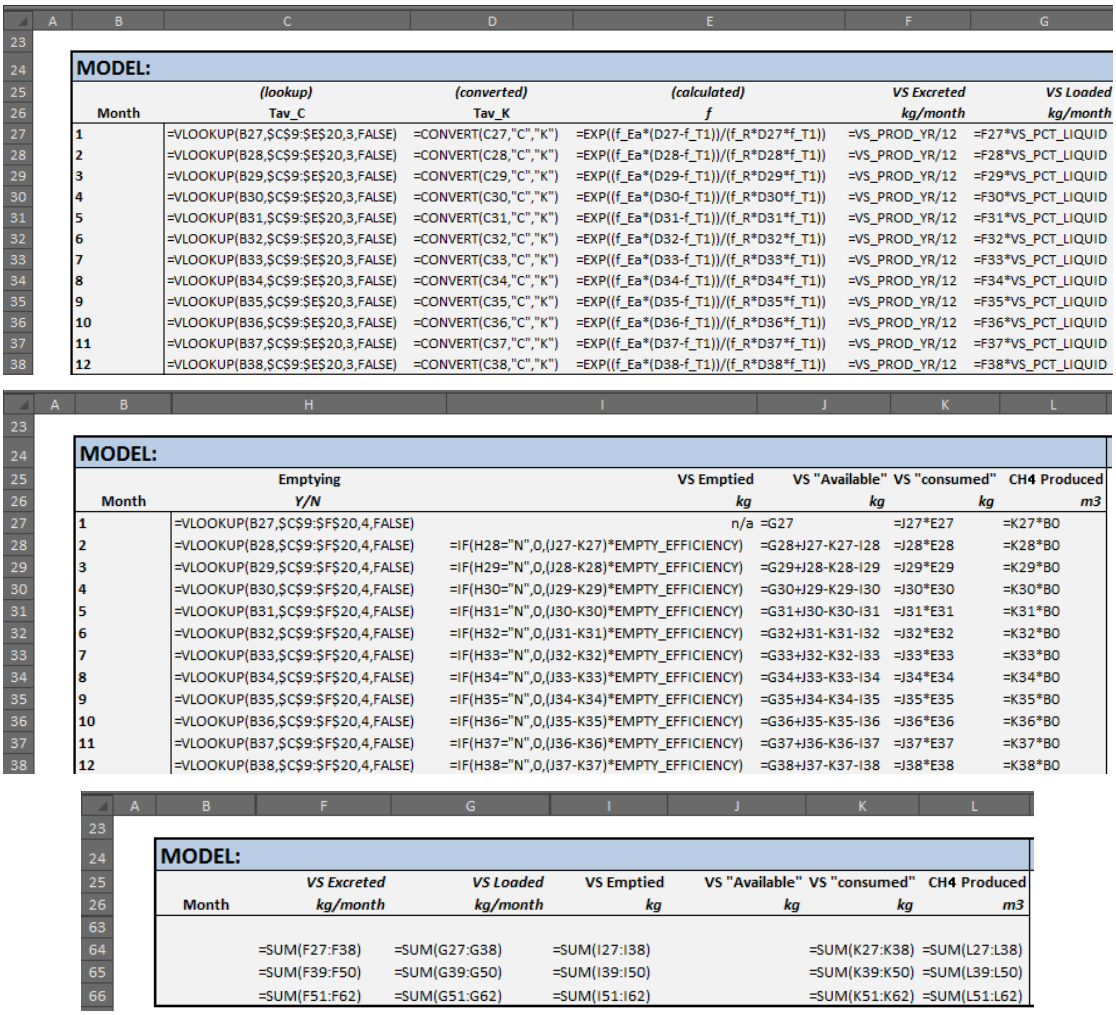
Using these values and equations, the compiler should be able to reproduce graphics such as the profile of manure temperature, volatile solids and methane production shown in Figure 10A.7(New).

Figure 10A.5 (New) Monthly model inputs and outputs over a three year period

MODEL:

Month	(lookup) Tav_C	(converted) Tav_K	(calculated) *f*	VS Excreted kg/month	VS Loaded kg/month	Emptying Y/N	VS Emptied kg	VS "Available" kg	VS "consumed" kg	CH4 Produced m3
1	1.0	274.15	0.02	100	100	N	n/a	100	2	0
2	1.0	274.15	0.02	100	100	N	-	198	4	1
3	1.0	274.15	0.02	100	100	N	-	294	6	1
4	1.0	274.15	0.02	100	100	N	-	388	8	2
5	4.7	277.85	0.03	100	100	Y	362	119	4	1
6	10.7	283.85	0.07	100	100	N	-	215	14	3
7	15.2	288.35	0.11	100	100	N	-	301	34	8
8	17.7	290.85	0.15	100	100	N	-	367	56	13
9	16.7	289.85	0.14	100	100	N	-	411	56	13
10	12.0	285.15	0.08	100	100	N	-	455	36	9
11	5.8	278.95	0.04	100	100	Y	398	121	4	1
12	1.0	274.15	0.02	100	100	N	-	217	4	1
1	1.0	274.15	0.02	100	100	N	-	312	6	1
2	1.0	274.15	0.02	100	100	N	-	406	8	2
3	1.0	274.15	0.02	100	100	N	-	498	10	2
4	1.0	274.15	0.02	100	100	N	-	588	12	3
5	4.7	277.85	0.03	100	100	Y	548	129	4	1
6	10.7	283.85	0.07	100	100	N	-	225	15	4
7	15.2	288.35	0.11	100	100	N	-	310	35	8
8	17.7	290.85	0.15	100	100	N	-	374	57	14
9	16.7	289.85	0.14	100	100	N	-	417	57	14
10	12.0	285.15	0.08	100	100	N	-	461	36	9
11	5.8	278.95	0.04	100	100	Y	403	121	4	1
12	1.0	274.15	0.02	100	100	N	-	217	4	1
1	1.0	274.15	0.02	100	100	N	-	312	6	1
2	1.0	274.15	0.02	100	100	N	-	406	8	2
3	1.0	274.15	0.02	100	100	N	-	498	10	2
4	1.0	274.15	0.02	100	100	N	-	588	12	3
5	4.7	277.85	0.03	100	100	Y	548	129	4	1
6	10.7	283.85	0.07	100	100	N	-	225	15	4
7	15.2	288.35	0.11	100	100	N	-	310	35	8
8	17.7	290.85	0.15	100	100	N	-	374	57	14
9	16.7	289.85	0.14	100	100	N	-	417	57	14
10	12.0	285.15	0.08	100	100	N	-	461	36	9
11	5.8	278.95	0.04	100	100	Y	403	121	4	1
12	1.0	274.15	0.02	100	100	N	-	217	4	1
			SUM:							
			Year 1	1,200	1,200		760	3,185	228	55
			Year 2	1,200	1,200		951	4,058	249	60
			Year 3	1,200	1,200		951	4,059	249	60

Figure 10A.6 (New) Formulae used in the model



MODEL:

Month	(lookup) Tav_C	(converted) Tav_K	(calculated) f	VS Excreted kg/month	VS Loaded kg/month
1	=VLOOKUP(B27,$C$9:$E$20,3,FALSE)	=CONVERT(C27,"C","K")	=EXP((f_Ea*(D27-f_T1))/(f_R*D27*f_T1))	=VS_PROD_YR/12	=F27*VS_PCT_LIQUID
2	=VLOOKUP(B28,$C$9:$E$20,3,FALSE)	=CONVERT(C28,"C","K")	=EXP((f_Ea*(D28-f_T1))/(f_R*D28*f_T1))	=VS_PROD_YR/12	=F28*VS_PCT_LIQUID
3	=VLOOKUP(B29,$C$9:$E$20,3,FALSE)	=CONVERT(C29,"C","K")	=EXP((f_Ea*(D29-f_T1))/(f_R*D29*f_T1))	=VS_PROD_YR/12	=F29*VS_PCT_LIQUID
4	=VLOOKUP(B30,$C$9:$E$20,3,FALSE)	=CONVERT(C30,"C","K")	=EXP((f_Ea*(D30-f_T1))/(f_R*D30*f_T1))	=VS_PROD_YR/12	=F30*VS_PCT_LIQUID
5	=VLOOKUP(B31,$C$9:$E$20,3,FALSE)	=CONVERT(C31,"C","K")	=EXP((f_Ea*(D31-f_T1))/(f_R*D31*f_T1))	=VS_PROD_YR/12	=F31*VS_PCT_LIQUID
6	=VLOOKUP(B32,$C$9:$E$20,3,FALSE)	=CONVERT(C32,"C","K")	=EXP((f_Ea*(D32-f_T1))/(f_R*D32*f_T1))	=VS_PROD_YR/12	=F32*VS_PCT_LIQUID
7	=VLOOKUP(B33,$C$9:$E$20,3,FALSE)	=CONVERT(C33,"C","K")	=EXP((f_Ea*(D33-f_T1))/(f_R*D33*f_T1))	=VS_PROD_YR/12	=F33*VS_PCT_LIQUID
8	=VLOOKUP(B34,$C$9:$E$20,3,FALSE)	=CONVERT(C34,"C","K")	=EXP((f_Ea*(D34-f_T1))/(f_R*D34*f_T1))	=VS_PROD_YR/12	=F34*VS_PCT_LIQUID
9	=VLOOKUP(B35,$C$9:$E$20,3,FALSE)	=CONVERT(C35,"C","K")	=EXP((f_Ea*(D35-f_T1))/(f_R*D35*f_T1))	=VS_PROD_YR/12	=F35*VS_PCT_LIQUID
10	=VLOOKUP(B36,$C$9:$E$20,3,FALSE)	=CONVERT(C36,"C","K")	=EXP((f_Ea*(D36-f_T1))/(f_R*D36*f_T1))	=VS_PROD_YR/12	=F36*VS_PCT_LIQUID
11	=VLOOKUP(B37,$C$9:$E$20,3,FALSE)	=CONVERT(C37,"C","K")	=EXP((f_Ea*(D37-f_T1))/(f_R*D37*f_T1))	=VS_PROD_YR/12	=F37*VS_PCT_LIQUID
12	=VLOOKUP(B38,$C$9:$E$20,3,FALSE)	=CONVERT(C38,"C","K")	=EXP((f_Ea*(D38-f_T1))/(f_R*D38*f_T1))	=VS_PROD_YR/12	=F38*VS_PCT_LIQUID

MODEL:

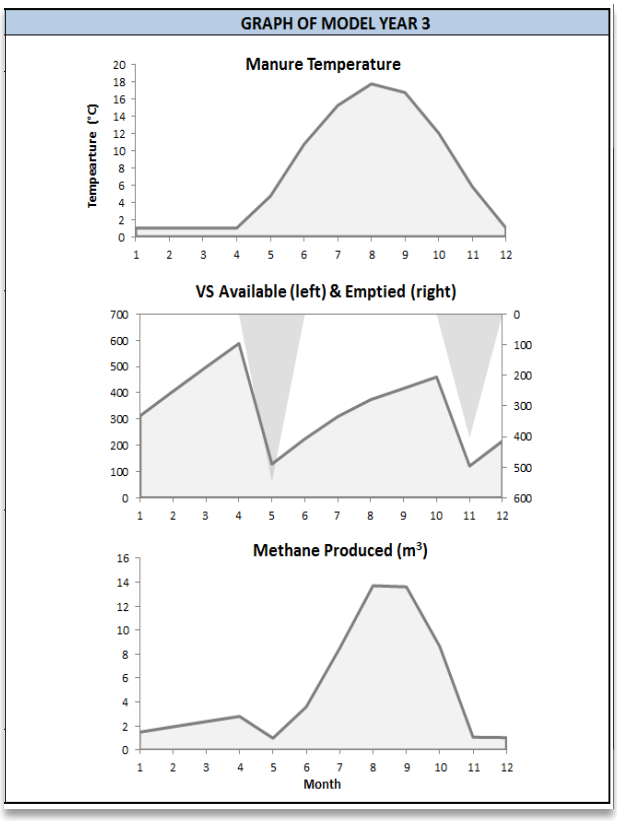
Month	Emptying Y/N	VS Emptied kg	VS "Available" kg	VS "consumed" kg	CH4 Produced m3
1	=VLOOKUP(B27,$C$9:$F$20,4,FALSE)	n/a	=G27	=J27*E27	=K27*B0
2	=VLOOKUP(B28,$C$9:$F$20,4,FALSE)	=IF(H28="N",0,(J27-K27)*EMPTY_EFFICIENCY)	=G28+J27-K27-I28	=J28*E28	=K28*B0
3	=VLOOKUP(B29,$C$9:$F$20,4,FALSE)	=IF(H29="N",0,(J28-K28)*EMPTY_EFFICIENCY)	=G29+J28-K28-I29	=J29*E29	=K29*B0
4	=VLOOKUP(B30,$C$9:$F$20,4,FALSE)	=IF(H30="N",0,(J29-K29)*EMPTY_EFFICIENCY)	=G30+J29-K29-I30	=J30*E30	=K30*B0
5	=VLOOKUP(B31,$C$9:$F$20,4,FALSE)	=IF(H31="N",0,(J30-K30)*EMPTY_EFFICIENCY)	=G31+J30-K30-I31	=J31*E31	=K31*B0
6	=VLOOKUP(B32,$C$9:$F$20,4,FALSE)	=IF(H32="N",0,(J31-K31)*EMPTY_EFFICIENCY)	=G32+J31-K31-I32	=J32*E32	=K32*B0
7	=VLOOKUP(B33,$C$9:$F$20,4,FALSE)	=IF(H33="N",0,(J32-K32)*EMPTY_EFFICIENCY)	=G33+J32-K32-I33	=J33*E33	=K33*B0
8	=VLOOKUP(B34,$C$9:$F$20,4,FALSE)	=IF(H34="N",0,(J33-K33)*EMPTY_EFFICIENCY)	=G34+J33-K33-I34	=J34*E34	=K34*B0
9	=VLOOKUP(B35,$C$9:$F$20,4,FALSE)	=IF(H35="N",0,(J34-K34)*EMPTY_EFFICIENCY)	=G35+J34-K34-I35	=J35*E35	=K35*B0
10	=VLOOKUP(B36,$C$9:$F$20,4,FALSE)	=IF(H36="N",0,(J35-K35)*EMPTY_EFFICIENCY)	=G36+J35-K35-I36	=J36*E36	=K36*B0
11	=VLOOKUP(B37,$C$9:$F$20,4,FALSE)	=IF(H37="N",0,(J36-K36)*EMPTY_EFFICIENCY)	=G37+J36-K36-I37	=J37*E37	=K37*B0
12	=VLOOKUP(B38,$C$9:$F$20,4,FALSE)	=IF(H38="N",0,(J37-K37)*EMPTY_EFFICIENCY)	=G38+J37-K37-I38	=J38*E38	=K38*B0

MODEL:

Month	VS Excreted kg/month	VS Loaded kg/month	VS Emptied kg	VS "Available" kg	VS "consumed" kg	CH4 Produced m3
	=SUM(F27:F38)	=SUM(G27:G38)	=SUM(I27:I38)		=SUM(K27:K38)	=SUM(L27:L38)
	=SUM(F39:F50)	=SUM(G39:G50)	=SUM(I39:I50)		=SUM(K39:K50)	=SUM(L39:L50)
	=SUM(F51:F62)	=SUM(G51:G62)	=SUM(I51:I62)		=SUM(K51:K62)	=SUM(L51:L62)

Note. To conserve space, only 12 months are shown. Top panel: Temperature (Column C and D), coefficient (Column E), VS excreted, (Column F) and VS loaded (Column G). Middle panel: month of emptying (Columns H), VS emptied (Column I), VS available (Column J), VS consumed (Column K) and CH_4 Produced (Column L). Bottom panel: sums in rows 64:66 for selected columns.

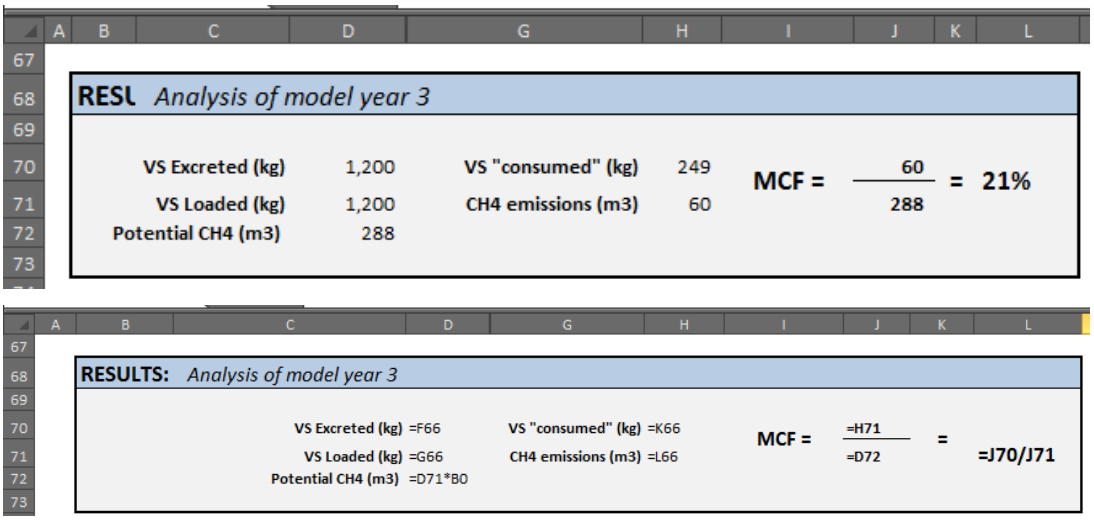
Figure 10A.7 (New) Example of monthly patterns in Year 3: manure temperature, VS available (kg), VS emptied (kg), and methane production.



MODEL RESULTS

The MCF is calculated in the Results section. This is done using the third year outputs. In this particular example, the input air temperature is from the Cool Temperate Moist region and the retention time is 6-months. The resulting MCF (21 percent) is identical with the guidance document (21 percent).

Figure 10A.8 (New) Summary of Year 3 VS and methane production, and calculation of MCF.



Note. Top panel shows results, bottom panel shows equations.

NOTE ABOUT TERMINOLOGY:

The terms "VS Available" and "VS Consumed" are used here to be consistent with the *2006 IPCC Guidelines* and Mangino *et al*. 2001 approach. However, these terms require some clarification to avoid misinterpretation: (1)

The term "VS Consumed" does not represent the real VS degraded but a conceptual quantity of VS removed from the liquid/slurry storage against the total biomethane potential at 35°C (i.e. the conceptual proportion of the B_0 consumed at that point). Therefore, just as B_0 reports the quantity of CH_4 produced per kg of VS (i.e. all fractions, degradable and non-degradable), the concept of "VS Consumed" removes all fractions of VS from storage. This approach is convenient because it uses the B_0 as the integrator of all fractions of VS degradability, and reports the total methane produced from all fractions as if they were incubated for infinite time, while the *f* parameter introduces a temperature dependence. Though this is convenient for modelling, and is consistent with the B_0, this does not represent the physical reality of the liquid/slurry storage. (2) Since "VS Consumed" does not equate with the amount of VS degraded in the storage, the "VS available" does equate with the amount of VS that would actually be measured in a storage. Therefore, researchers should not attempt to compare measured VS with "VS available". (3) The strength of this approach is its simplicity and the fact that the maximum amount of methane that can be produced is equal to the total VS produced multiplied by the B_0. In other words, the model cannot produce more methane than the B_0. (4) The MCF is the ratio of predicted "VS Consumed" to the total VS that entered the storage over one year. The method does not address VS destruction. If the "VS Consumed" were multiplied by B' (m^3 CH_4/kg VS destroyed), the result be would be erroneous because "VS Consumed" is not VS Destroyed. This is not to say that B' cannot be used to model methane production, but simply that it is not compatible with the "VS Consumed" concept. (5) Although B_0 does not need to enter the MCF calculation, the role of B_0 is to be multiplied by the MCF, as stated in equation 10.23 of the *IPCC 2006 Guidelines* and this *2019 Refinement*.

Annex 10A.4 Calculations of Methane Conversion Factors (MCFs) for biogas systems

MCFs for the biogas digester

Biogas digesters are an important manure management systems. There are different types of biogas digesters, including centralised biogas digester plants, animal farm based biogas digesters, and digesters that co-digest animal manures and organic residues. Some biogas digesters such as farm based biogas digesters may include prestorage, like pit storage below animal confinement, or outdoor storage. Co-digestion may include energy crops, and/or different types of organic waste in varying combinations.

Default MCFs of biogas digesters are provided in Table 10.17 and Table 10A.11.

MCFs depend on the amount of B_0 that is realised under on farm conditions and on the amount of produced biogas that leakes from the biogas plant either during storage or energy production. Calculations to identify default factors were carried out by varying the level of leakage from the biogas installations. Calculations are based on a modification of the default values in Table 10.17 and Table 10A.11using the equation defined in Haenel *et al*. (2018).

TABLE 10A.11 (NEW)
METHANE CONVERSION FACTOR (MCF_{DG}) INCLUDING BIOGAS DIGESTER AND DIGESTATE STORAGE[1]

Biogas digester quality	Storage gastight level	Climate Zone		
		cold	temperate	warm
high quality biogas digester, Ldig=0.01	High quality gastight storage, $L_{sto,gt}$ =0.01	1.00%	1.00%	1.00%
	Low quality gastight storage, $L_{sto,gt}$ =0.1	1.41%	1.41%	1.41%
	Open storage, $L_{sto,gt}$=1	3.55%	4.38%	4.59%
	Average	1.99%	2.27%	2.33%
low quality biogas digester, Ldig=0.1	High quality gastight storage, $L_{sto,gt}$=0.01	9.59%	9.59%	9.59%
	Low quality gastight storage, $L_{sto,gt}$ =0.1	10.00%	10.00%	10.00%
	Open storage, $L_{sto,gt}$ =1	12.14%	12.97%	13.17%
	Average	10.58%	10.85%	10.92%

[1] the value of MCF for digestate storage (MCF_{ngts}) is based on the MCF value of anaerobic lagoon.

Methane emissions from biogas digesters include the unused biogas (can be defined as leakage) and emissions from storage of the digestate. The MCF calculation from biogas digesters should be based on the following equation (Haenel *et al*. 2018):

EQUATION 10A.1 (NEW)
CALCULATION OF MCF FOR THE COMBINATION "DIGESTER + DIGESTATE STORAGE"

$$MCF_{dg} = \frac{v_{CH_4,prod} - v_{CH_4,used} - v_{CH_4,\ flared} + MCF_{residues} \bullet \left(B_0 - v_{CH_4,prod}\right)}{B_0}$$

Where:

MCF_{dg} = effective methane conversion factor for the combination "digester + digestate storage", percent

$v_{CH_4,prod}$ = specific volume of methane produced in the digester (related to VS input), m^3 CH_4 kg^{-1} VS

$v_{CH_4,used}$ = specific volume of methane used for energy production (related to VS input), m^3 CH_4 kg^{-1} VS

$v_{CH_4,\ flared}$ = specific volume of methane flared (related to VS input), m^3 CH_4 kg^{-1}VS

$MCF_{residues}$ = methane conversion factor for the storage of digested manure, percent

B_0 = maximum methane producing capacity per kg of VS input T, m^3 CH_4 kg^{-1} of VS excreted

In practice, the residence time necessary to fully exploit the maximum methane producing capacity B_0 is not fully reached in the gas collection system. In the following, the difference, i.e. the potentially still purgeable amount of gas ($B_0 - v_{CH_4,prod}$), is denoted as "potential of residual gas" that is assumed to be known, and the ratio of which to B_0 is described by the entity μ_{rg}:

EQUATION 10A.2 (NEW)
CALCULATION OF RELATIVE AMOUNT OF POTENTIAL OFF GAS RELATED TO B_0

$$\mu_{rg} = \frac{B_0 - v_{CH_4,prod}}{B_0}$$

Where:

μ_{rg} = relative amount of residual gas related to B_0 (with $0 \leq \mu_{rg} \leq 1$ m^3 m^{-3})

B_0 = maximum methane producing capacity per kg of VS, m^3 CH_4 kg^{-1} VS

$v_{CH_4,prod}$ = specific volume of methane produced in the digester (related to VS input), m^3 CH_4 kg^{-1} VS

In practice, the amount of residual gas, μ_{rg} is not given as a share of the maximum methane producing capacity B_0, but as a share of the amount of gas usable for energy production. Hence, a new entity v_{rg} can be defined which is closely related to μ_{rg} .

The μ_{rg} can be calculated as follows:

EQUATION 10A.3 (NEW)
CALCULATION OF RELATIVE AMOUNT OF RESIDUAL GAS RELATED TO B_0

$$\mu_{rg} = \frac{v_{rg}}{1 + v_{rg}}$$

Where:

μ_{rg} = relative amount of residual gas related to B_0 (with $0 \leq \mu_{rg} \leq 1$ m^3 m^{-3})

v_{rg} = relative amount of residual gas related to $v_{CH4,prod}$ (with $0 \leq v_{rg} \leq 1$ m^3 m^{-3})

EQUATION 10A.4 (NEW)
CALCULATION OF RELATIVE AMOUNT OF RESIDUAL GAS RELATED TO CH_4 PRODUCTION

$$v_{rg} = \frac{B_0 - v_{CH_4,prod}}{v_{CH_4,prod}}$$

Where:

v_{rg} = relative amount of residual gas related to $v_{CH4,prod}$ (with $0 \leq v_{rg} \leq 1$ m^3 m^{-3})

B_0 = maximum methane producing capacity per kg of VS, m^3 CH_4 kg^{-1}VS

$v_{CH_4,prod}$ = specific volume of methane produced in the digester (related to VS input), m^3 CH_4 kg^{-1}VS

The term $v_{CH_4,prod} - v_{CH_4,used} - v_{CH_4,\ flared}$ in equation 10A.1 is part of the digester's methane balance (related to VS input) which can be completed by the methane loss $v_{CH_4,leak}$ due to leakage.

EQUATION 10A.5 (NEW)
DIGESTER'S METHANE BALANCE

$$v_{CH_4,prod} - v_{CH_4,used} - v_{CH_4,\ flared} - v_{CH_4,leak} = 0$$

Where:

$v_{CH_4,prod}$ = specific volume of methane produced in the digester (related to VS input), m^3 CH_4 kg^{-1} VS

$v_{CH_4,used}$ = specific volume of methane used for energy production (related to VS input), m^3 CH_4 kg^{-1} VS

$v_{CH_4,\ flared}$ = specific volume of methane flared (related to VS input), m^3 CH_4 kg^{-1}VS

$v_{CH_4,leak}$ = specific volume of methane due to leakage and maintenance works (related to VS input), m^3 CH_4 kg^{-1} VS

The loss of methane $v_{CH_4,leak}$ due to leakage is calculated as part of the total amount of CH_4 produced in the digester. The ratio of these two quantities is defined as the leakage rate L_{dig} of the digester. L_{dig} is assumed to be known.

EQUATION 10A.6 (NEW)
CALCULATION OF METHANE LEAKAGE RATE OF DIGESTER

$$v_{CH4,leak} = L_{dig} \bullet v_{CH4,prod}$$

Where:

$v_{CH_4,leak}$ = specific volume of methane due to leakage and maintenance works (related to VS input), m^3 CH_4 kg^{-1} VS

L_{dig} = leakage rate of the digester, related to $v_{CH4,prod}$ (with $0 \leq L_{dig} \leq 1$ m^3 m^{-3}).

$v_{CH_4,prod}$ = specific volume of methane produced in the digester (related to VS input), m^3 CH_4 kg^{-1} VS

In order to give the effective methane conversion factor of the combination, "digester + digestate storage" as a function of the three parameters, "relative amount of residual gas", "leakage rate" and "MCF of the digestate storage", the methane conversion factor of the combination, "digester + digestate storage" can be calculated as follows (Equation 10A.7):

EQUATION 10A.7 (NEW)
CALCULATION OF METHANE CONVERSION FACTOR

$$MCF_{dg} = \left(1 - \mu_{rg}\right) \bullet L_{dig} + \mu_{rg} \bullet MCF_{residues}$$

Where:

MCF_{dg} = effective methane conversion factor for the combination "digester + digestate storage", percent

μ_{rg} = relative amount of residual gas related to B_0 (with $0 \leq \mu_{rg} \leq 1$ m^3 m^{-3})

L_{dig} = leakage rate of the digester, related to $v_{CH4,prod}$ (with $0 \leq L_{dig} \leq 1$ m^3 m^{-3})

$MCF_{residues}$ = methane conversion factor for the storage of digested manure, percent

For the factors of L_{dig} and μ_{rg} it is recommended to use country-specific data; if country specific data are unavailable. the following procedure is recommended: For high quality biogas digesters, the default L_{dig} is recommended to be 0.01 (Rösemann *et al*. 2017); for low quality biogas digesters, L_{dig} = 0.1 is recommended (Table 10A-4 to Table 10A-9 *2006 IPCC Guidelines*). The value of 0.046 is used for µrg based on Haenel *et al*. (2018) The values presented in Table 10A.11 are derived using Equation 10A.7 and the values cited here. Pre-storage loss estimates are not included as no default values can be identified from the literature. Also, it is assumed that these losses will be low as they represent economic losses due to lower biogas production. However equations are included below if compilers wish to adapt their emission estimates to country-specific circumstances.

It is assumed that even a gastight storage of digestate has a certain leakage. This leakage rate is described by the storage-specific leakage rate $L_{sto,gt}$. Taking into account the leakage rate and the relative share of gastight storage of digestate x_{gts} , the $MCF_{residues}$ can be calculated following Equation 10A.8:

EQUATION 10A.8 (NEW)
CALCULATION OF METHANE CONVERSION FACTOR OF RESIDUES

$$MCF_{residues} = x_{gts} \bullet L_{sto,gt} + \left(1 - \frac{x_{gts}}{100}\right) \bullet MCF_{ngts}$$

Where:

$MCF_{residues}$ = methane conversion factor for the storage of digestate, percent

x_{gts} = share of gastight storage of the digestate, percent

$L_{sto,gt}$ = leakage rate of the gastight storage (with $0 \leq L_{sto,gt} \leq 1$ m^3 m^{-3}). For high quality gastight storage of the digestate $L_{sto,gt}$ is assumed to be 0.01 m^3 m^{-3}. For low quality gastight storage of the digestate, $L_{sto,gt}$ is assumed to be 0.1 m^3 m^{-3}. For open storage of the digestate, $L_{sto,gt}$ is assumed to be 1.0 m^3 m^{-3}

MCF_{ngts} = methane conversion factor for the non-gastight storage of digestate, percent. It is assumed that MCF_{ngts} is same to the storage of raw manure.

Biogas plants that are fed with animal manures have, as a rule, a pre-storage for the feedstock before it enters the digester. The CH_4 losses from the pre-storage reduce the CH_4 production potential in the digester and the storage of the digestate. This could be taken into account by modifying equations 10A.7. As a consequence Equation (10A.7) is transformed to the MCF_{dg+ps} equation as Equation 10A.9.

EQUATION 10A.9 (NEW)
CALCULATION OF METHANE CONVERSION FACTOR FOR THE COMBINATION "PRESTORAGE + DIGESTER + DIGESTATE STORAGE"

$$MCF_{dg+ps} = MCF_{ps} + \left(1 - MCF_{ps}\right) \bullet MCF_{dg}$$
$$= MCF_{ps} + (1 - MCF_{ps}) \bullet [(1 - \mu_{rg}) \bullet L_{dig} + \mu_{rg} \bullet MCF_{residues}]$$

Where:

MCF_{dg+ps} = effective methane conversion factor for the combination "prestorage + digester +digestate storage", percent

MCF_{ps} = methane conversion factor for prestorage, percent; Table 10.17 provides the default values for different prestorage systems

MCF_{dg} = methane conversion factor for combination "digester+digestate storage", percent, see above

μ_{rg} = relative amount of residual gas related to B_0 (with $0 \leq \mu_{rg} \leq 1$ m^3 m^{-3})

L_{dig} = leakage rate of the digester, related to $\nu_{CH4,prod}$ (with $0 \leq L_{dig} \leq 1$ m^3 m^{-3})

$MCF_{residues}$ = methane conversion factor for the storage of digestate (in m^3 m^{-3}).

Annex 10A.5 Equations relating all direct and indirect N_2O emissions from manure along all stages in agricultural production for livestock

As explained in section 10.5.6, nitrogen excreted by animals contributes to several direct and indirect N_2O emission as it cascades through livestock and crop cultivation systems. It is therefore crucial to accurately estimate nitrogen excretion rates. The total direct and indirect N_2O emissions associated with the excretion of nitrogen of an animal type is an important quantity to assess the benefit from improving the estimation of the N-excretion coefficient for that animal type. However, the total direct and indirect N_2O emissions from animal excretion cannot be easily estimated using the equations given in Chapter 10 and 11 of the *2006 IPCC Guidelines* and this *2019 Refinement*. This annex provides a set of equations, based on the equations given in Chapter 10 and 11, that allows the quantification of total direct and indirect N_2O emissions from nitrogen excretion of each animal type *T*. They are reported in Equations 10A.10 through 10A27.

The definition of the symbols used in the set of equations is given below Equation 10A.27, grouped by symbols. Note that for internal consistency, the symbol *N* is used for all nitrogen flows in kg N animal^{-1} yr^{-1}; the symbol *F* is used for all animal-independent nitrogen flows or nitrogen flows for the total animal population in kg N yr^{-1}; the symbol *Frac* is used for all fractions in kg N (kg N)$^{-1}$ or percent, the symbol *EF* is used for all N_2O emission factors in kg N_2O-N (kg N)$^{-1}$, and the symbol N_2O is used for all N_2O emissions in kg N_2O-N yr^{-1} . Not in all cases therefore, the symbols are identical to those used in the Equations given in Chapters 10 and 11.

EQUATION 10A.10 (NEW)
TOTAL N_2O EMISSIONS FOR ANIMAL TYPE *T*

$$N_2O_{(T)} = N_2O_{mm(T)} + N_2O_{AM(T)} + N_2O_{PRP(T)}$$

EQUATIONS 10A.11 AND 10A.12 (NEW)
TOTAL N_2O EMISSIONS FROM MANURE MANAGEMENT FOR ANIMAL TYPE *T*

$$N_2O_{(mm,T)} = N_2O_{D(mm,T)} + N_2O_{G(mm,T)} + N_2O_{L(mm,T)}$$

$$N_2O_{mm(T)} = \left(\sum_S F_{mm(T,S)} \bullet \left[EF_{3(S)} + \left(Frac_{GasMS} \right)_{(T,S)} \bullet EF_4 + \left(Frac_{LeachMS} \right)_{(T,S)} \bullet EF_5 \right] \right) \bullet \frac{44}{28}$$

EQUATIONS 10A.13 THROUGH 10A.14 (NEW)
TOTAL, DIRECT AND INDIRECT N_2O EMISSIONS FROM THE APPLICATION OF MANURE TO MANAGED SOILS FOR ANIMAL TYPE *T*

$$N_2O_{AM(T)} = N_2O_{D,AM(T)} + N_2O_{I,AM(T)}$$

$$N_2O_{D,AM(T)} = F_{AM(T)} \bullet \left[\left(1 - Frac_{AM,Rice} \right) \bullet EF_1 + Frac_{AM,Rice} \bullet EF_{1FR} \right] \bullet \frac{44}{28}$$

$$N_2O_{I,AM(T)} = F_{AM(T)} \bullet \left[Frac_{GASM} \bullet EF_4 + Frac_{LEACH-(H)} \bullet EF_5 \right] \bullet \frac{44}{28}$$

EQUATION 10A.15 (NEW)
TOTAL AMOUNT OF ANIMAL MANURE N APPLIED TO SOILS OTHER THAN BY GRAZING ANIMALS FOR ANIMAL TYPE *T*

$$F_{AM(T)} = \left\{ \sum_{S} \left[\left(F_{mm(T,S)} \bullet \left(1 - Frac_{LossMS}\right)_{(T,S)} \right) + F_{bedding(T,S)} \right] + F_{codigestate} \right\} \bullet Frac_{APPL(T)}$$

EQUATION 10A.16 (NEW)
FRACTION OF TOTAL ANIMAL MANURE N LOST IN MANURE MANAGEMENT SYSTEMS FOR ANIMAL TYPE *T*

$$Frac_{LossMS(T,S)} = Frac_{GASMS(T,S)} + Frac_{LEACHMS(T,S)} + Frac_{N_2MS(S)} + EF_{3(S)}$$

EQUATION 10A.17 (NEW)
FRACTION OF ANIMAL MANURE N AVAILABLE FOR APPLICATION TO MANAGED SOILS, APPLIED TO MANAGED SOILS FOR ANIMAL TYPE *T*

$$Frac_{APPL(T)} = 1 - \left(Frac_{FEED(T)} + Frac_{FUEL(T)} + Frac_{CNST(T)} \right)$$

EQUATION 10A.18 THROUGH 10A.19 (NEW)
TOTAL, DIRECT AND INDIRECT N_2O EMISSIONS FROM N IN URINE AND DUNG DEPOSITED BY GRAZING ANIMALS ON PASTURE, RANGE AND PADDOCK (TIER 1) FOR ANIMAL TYPE *T*

$$N_2O_{PRP(T)} = N_2O_{D,PRP(T)} + N_2O_{I,PRP(T)}$$

$$N_2O_{D,PRP(T)} = \left[\left(F_{PRP,CPP(T)} \bullet EF_{3PRP,CPP} \right) + \left(F_{PRP,SO(T)} \bullet EF_{3PRP,SO} \right) \right] \bullet \frac{44}{28}$$

$$N_2O_{I,RPR(T)} = F_{RPR(T)} \bullet \left[Frac_{GASM} \bullet EF_4 + Frac_{LEACH-(H)} \bullet EF_5 \right] \bullet \frac{44}{28}$$

EQUATION 10A.20 (NEW)
RELATIONSHIP BETWEEN AVERAGE ANNUAL NITROGEN FLOWS ASSOCIATED WITH AN INDIVIDUAL ANIMAL [KG N ANIMAL^{-1} YR^{-1}] AND THE ANNUAL NITROGEN FLOW FOR THE ANIMAL POPULATION OF LIVESTOCK CATEGORY/SPECIES *T* IN A COUNTRY [KG N YR^{-1}]

$$F = POP_{(T)} \bullet N$$

EQUATION 10A.21 (NEW)
TOTAL MANURE-N EXCRETED

$$N_{(T)} = N_{MMS(T)} + N_{PRP(T)}$$

EQUATION 10A.22 AND 10A.23 (NEW)
NITROGEN EXCRETION CALCULATED EITHER USING A DEFAULT FRACTION OF RETENTION (TIER 1) OR DIRECTLY FROM RETENTION DATA

$$Nex_{(T)} = N_{intake(T)} \bullet \left(1 - Frac_{RET(T)}\right)$$

$$Nex_{(T)} = N_{\text{int}ake(T)} - N_{RET(T)}$$

EQUATION 10A.24 (NEW)
TOTAL MANURE-N IN MANURE MANAGEMENT SYSTEMS

$$N_{MMS(T)} = \sum_{S} \left(POP_{(T)} \bullet Nex_{(T)} \bullet Frac_{S(T,S)} \right)$$

EQUATION 10A.25 (NEW)
MANURE-N MANAGED IN SYSTEM *S*

$$N_{mm\,(T,S)} = POP_{(T)} \bullet Nex_{(T)} \bullet Frac_{S(T,S)}$$

EQUATION 10A.26 (NEW)
MANURE-N DEPOSITED BY GRAZING ANIMALS, WITH X=CPP,SO

$$N_{PRP(X)} = POP_{(X)} \bullet Nex_{(X)} \bullet Frac_{S(X,G)}$$

EQUATION 10A.27 (NEW)
N IN BEDDING MATERIAL ADDED TO MANAGED MANURE

$$N_{bedding(T,S)} = POP_{(T)} \bullet N_{beddingMS(T,S)}$$

Where,

$POP_{(T)}$ = number of head of livestock species/category *T* in the country, heads

Annual total nitrogen flows, F, and annual average nitrogen flows per head, N:

$F_{(T)}$ and $N_{(T)}$ = animal manure nitrogen excreted for livestock species/category *T* in the country, kg N yr^{-1} and kg N $animal^{-1}$ yr^{-1}

$F_{codigestate}$ = amount of nitrogen from co-digestates added to biogas plants, kg N yr^{-1}

$F_{MMS(T)}$ and $N_{MMS(T)}$ = animal manure nitrogen excreted for livestock species/category *T* in manure management systems in the country, kg N yr^{-1} and kg N $animal^{-1}$ yr^{-1}

$F_{PRP(T)}$ and $N_{PRP(T)}$ = animal manure nitrogen excreted for livestock species/category *T* on pasture, range and paddock in the country, kg N yr^{-1} and kg N $animal^{-1}$ yr^{-1}

$F_{PRP,CPP(T)}$ and $N_{PRP,CPP(T)}$ = animal manure nitrogen excreted for cattle, pig and poultry species/category *T* on pasture, range and paddock in the country, kg N yr^{-1} and kg N $animal^{-1}$ yr^{-1}

$F_{PRP,SO(T)}$ and $N_{PRP,SO(T)}$ = total animal manure nitrogen excreted for sheep and other livestock species/category *T* on pasture, range and paddock in the country, kg N yr^{-1} and kg N $animal^{-1}$ yr^{-1}

$F_{mm(T,S)}$ and $N_{mm(T,S)}$ = animal manure nitrogen excreted for livestock species/category *T* in manure management system *S* in the country, kg N yr^{-1} and kg N $animal^{-1}$ yr^{-1}

$F_{bedding(T,S)}$ and $N_{bedding(T,S)}$ = nitrogen in bedding material added for livestock species/category *T* in manure management system *S* in the country, kg N yr^{-1} and kg N in bedding $animal^{-1}$ yr^{-1}

$F_{AM(T,S)}$ and $N_{AM(T,S)}$ = annual amount of animal manure N applied to soils for each livestock species/category *T*, kg N yr^{-1} and kg N $animal^{-1}$ yr^{-1}

$F_{intake(T)}$ and $N_{intake(T)}$ = annual intake of N in feed for each livestock species/category *T*, kg N yr^{-1} and kg N $animal^{-1}$ yr^{-1}

$F_{retention(T)}$ and $N_{retention(T)}$ = annual retention of N each livestock species/category *T*, kg N yr^{-1} and kg N $animal^{-1}$ yr^{-1}

$F_{ex(T)}$ and $N_{ex(T)}$ = annual average N excretion of species/category *T* in the country, kg N yr^{-1} and kg N $animal^{-1}$ yr^{-1}

Annual N_2O emissions for the total population of each livestock species/category T

$N_2O_{(T)}$ = total annual N_2O emissions

$N_2O_{mm(T)}$ = total annual N_2O emissions from Manure Management for each livestock species/category *T* in the country, kg N_2O yr^{-1}

$N_2O_{D,mm(T)}$ = direct annual N_2O emissions from Manure Management for each livestock species/category *T* in the country, kg N_2O yr^{-1}

$N_2O_{G,mm(T)}$ = indirect annual N_2O emissions from volatilization of NH_3+NO_x from Manure Management for each livestock species/category *T* in the country, kg N_2O yr^{-1}

$N_2O_{L,mm(T)}$ = indirect annual N_2O emissions from leaching and run-off from Manure Management for each livestock species/category *T* in the country, kg N_2O yr^{-1}

$N_2O_{AM(T)}$ = total annual N_2O emissions from manure nitrogen applied to cultivated soils for each livestock species/category *T*, kg N_2O yr^{-1}

$N_2O_{PRP(T)}$ = total annual N_2O emissions from manure nitrogen deposited on pasture, range and paddock for each livestock species/category *T*, kg N_2O yr^{-1}

$N_2O_{D,AM(T)}$ = direct annual N_2O emissions from manure nitrogen applied to cultivated soils for each livestock species/category *T* in the country, kg N_2O yr^{-1}

$N_2O_{I,AM(T)}$ = indirect annual N_2O emissions from manure nitrogen applied to cultivated soils for each livestock species/category *T* in the country, kg N_2O yr^{-1}

$N_2O_{D,PRP(T)}$ = direct annual N_2O emissions from pasture, range and paddock for each livestock species/category *T* in the country, kg N_2O yr^{-1}

$N_2O_{I,PRP(T)}$ = indirect annual N_2O emissions from pasture, range and paddock for each livestock species/category *T* in the country, kg N_2O yr^{-1}

N_2O emission factors

EF_1 = emission factor for direct N_2O emissions from N inputs to cultivated soils, kg N_2O –N (kg N input)$^{-1}$

EF_{1FR} = emission factor for direct N_2O emissions from N inputs to flooded rice, kg N_2O –N (kg N input)$^{-1}$

$EF_{3PRP,X}$ = emission factor for direct N_2O emissions from urine and dung N deposited on pasture, range and paddock by grazing animals, kg N_2O –N (kg N input)$^{-1}$; X=CPP: Cattle, Poultry and Pigs; X=SO: Sheep and Other animals

$EF_{3(S)}$ = emission factor for direct N_2O emissions from manure management system *S* in the country, kg N_2O -N/(kg N in manure management system *S*)$^{-1}$

EF_4 = emission factor for N_2O emissions from atmospheric deposition of nitrogen on soils and water surfaces, kg N_2O -N (kg NH_3-N + NOx-N volatilised)$^{-1}$

EF_5 = emission factor for N_2O emissions from nitrogen leaching and runoff, kg N_2O -N (kg N leached and runoff)$^{-1}$

Fractions

$Frac_{S(T,S)}$ = fraction of manure N excreted that is managed in manure management system *S* for each livestock species/category *T*, dimensionless

$Frac_{S(X,G)}$ = fraction of manure N excreted that is deposited by grazing cattle, poultry or pigs (X=CPP) or sheep or other animals (X=SO), dimensionless

$Frac_{GasMS(T,S)}$ = fraction of managed manure nitrogen for livestock species/category *T* that volatilises as NH_3 and NOx in the manure management system *S*

$Frac_{LeachMS(T,S)}$ = fraction of managed manure nitrogen losses for livestock species/category *T* due to runoff and leaching during solid and liquid storage of manure in manure management system *S*

$Frac_{N_2MS}$ = fraction of managed manure nitrogen for each livestock species/category *T* that is lost in the manure management system *S*, percent as N_2

$Frac_{LossMS(T,S)}$ = total fraction of managed manure nitrogen for livestock category *T* that is lost in the manure management system *S*

$Frac_{GASM(T,S)}$ = fraction of applied organic N fertiliser materials (F_{ON}) and of urine and dung N deposited by grazing animals (F_{PRP}) that volatilises as NH_3 and NOx, kg N volatilised (kg of N applied or deposited)$^{-1}$

$Frac_{LEACH-(H)}$ = fraction of all N added to/mineralised in managed soils in regions where leaching/runoff occurs that is lost through leaching and runoff, kg N (kg of N additions)$^{-1}$

$Frac_{APPL(T)}$ = fraction of animal manure N available for application to managed soils which is applied to managed soils for each livestock species/category *T*, dimensionless

$Frac_{FEED(T)}$ = fraction of managed manure used for feed for each livestock species/category *T*, dimensionless

$Frac_{FUEL(T)}$ = fraction of animal manure N available for application to managed soils used for fuel for each livestock species/category *T*, dimensionless

$Frac_{CNST(T)}$ = fraction of animal manure N available for application to managed soils used for construction for each livestock species/category *T*, dimensionless

$Frac_{AM,Rice}$ = fraction of animal manure N applied to managed soils which is applied to flooded rice, dimensionless

$Frac_{RET}$ = fraction of feed intake N that is retained by the animal in body mass or livestock products for each livestock species/category *T*, dimensionless

Annex 10.B Data and Explanatory Text for Development of New Parameters in the *2019 Refinement*

10B.1 Raw data used to compile Annex 10A.1 enteric fermentation Tier 1 emission factors, volatile solids and nitrogen excretion for cattle and buffalo

A database was compiled from peer-reviewed articles, scientific and statistical reports found via a comprehensive literature search in google scholar (https://scholar.google.com) and Elsevier (www.sciencedirect.com) web search engines.

All raw data collected from literature sources and used as a basis by the IPCC authors to refine the final values presented in Tables 10A.1–10A.4 are available in the supplemental data supplied with this Chapter, maintained on the IPCC document website, there identified as Supplemental Information Chapter 10, Volume IV, *2019 Refinement*.

Since agricultural production systems of certain countries may be transitioning from low productivity local subsistence systems to higher productivity systems, the IPCC expert team of the *2019 Refinement* aimed to collect from a variety of literature sources published to date and report the final data differentiated by production system and performance parameters on cattle (dairy and non-dairy) and buffaloes for each world region.

It should be noted that the IPCC expert team assumed that such regions as North America, Western and Eastern Europe, and Oceania may be defined as regions where only high-production systems are in practice. However, Latin America, Asia, Africa, Middle East and Indian subcontinent experience transition period from low productivity local subsistence systems to higher productivity systems, hence, data on performance parameters and feeding situations of cattle and buffaloes reared in the two production systems were recorded by the IPCC expert team.

Moreover, the IPCC expert team of the *2019 Refinement* updated regional representation in Tables 10A.1–10A.4. The *2006 IPCC Guidelines* contain data aggregated performance parameters and enteric fermentation emission factors (EFs) for Africa and Middle East, however, values of nitrogen excretion rate (Nex) were presented separately for these regions, i.e. for Africa and Middle East. Hence, the IPCC expert team improved consistency in the reporting, and the team collected raw data and conducted the estimation of enteric fermentation EFs, Volatile solids (VS) and Nex rates for Africa and Middle East, separately, for the both productivity systems.

In addition, the IPCC expert team updated the representation of non-dairy cattle and buffalo sub-categories. Namely, the *2006 IPCC Guidelines* contain data on performance parameters, diets and feeding situations, and corresponding EFs, VS and Nex for three main sub-categories of non-dairy cattle (i.e., mature females, mature males and young), the 2019 *Refinement* contains data and corresponding EFs, VS and Nex for four main sub-categories: mature females, mature males, replacement and growing animals, and calves.

The majority of values determining performance parameters, diets and feeding situations in different regions of the world were updated by the IPCC expert team in the *2019 Refinement*. Namely:

To develop region-average performance parameters, diets and feeding situations of dairy and non-dairy cattle for *North America*, 12 peer-reviewed publications were examined by the IPCC expert team (Appuhamy *et al*. 2016; Basarab *et al*. 2005; Capper 2011; Dong *et al*. 2014; Jayasundara *et al*. 2016; Legesse *et al*. 2016; Mulliniks *et al*. 2017; Niu *et al*. 2018; Ominski *et al*. 2007; Sheppard *et al*. 2015; Stackhouse-Lawson *et al*. 2012; Waldrip *et al*. 2013). Final values relied on the expert judgement and consensus of the authoring team.

To update performance parameters, diets and feeding situation of dairy and non-dairy cattle reared in *Western Europe*, 7 peer-reviewed publications were examined by the IPCC expert team (Bannink *et al*. 2011; *Bannink et al*. 2016; FAO 2017; Gerrits *et al*. 2014; Hammond *et al*. 2016; Huuskonen 2017; Spek *et al*. 2013). Data determining diets and feeding situations for dairy and non-dairy cattle of Western Europe were updated; all performance parameters, with exception of milk yield per head of dairy cow, were carried over from the *2006 IPCC Guidelines*.

To deliver the regional-average final value on performance parameters, diets and feeding situation of dairy and non-dairy cattle of *Oceania*, 10 data sources were examined by the IPCC expert team (studies and datasets of statistical offices) were examined by the IPCC expert team (Australian Government Department of Climate Change 2006; Dairy Technical Working Group 2015; Fick 2016; Pickering & Wear 2013; Statistics NZ 2018a; Australian Bureau of Agricultural and Resource Economics and Sciences 2018; Dairy Australia 2018; Dairy NZ & LIC 2018; Statistics NZ 2018b). The final values (reported in Table 10A.1 and Table 10A.2) were refined based

on data collected for Australia and New Zealand. Hence, the IPCC expert team encourages small Pacific Island nations to use enteric fermentation EFs, VS and Nex rates developed for Asian region, as productivity systems are more similar.

Overall, 35 data sources (scientific publications and statistical datasets) were examined by the IPCC expert team to obtain raw data on performance parameters, diets and feeding situations required to develop region-average final values for dairy and non-dairy cattle reared in *Eastern Europe* (Amerkhanov *et al*. 2016; Azaubaeva 2008; Bakharev 2012; Dunin *et al*. 2011; FAOSTAT 2017; Furaeva 2013; Gayirbegov & Mandjiev 2013; Golubkov 2015; Golubkov *et al*. 2015; Goncharova & Kibkalo 2011; Goncharova *et al*. 2009; Gren 2013; Gubaidullin *et al*. 2011; Haysanov 2011; Ilichev *et al*. 2011; IPCC 2006; Kalnickij & Haritonov 2008; Kostenko & Pyrozhenko 2012; Leontev *et al*. 2013; Levakhin *et al*. 2011; Litovchenko 2012; Mamaev *et al*. 2017; Nekrasov *et al*. 2013; Nosyreva Yu & Tokareva 2014; Pracht 2013; RUSSTAT 2016; Samorukov *et al*. 2013a; Samorukov *et al*. 2013b; Sharkaev & Kochetkov 2012; Sharkaeva 2012; Sharkaeva 2013; Sheveleva & Bakharev 2013; Shevkhuzhev *et al*. 2015; Tekeev & Chomaev 2011; Zadnepryanskiy & Zakirko 2012). Since Russian Federation, Ukraine and Belarus have the largest herd among other Eastern European countries (FAOSTAT 2017), the IPCC expert team focused mainly on the analysis of cattle management practice of these countries. Initial data for other Eastern European countries were taken from GLEAM model (FAO 2017). To make adjustment regarding the region-average final values reported in Table 10A.1 and Table 10A.2, the IPCC expert team considered the contribution of each country to the total dairy and non-dairy cattle population of Eastern Europe and corresponding parameters.

Raw data on cattle performance parameters, diets and feeding situations were distinguished between two production systems (i.e. low and high) of *Latin America* and collected by the IPCC expert team respectively. In total, 52 publications were examined by the IPCC expert team (Albarrán-Portillo *et al*. 2015; Albertini *et al*. 2012; Amaral *et al*. 2005; Ancco 2015; Ministerio de Ganadería 2017; Barajas Merchan *et al*. 2017; Barrantes 2000; Bartl *et al*. 2009; IPCC 2006; IBGE 2017; Becoña 2012; Ítavo *et al*. 2014; Cândido *et al*. 2015; Cardoso *et al*. 2017b; Castro *et al*. 2012; Chavez 2010; Ciudad de México Financiera Rural 2009; Cunha *et al*. 2016; Euclides & Medeiros 2003; FAO 2017; Huhn *et al*. 1982; Ítavo *et al*. 2014; Kolling *et al*. 2018; Lima *et al*. 2018; Machado Filho *et al*. 2014; Mariani *et al*. 2009; Mata e Silva *et al*. 2017; McManus *et al*. 2011; Medeiros *et al*. 2010; Modernel *et al*. 2013; Oliveira *et al*. 2014; Pajuelo Montalvo 2003; Pajuelo Montalvo 2008; Peres *et al*. 2012; Primavesi *et al*. 2004; Queiroz *et al*. 2011; Quispe *et al*. 2016; Reis 1998; Restle *et al*. 2003; Ribeiro *et al*. 2016; Rodriguez 2018; Rojas & Gómez 2005; Rosa *et al*. 2001; Ruiz & Sandoval 2014; Santos *et al*. 2011; Sgroi 2017; Silva *et al*. 2017; Simões *et al*. 2009; Teixeira *et al*. 2013; Teodoro & Madalena 2002; Teodoro & Madalena 2005; Verruma & Salgado 1994). Moreover, to clarify some parameters, the IPCC expert team conducted interviews with lead researchers of Latin America, namely: Sebastián Galbusera (Argentina); Dr. Pablo Soca, Faculty of Agronomy (Uruguay); Santiago Fariña, Dirceto of the Dairy Redearch Progmaram. National Institute of Agricultural Research (Uruguay); Dr. Laura Astigarraga, Faculty of Agronomy (Uruguay); Dr. Luiz Gustavo Ribeiro Pereira (Embrapa Dairy Cattle, Brazil); Dr. Pablo Soca, Faculty of Agronomy (Brazil). It should be noted that these above-listed publications were sources for initial data mostly for non-dairy cattle reared in Brazil, Uruguay, Peru and Argentina, and for dairy cattle husbandry practice applied in Brazil. However, initial data on performance parameters, diets and feeding situations applied for dairy cattle of other countries of Latin America were obtained from GLEAM model (FAO 2017). To adjust the final values recorded in Table 10A.1 and Table 10A.3, the dairy and non-dairy cattle population kept in each country of Latin America was taken into consideration by the IPCC expert team.

Performance parameters, diet and feeding situation of dairy and non-dairy cattle of the whole *Asian region* for low- and high-productivity systems were refined based on detailed data obtained from 50 publications (Alejandrino *et al*. 1999; Zi *et al*. 2003; Sutarno 2015; Hieu Vu *et al*. 2016; Widiawati *et al*. 2016; Gunawan & Jakaria 2011; Lapitan *et al*. 2008; Ramírez-Restrepo *et al*. 2017; Martojo 2012; Philippines Statistics Authority 2017; Moran 2012; Thanh 2014; Ichinohe *et al*. 2014; Dinh 2007; Department of Veterinary Services 2013; Panandam & Raymond 2005; Lam 2011; Gioi *et al*. 2012; Ariff *et al*. 2015; Waldron *et al*. 2015; Putra *et al*. 2015; Garcia *et al*. 2006; Zhai *et al*. 2006; FAO *et al*. 2014; Gerber *et al*. 2011; Xie *et al*. 2016; Cui *et al*. 2014; Yang *et al*. 2013; Xue *et al*. 2014; Dong *et al*. 2015; Zi *et al*. 2003; Huai *et al*. 1993; Ma *et al*. 2007; Ma *et al*. 2012; Wattiaux *et al*. 2002; Zhou 1998; Beldman *et al*. 2014; Xie *et al*. 2012b; Qiao *et al*. 2013; Dong *et al*. 2017; Han *et al*. 2016; Wang *et al*. 2014; Taneja 1999; FAO 2003; Wang *et al*. 2017; MAAR 2013; Hu & Zhang 2003; Gao *et al*. 2011; Cheng 1984; Gao *et al*. 2013). Raw data were obtained from the literature sources to determine parameters corresponding to low- and high-producing systems. Performance parameters of dairy and non-dairy cattle and their feeding systems were investigated for the following countries: China, Indonesia, Malaysia, Philippines and Vietnam. Moreover, the data of GLEAM model (FAO 2017) were used in a greater degree. A contribution of each country to the total cattle population of Asian region was considered by the IPCC expert team to adjust final values reported in Table 10A.1 and Table 10A.3.

Data on performance parameters, diets and feeding situations of dairy cattle reared in low- and high-productivity systems of *African region* were directly obtained from GLEAM model (FAO 2017). The model contains a compherensive dataset for the both types of productivity system applied in Kenya, Ethiopia, Uganda, Tanzania.

Moreover, performance parameters, diet and feeding situation of non-dairy cattle reared in the both productivity systems of African region were obtained as results of the analysis of 101 scientific articles and statistical reports (Abdel Rahman 2007; Abdelhadi & Babiker 2009; Abera 2016; Abraha *et al*. 2009; Addisu *et al*. 2010; Adebambo 2001; Adesina 2012; Ageeb & Hillers 1991; Ahamefule *et al*. 2007; Ahmed & Zubeir 2013; Ahmed Hassan 2010; Alemayehu *et al*. 2013; Ali *et al*. 2015; Alsiddig *et al*. 2010; Asimwe *et al*. 2015; Bashir & El Zubeir 2013; Bayemi *et al*. 2005; Behnke & Osman 2012; Blench 1999; Central Statistical Agency 2017; Chabo *et al*. 2003; Corbet *et al*. 2006; Dekeba *et al*. 2006; Du Toit *et al*. 2013; Edea *et al*. 2013; Elrshied & Ishag 2015; Engida *et al*. 2015; Essien 2003; Ethiopia F.D.R. 2011; FAO 2017; FAO & IAEA 2011; FAOSTAT 2017; Farmer & Mbwika 2012; Gebre Mariam *et al*. 2013; Goopy *et al*. 2018; Groeneveld *et al*. 1998; Gwaza & Momoh 2016; Haile *et al*. 2011; Halala 2015; Haren & Idris 2015; Ilatsia *et al*. 2011; International Livestock Centre for Africa 1977; Ismail *et al*. 2014; Kahi *et al*. 2006; Kanai & Zagi 2013; Kashoma *et al*. 2011; Kouazounde *et al*. 2015; Kubkomawa 2017; Kurwijila & Bennett 2011; Lukuyu *et al*. 2012; Lukuyu *et al*. 2016; Mai *et al*. 2012; Mandefro *et al*. 2017; Mapiye *et al*. 2011; Masama *et al*. 2003; Mekonnen *et al*. 2012; Ministry of Livestock and Fisheries Development of Tanzania 2014; Ministry of Livestock and Fisheries Development of Tanzania 2015; Mlote 2013; Mpofu 1996; Msanga *et al*. 2012; Muhuyi *et al*. 1999; Muriuki 2011; Musa *et al*. 2011; Mwambene *et al*. 2012; Mwambene *et al*. 2014; Mwanyumba *et al*. 2015; Myburgh *et al*. 2012; Nell 2006; Nell *et al*. 2014; Nouala *et al*. 2003; Nweze *et al*. 2012; Olorunnisomo 2013; Onono *et al*. 2013; Osman 1985; Pico 2004; Rakwadi *et al*. 2016; Raphaka 2008; Rege 1999; Rewe *et al*. 2006; Said *et al*. 2003; Salako 2014; Scholtz & Theunissen 2010; Shirima *et al*. 2016; Shittu *et al*. 2008; Siegmund-Schultze *et al*. 2012; Statistics Botswana 2016; Stein *et al*. 2009; Strous 2010; Strydom 2008; Strydom *et al*. 2000; Strydom *et al*. 2008; Tefera 2013; Tegegne *et al*. 2013; Temoso *et al*. 2016; Tesfa *et al*. 2016; Theunissen *et al*. 2013; Wurzinger *et al*. 2006; Young *et al*. 2005; Yousif & El- Moula 2006; Zerabruk & Vangen 2005). In addition to a rich dataset developed for low- and high-productivity systems, total population of non-dairy cattle of African region and contribution of the non-dairy population reared in each African country to the total (FAOSTAT (2017) was taken into consideration by the IPCC expert team to determine the final values on performance parameters, diet and feeding situation representative for the whole African region.

Overall, 24 publications were examined by the IPCC expert team to obtain raw data on performance parameters, diets and feeding situations of dairy and non-dairy cattle reared in low- and high-productivity systems of *Middle East* (Akbaş *et al*. 2006; Turkish Statistical Institute 2017; Karakok 2007; CBAT 2017; Chashnidel *et al*. 2007; da Cunha *et al*. 2010; Sadeghi-Sefidmazgi *et al*. 2012; FAO *et al*. 2014; Fatahnia *et al*. 2010; Gerber *et al*. 2011; IPCC 2006; Kamalzadeh *et al*. 2008; Kara *et al*. 2014; Karakok 2007; Koçyiğit *et al*. 2014; MFAL 2011; Sadeghi-Sefidmazgi *et al*. 2012; Statistical Centre of Iran 2011; Tasdemir *et al*. 2011; Ula 2016; USDA 2015; *Ustuner et al*. 2016; Özlütürk *et al*. 2006; Yalcin *et al*. 2017; Yilmaz *et al*. 2012). Due to an extend of contribution to the total dairy and non-dairy cattle population of Middle East, the focus of the IPCC expert team was made to investigate dairy and non-dairy cattle management practice applied in Turkey and Iran. The raw data obtained from literature sources for these two countries were adjusted to be a basis to evaluate the final values on performance parameters, diets and feeding situations representative for low- and high-productivity systems of the whole Middle East region.

Raw data on performance parameters, diets and feeding situations of low- and high-productivity systems applied for dairy and non-dairy cattle in *Indian subcontinent* were derived as a result of the analysis of 47 publications (Ahmad *et al*. 2004; Ahmad *et al*. 2013; Birthal & Parthasarathy Rao 2002; Boro *et al*. 2016; Bradfield & Ismail 2012; Chowdhry 2007; da Cunha *et al*. 2010; Department of Animal Husbandry 2013; Deshetti *et al*. 2016; Dhingra *et al*. 2017; FAO 2017; FAO *et al*. 2014; Garg *et al*. 2013; Gerber *et al*. 2011; IPCC 2006; Jabbar *et al*. 2009; Kayastha *et al*. 2008; Kenyanjui *et al*. 2009; Khan 2011; Khan *et al*. 2008; Khan *et al*. 2009; Khan *et al*. 2016; Landes *et al*. 2017; Mahakur *et al*. 2017a; Mahakur *et al*. 2017b; Manoj 2009; Moaeen-ud-Din & Bilal 2017; Nahar *et al*. 2016; National Bureau of Animal Genetic Resources 2017; Pathak *et al*. 2013; Patra 2012; Rahman *et al*. 2012; Rahman *et al*. 2015; Roy *et al*. 2016; Saha *et al*. 2004; Saha *et al*. 2012; Sambhaji 2013; Sarkar *et al*. 2006; Sharma *et al*. 2014; Singhal *et al*. 2005; Sirohi *et al*. 2012; Sodhi *et al*. 2007; Sontakke *et al*. 2014; Thombre *et al*. 2015; Tomar & Sharma 2002; Yadava 2009; Yasothai 2014). Taking into consideration, the largest contribution of cattle population of India, Pakistan and Bangladesh to the total dairy and non-dairy cattle population of the region, the main focus of the IPCC expert team was to collect and investigate low-productivity and high-productivity cattle farming of these countries. The final values reported in Table 10A.1 and Table 10A.3 were refined by the IPCC expert team based on consensus and were used to conduct estimations of enteric fermentation EFs, VS and Nex rates for dairy and non-dairy cattle in low- and high-productivity systems of Indian subcontinent.

Data to complete calculations of enteric fermentation emission factors, VS and nitrogen excretion rates for buffaloes were significantly updated in the *2019 Refinement* in comparison with the information reported in the *2006 IPCC Guidelines*. Namely, the *2006 IPCC Guidelines* report the initial data employed and corresponding EFs for two main regions: Indian subcontinent and Other regions. The IPCC expert team of the *2019 Refinement* extended regional representation and collected data for the same regions, which were applied to present EFs of cattle. Hence, data on buffalo performance parameters, diets and feeding situation for Western Europe, Eastern Europe, Latin America, Asia, Africa and Middle East were developed and reported in addition to presented dataset developed for Indian subcontinent. North America and Oceania were omitted from the reporting as according to

the data presented in (FAOSTAT 2017), the regions do not have any buffalo husbandry practice. Moreover, region-average final values on performance parameters, diets and feeding situations were reported for four buffalo subcategories for all regions: mature males, mature females, growing and replacing animals and calves. The only exception was made for Indian subcontinent, where the final values were presented for five subcategories: breeding mature males, working mature males, mature females, growing and replacing animals and calves.

The IPCC expert team has decided not to distinguish performance parameter values, diets and feeding situation between low productivity and high-productivity systems implemented in buffalo husbandry across the world regions as it was conducted for dairy and non-dairy cattle, but to collect and report region-average values.

Overall, eight peer-reviewed publications were examined by the IPCC expert team to deliver performance parameters, diets and feeding situation of buffaloes kept in *Western Europe* (Borghese 2013; Condor *et al*. 2008; FAO 2005; FAO 2017; Gonzalez Gonzalez 2011; IPCC 2006; Neglia *et al*. 2014; Sabia *et al*. 2014; Zicarelli *et al*. 2007). Since Italy is a main contributor to the total buffalo population of Western Europe (FAOSTAT 2017), the buffalo husbandry practice of Italy was considered to be a representative for the whole Western Europe. However, data on buffalo performance parameters of Germany and Greece were also taken into consideration to adjust final values reported in Table 10A.4. The calculation of enteric fermentation EFs, VS and Nex rates were conducted based on Tier 2 method of the *2019 Refinement*.

To deliver data on performance parameters, diet characterisation and feeding situation of buffaloes of *Eastern Europe*, the focus in the research completed by the IPCC expert team was mainly made on investigation of buffalo husbandry implemented in Bulgaria and Romania. In total, 11 publications (i.e. case studies and statistical reports) were examined to complete a dataset needed to compute enteric fermentation EFs, VS and Nex rates (*Atanasov et al*. 2012; Borghese 2013; Dimov & Tzankova 2003; FAO 2005; FAOSTAT 2017; IPCC 2006; MZH 2016; MZH 2017; Nikolov 2011; Peeva *et al*. 2011; Peeva *et al*. 2013; Tzankova & Dimov 2003).

To develop a dataset on performance parameters, diets and feeding situation representing buffalo husbandry practice of *Latin America*, overall 25 studies were examined by the IPCC expert team (Andrade & Garcia 2005; Andrighetto *et al*. 2003; Andrighetto *et al*. 2003; Bailone *et al*. 2017; Cardoso *et al*. 1997; Cardoso *et al*. 2017a; Coelho *et al*. 2004; Damé *et al*. 2010; dos Santos *et al*. 2016; Gonçalves 2008; Jorge 2005; Jorge *et al*. 2002; Lima *et al*. 2014; Macedo *et al*. 2001; Maeda *et al*. 2007; Oliveira *et al*. 2009; Rassi *et al*. 2009; Rezende *et al*. 2017; Rodrigues *et al*. 2001; Sales *et al*. 2018; Santos *et al*. 2014; Zeoula *et al*. 2014; Tonhati *et al*. 2000; Tonhati *et al*. 2009; Verruma & Salgado 1994). Moreover, the IPCC expert team organized interviews with top researchers in this area to specify the findings and to cover lacking information from the scientific publications (Cristiana Andrighetto (UNESP-Dracena); Dr. José Ribamar Felipe Marques (Embrapa Amazônia Oriental)). In general, the final values recorded in Table 10A.4 for Latin America represent mainly characteristics of buffalo herd of Brazil, as the investigation of buffalo performance parameters reared in other countries of Latin America was not conducted by the IPCC expert team.

Overall, 42 publications (case studies and statistical reports) were examined by the IPCC expert team to derive raw data on buffalo performance parameters, diets and feeding situation of *Asian region* (Abd El-Salam & El-Shibiny 2011; Batosarnma 2006; Berthouly 2008; Carabao situation report 2017; Chang & Huang 2003; Cruz 2007; Cruz 2010; Cruz 2012; Das *et al*. 2004; Deb *et al*. 2016; Djaja 2011; Djajanegara & Diwyanto 2002; FAO 2003; FAO 2017; Flores *et al*. 2007; Han *et al*. 2007; Huai & Jun 1995; Kusnadi & Praharani 2009; Lambertz *et al*. 2014; Li *et al*. 2018a; Loculan 2002; Meyer *et al*. 2000; Mingala *et al*. 2017; Nanda & Nakao 2003; Nha *et al*. 2008; Phomsouvanh 2002; Prabowo 2012; Premasundera 2002; Qin *et al*. 2013; Qingkun *et al*. 2002; Riedel *et al*. 2012; Sanh 2007; Sivarajasingam 1987; Skunmun *et al*. 2002; Somapala 2002; Suryanto *et al*. 2002; Taneja 1999; Tuyen 2009; Van Sanh 2007; Wanapat & Rowlinson 2007; Yang *et al*. 2007; Yang *et al*. 2013a). The detailed analysis of buffalo husbandry practice applied in China, Indonesia, Laos, Philippines, Sri Lanka, Thailand and Vietnam was conducted to underlay for adjustment, based on consensus of the authoring team, of the final values of Table 10A.4.

According to the data reported (FAOSTAT 2017), only Egypt has population of domesticated buffaloes among other African counties. Hence, to deliver data on performance parameters, diets and feeding situation employed to compute enteric fermentation EFs, VS and Nex rates for buffaloes reared in *African region*, 22 publications determining Egyptian buffalo husbandry practice was examined by the IPCC expert team (Abd-Allah *et al*. 2015; Ali *et al*. 2009; Asheeri & Amal 2012; Ashour *et al*. 2007; Habeeb *et al*. 2016; FAO 2005; FAO *et al*. 2014; FAOSTAT 2017; Gerber *et al*. 2011; Habeeb *et al*. 2016; Hassan & Abdel-Raheem 2013; Ibrahim 2012; Ibrahim 2012; IPCC 2006; Khattab *et al*. 2011; Marai *et al*. 2001; Marai *et al*. 2009; Morsy *et al*. 2016; Presicce 2011; Radwan 2016; Shahin *et al*. 2010; Soliman 2009; WAAP 2007). Data on buffalo for other African countries were omitted from the analysis, the final values reported in Table 10A.4 and used in the calculations are relied on the expert judgement and consensus of the authoring team.

The analysis of 27 publications (case studies and statistical reports) resulted in evaluation of the region-average final values on performance parameters, diets and feeding situation of buffaloes husbandry for *Middle East* (Azary

et al. 2007; Turkish Statistical Institute 2017; Çelikeloğlu *et al*. 2015; Chashnidel *et al*. 2007; DAD-IS 2017; Dezfuli 2010; Dezfuli *et al*. 2011; FAO 2017; FAO *et al*. 2014; FAOSTAT 2017; Gerber *et al*. 2011; GLEAM FAO 2017; Hossein-zadeh *et al*. 2012; IPCC 2006; Işik & Gül 2016; Jaayid *et al*. 2011; Mahmoudzadeh & Fazaeli 2009; Mahmoudzadeh *et al*. 2007; Manafiazar *et al*. 2007; Naserian & Saremi 2007; Porter *et al*. 2016; Şekerden 2013; Soysal 2013; Soysal *et al*. 2005; Tariq *et al*. 2013; Turkish Statistical Institute 2017; Yavuz & Zulauf 2004). Due to the availability and representation of publications, the focus of the IPCC expert team was mostly made on buffaloes reared in Tukey and Iran, the data collected for these countries were considered as a basis to made adjustment regarding region-average final values for Middle East reported in Table 10A.4.

To deliver initial data required to calculate enteric fermentation EFs, VS and Nex rates for buffaloes reared in *Indian subcontintent*, 37 publications (case studies and statistical reports) were examined by the IPCC expert team (Afzal *et al*. 2009; AGRI-IS 2017; Anitha *et al*. 2011; Anjum *et al*. 2012a; Anjum *et al*. 2012b; Basra & Nisa 2003; Breeding survey book 2013; Dahiya & Singh 2013; Dhingra *et al*. 2017; FAO 2017; FAO *et al*. 2014; FAOSTAT 2017; FICCI 2014; Gami *et al*. 2017; Garg *et al*. 2018; Gerber *et al*. 2011; Gupta *et al*. 2016; IPCC 2006; Jabbar *et al*. 2009; Jha *et al*. 2011; Khan *et al*. 2008; Khan *et al*. 2010; Khare & Baghel 2010; Kumar & Dass 2006; Kumar *et al*. 2011; Pathak 2005; Patra 2012; Prusty *et al*. 2016; Ranjhan 2007; Shahzad *et al*. 2011; Shekhar *et al*. 2010; Singal 2001; Singh 2002; Singh *et al*. 2012; Singh *et al*. 2015; Singh *et al*. 2017; Tariq *et al*. 2013; Tauqir *et al*. 2011). Data on performance parameters, diets and feeding situation of different breeds of buffaloes in India and Pakistan were adjusted to make the expert decision on the final values reported in Table 10A.4 and to conduct the calculations.

10B.2 Estimation of Cattle/Buffalo CH_4 conversion factors (Y_m)

Dairy Y_ms were developed considering summary statistics from the database consisting of results from 3,353 cows used in Niu *et al*. (2018) (Table 10B.1(New)) as well as data synthesis presented in the articles of Appuhamy *et al.* (2016), Hellwing *et al.* (2016) and Jayasundera *et al.* (2016). It was noted by the IPCC panel that these studies were not representative of global dairy systems and for that reason simple means developed through statistical analyses were deemed not to be reliable. Final values relied on the expert judgement and consensus of the authoring team. The summary statistics from Niu *et al.* (2018) are presented below (Table 10B.1), dividing that large data set into high, medium and low levels of milk productivity.

In the case of all productivity systems, clear differences were identified between the North American and the European feeding and production systems. The strongest contrasting factor was the proportion of neutral detergent fibre (NDF) in the diets of the two regions. Based on these summary statistics the Y_m is clearly driven by the relationship with NDF within the two regional production categories (Figure 10B.1).

To provide additional guidance for the selection of the methane conversion rates, NDF thresholds were established (Table 10B.1). For the highest production categories based on the North American and European statistics a low NDF <35 percent DMI and a high NDF >35 percent DMI categories were developed with values equivalent to 5.7 and 6.0 percent GEI respectively.

In the case of the values for the mid-range productivity, the value of 6.3 was determined assuming that NDF values were greater than 37 percent DMI as the values for medium and low producing animals from North America could not be considered to be representative of low production and lower quality diets. For countries that can clearly demonstrate that the NDF of their feed has been greater than 37 percent DMI, it is recommended to use the high production value that corresponds to the NDF content of the feed.

For low-productivity, the unweighted mean value of 6.5 from the European and North American data, consistent with the *2006 IPCC Guidelines* was selected. The panel did not consider that there was reliable data to modify the value from the *2006 IPCC Guidelines* value considering the very wide variety of diets that could be occurring globally for low productivity dairy cattle. However, it is proposed in the text that if dairy cattle are fed mainly on low quality forages countries are recommended to use the non dairy forage diet Y_m of 7.0.

Figure 10B.1 (New) **Relationships between mean and median neutral detergent fibre (NDF) and methane conversion rate (Y_m) from summary statistics of Niu *et al.* (2018).**

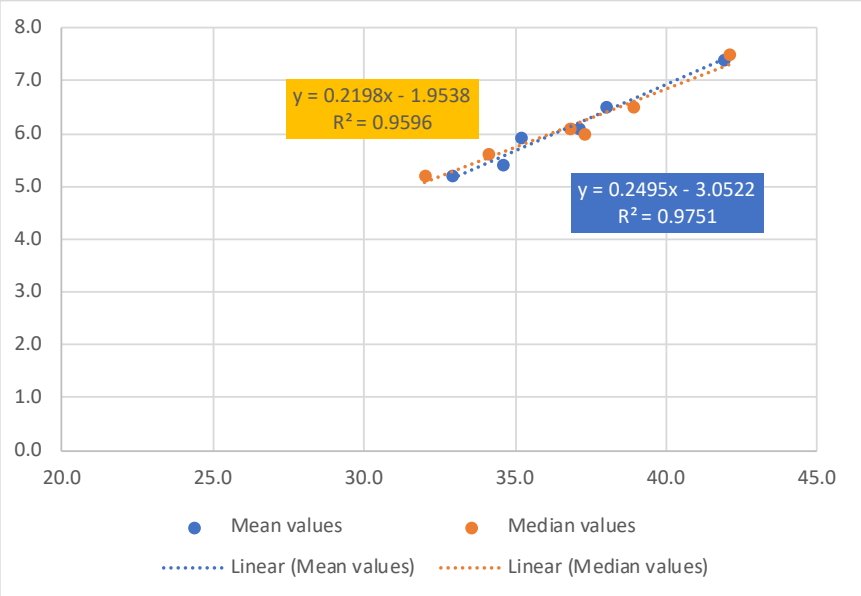


TABLE 10B.1 (NEW)
SUMMARY STATISTICS FROM NIU *ET AL.* (2018) DATABASE

Annual milk production grouping	All data			Europe			North America		
	<5000	5000-8500	>8500	<5000	5000-8500	>8500	<5000	5000-8500	>8500
Y_m median (%GEI)	6.3	6.0	5.7	7.3	6.4	6.0	5.9	5.5	5.2
Y_m mean (%GEI)	6.2	5.9	5.7	7.1	6.4	6.1	5.8	5.3	5.2
Y_m SD (%GEI)	1.3	1.2	1.1	1.0	1.1	0.9	1.2	1.1	1.04
Y_m unweighted mean (%GEI)	6.5	5.9	5.7	NA					
Annual milk production median (kg)	3,809	6,784	10,511	4,192	6,884	10,184	3,716	6,667	11,018
Annual milk production mean (kg)	3,619	6,783	10,840	4,036	6,849	10,538	3,483	6,709	11,245
Annual milk production SD (kg)	988	980	1706	740	965	1603	1,034	995	1,757
NDF median (%DM)	38	37	35	41	39	37	35	34	32
NDF mean (%DM)	37	37	35	41	38	37	34	35	33
NDF SD (%DM)	8.3	7.7	5.5	6.5	8.0	4.9	8.0	7.0	5.2
EE median (%DM)	2.8	3.0	3.9	3.5	3.4	3.9	2.5	2.7	3.8
EE mean (%DM)	2.9	3.2	3.8	3.4	3.4	3.9	2.6	2.9	3.8
EE SD (%DM)	0.8	1.0	1.1	0.7	0.9	1.0	0.8	1.2	1.2
Number of cows	551	1,392	1,410	165	814	805	326	556	604

Note: EE refers to ether extract an analytical method to estimate dietary fats and fatty acids

TABLE 10B.2 (NEW)
THRESHOLD CALCULATION BASED ON NDF CORRECTION

NDF	Mean	Median
32	5.08	4.93
33	5.30	5.18
34	5.52	5.43
35	**5.74**	**5.68**
36	5.96	5.93
37	**6.18**	**6.18**
38	**6.40**	**6.43**
39	6.62	6.68
40	6.84	6.93

In the case of beef cattle, a total of 113 measurements were compiled from 35 studies. Studies were divided by their dominant diet type into three categories, high forage diets, mixed diets (mixed forage and concentrate) and feedlot diets. Summary statistics were compiled and group averages are reported. Due to the variability in the data, values were rounded based on expert judgement. An overall average was developed for the feedlot and non-feedlot diets. Non feedlot diets were differentiated between dominantly forage based diets and mixed concentrate diets.

There is important variability in the results of studies that attempt to develop relationships between feed quality and methane yield. Nonetheless, numerous empirical and biochemical modelling studies demonstrate both the statistical significance and the biochemical processes that relate reductions in methane production with the introduction of concentrates to ruminant diets (Mills *et al.* 2001; Mills *et al.* 2003; Ellis *et al.* 2006; Ellis *et al.* 2007; Ellis *et al.* 2009; Ellis *et al.* 2010; Alemu *et al.* 2011; Bannink *et al.* 2011; Ellis *et al.* 2014; Escobar-Bahamondes *et al.* 2016; Kebreab *et al.* 2016). For this reason, methane conversion rates are produced from a summary of low, medium and high dietary forage proportions. Raw data used in the development of these values are published in the IPCC TFI website.

TABLE 10B.3 (NEW)
SUMMARY OF DATA COMPILED FOR THE COMPILATION OF Y_M VALUES FOR CATTLE AND BUFFALO

Category	Measurement method	Average Body Weight (kg)	Methane yield (g/kg DMI)	SD (±)	Y_m (% GEI)	SD (±)	n
High forage	Chambers (24), SF_6 (30), Micro-meteorological (2)	451	23.0	4.6	7.2[1]	1.5	56
Intermediate forage	Chambers (17), SF_6 (7)	401	21.0	3.8	6.3	1.2	24
Feedlot (low forage)	Chambers (11), SF_6 (5), Head boxes (17)	450	12.99	3.3	3.84[2]	1.0	33

Boadi and Wittenberg (2002); Pinares-Patiño *et al.* (2003); Boadi *et al.* (2004); Beauchemin and McGinn (2005); Beauchemin and McGinn (2006a); Beauchemin and McGinn (2006b); Chaves *et al.* (2006); Doreau *et al.* (2011); Jordan *et al.* (2006a); Jordan *et al.* (2006b); Lovett *et al.* (2003); Beauchemin *et al.* (2007); Hegarty *et al.* (2007); Hart *et al.* (2009); McGinn *et al.* (2009); Mc Geough *et al.* (2010a); Mc Geough *et al.* (2010b); Doreau *et al.* (2011); Hales *et al.* (2012); Kennedy and Charmley (2012); Staerfl *et al.* (2012); Chung *et al.* (2013); Hünerberg *et al.* (2013a); Hünerberg *et al.* (2013b); Fiorentini *et al.* (2014); Hales *et al.* (2014); Hales *et al.* (2015); Romero-Perez *et al.* (2014); Troy *et al.* (2015); Romero-Perez *et al.* (2015); Nascimento *et al.* (2016); Vyas *et al.* (2016a); Vyas *et al.* (2016b); Baron *et al.* (2017); Hales *et al.* (2017).

[1] Rounded to 7.0 for Table 10.12.

[2] Rounded to 4.0 for Table 10.12.

10B.3 Estimation of Default Emission Factor(s) based on Goat Tier 2 parameters

A database was compiled from peer-reviewed articles that studied in-vivo methane (CH_4) production from goat enteric fermentation and N excretion. These studies were identified through a comprehensive literature search performed in Google scholar and ResearchGate and from sources that carried out review work such as a recent study attempting to derive statistical models for prediction of enteric CH_4 from goats (Patra & Lalhriatpuii 2016) and a New Zealand technical report for CH_4 and N excretion rates for goats (Lassey 2012). Data were directly extracted from the individual studies identified. Authors were contacted in order to fill in gaps of information from the studies.

Overall, 63 publications were obtained from a varied sample of countries and 18 different goat breeds (Aguilera *et al*. 1990; Prieto *et al*. 1990; Shibata *et al*. 1992; Haque *et al*. 1997; AFRC 1998; Haque *et al*. 1998; Islam *et al*. 2000; Islam *et al*. 2001; Rapetti *et al*. 2002; Puchala *et al*. 2005; Rapetti *et al*. 2005; Tovar-Luna *et al*. 2007b; Tovar-Luna *et al*. 2007c; Tovar-Luna *et al*. 2007a; Animut *et al*. 2008; Bhatta *et al*. 2008; Haque *et al*. 2008; Vermorel *et al*. 2008; Li *et al*. 2010; López *et al*. 2010a; López *et al*. 2010b; Tovar-Luna *et al*. 2010b; Tovar-Luna *et al*. 2010a; Gerber *et al*. 2011; López *et al*. 2011; Tovar-Luna *et al*. 2011; Abecia *et al*. 2012; Jeong *et al*. 2012; Lassey 2012; López *et al*. 2012; Mitsumori *et al*. 2012; Puchala *et al*. 2012a; Puchala *et al*. 2012b; Romero-Huelva *et al*. 2012; Yang *et al*. 2012; Bhatta *et al*. 2013; Chethan *et al*. 2013; López & Fernández 2013; Martínez-Fernández *et al*. 2013; Miri *et al*. 2013; López *et al*. 2014; Martínez-Fernández *et al*. 2014; Nielsen *et al*. 2014; Romero-Huelva & Molina-Alcaide 2014; Ibáñez *et al*. 2015a; Ibáñez *et al*. 2015b; Lu *et al*. 2015; Wang & Xue 2015; Arif *et al*. 2016; Castro-Lima *et al*. 2016; Criscioni & Fernández 2016; Lu *et al*. 2016; Patra & Lalhriatpuii 2016; Wang *et al*. 2016a; Wang *et al*. 2016b; Arco-Pérez *et al*. 2017; Barbosa *et al*. 2017; Keli *et al*. 2017; Kumar *et al*. 2017; Na *et al*. 2017; Romero-Huelva *et al*. 2017; Tovar-Luna *et al*. 2017; Azlan *et al*. 2018; Fernández *et al*. 2018; Li *et al*. 2018b; Na *et al*. 2018a; Na *et al*. 2018b; Puchala *et al*. 2018).

Although there was a total of 290 treatment means, treatments that were using substances with antimethanogenic properties were excluded before analysis. The minimum prerequisite for a study to be included in the data set was that Y_m values (or gross energy and CH_4 output energy) were reported.

Information on feed and diet characteristics, feed intake, breed, animal type, digestibility, and rumen were collected in the final data set. Table 10B.4 shows the mean and the range of some of the diet and animal variables for the different studies. Values were quite heterogeneous. For example, dry matter intake ranged between 0.14 and 2.51 kg DM intake/day animal (0.93 on average).

The concentrations of crude protein (CP), neutral detergent fibre (NDF) and starch were within the range of 6-26 percent (mean value of 15 percent), 18-74 percent (mean value of 42 percent) and 1-42 percent (mean value of 19 percent), respectively.

Methane production was expressed as grams per day, liters per day, megajoules per day, or as a proportion of GE or DE; therefore, the following factors were used in converting units: 1 g = 1.40 L =55.5 kJ; 1 L = 0.716 g = 39.54 kJ.

TABLE 10B.4 (NEW)
MEAN, MEDIAN, MAXIMUM, MINIMUM AND QUARTILE 1 AND 3 (Q1 AND Q3) VALUES FOR A SELECTION FEED DIET COMPOSITION, FEED INTAKE, BODY WEIGHT AND MILK PRODUCTIVITY

	Digestibility (%)					Feed intake			Body weight	Milk yield
	DM	OM	N	NDF	GE	DM (kg/day)	GE (MJ/day)	DE (MJ/day)	kg/animal	(kg/day animal)
Mean	68%	69%	72%	54%	71%	0.94	18.77	12.18	39.82	1.90
Median	69%	71%	73%	53%	72%	0.78	15.20	9.44	40.05	1.59
Max	83%	91%	84%	82%	83%	2.59	46.68	29.90	64.00	3.69
Min	49%	40%	44%	18%	52%	0.14	4.64	6.02	14.53	0.81
Q1	64%	65%	67%	46%	67%	0.62	11.80	8.44	33.45	1.31
Q3	74%	76%	78%	60%	76%	1.14	26.12	11.09	47.55	2.28

The CH_4 emissions also varied greatly in the dataset. Table 10B.5 shows the methane emissions expressed in different units and metrics.

TABLE 10B.5 (NEW)
MEAN, MEDIAN, MAXIMUM, MINIMUM AND QUARTILE 1 AND 3 (Q1 AND Q3) VALUES FOR CH_4 PRODUCTION RESULTS REFERRED AS A PROPORTION OF GROSS ENERGY INTAKE (CH_4 CONVERSION FACTOR: Y_M), DAY^{-1}, KG DM $INTAKE^{-1}$, KG OF MILK $PRODUCED^{-1}$ AND KG OF BODY $WEIGHT^{-1}$

	CH_4				
	Y_m	***MJ/day***	***MJ/kg DM***	***MJ/kg milk***	***J/kg BW***
Mean value	5.3%	0.9	1.0	0.8	23.1
Median	5.3%	0.8	1.0	0.8	20.5
Max	10.3%	3.8	4.7	1.7	73.6
Min	1.2%	0.2	0.3	0.2	5.3
Q1	4.3%	0.6	0.8	0.6	15.8
Q3	6.3%	1.0	1.2	1.1	27.4

The average methane emission was 16.2 g CH_4/animal day, 18.3 g CH_4/kg DM intake, 0.42 g CH_4/ kg BW (*data not shown*). Average/median methane conversion factor (Y_m) was 5.3 percent, which is in the range of the recent value obtained by the study by Patra & Lalhriatpuii (2016), which included 42 studies.

We analyzed the relationship between methane output and diet type (e.g. diet digestibility, percent forage use) but there were no any clear statistical relationships between diet type and enteric methane output (*data not shown*). In general increased body weight and milk yield resulted in greater CH_4 output but body weight and milk yield did not show any statistical relationship with Y_m (*data not shown*).
Methane output per animal was positively correlated with dry matter (Fig 10B.2) and gross energy (Fig 10B.3) intake (R^2=0.60; P<0.00001).

Figure 10B.2 (New) Annual enteric methane output per animal expressed in mass in relation to daily dry matter (DM) intake.

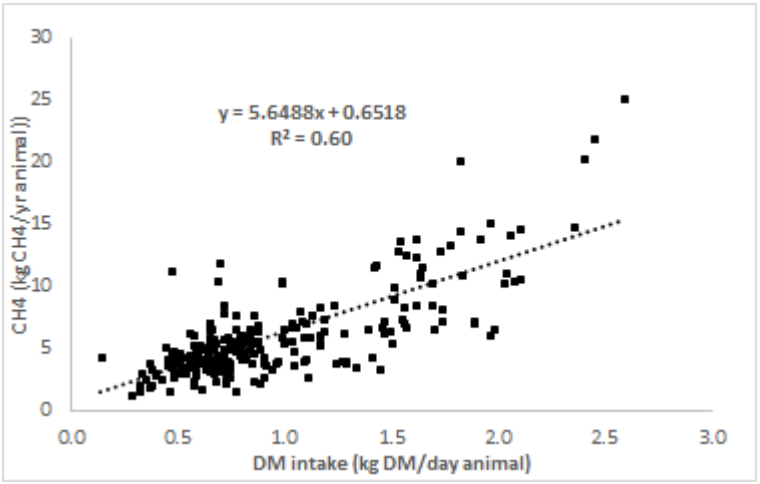
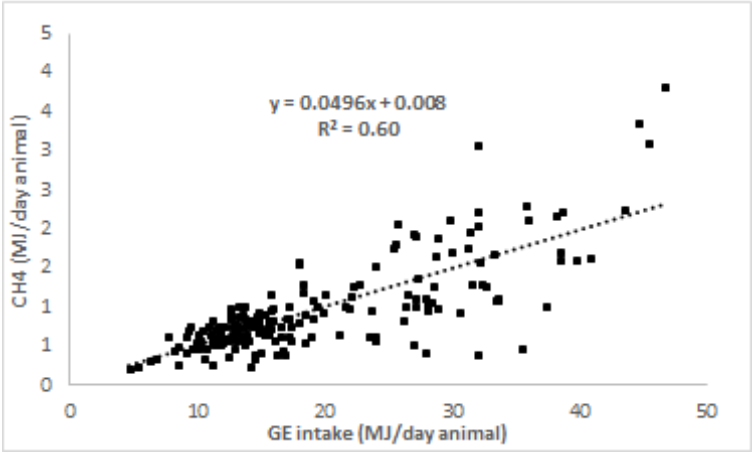


Figure 10B.3 (New) Daily enteric methane output per animal expressed in energy in relation to daily gross energy (GE) intake.



In order to develop Tier 1 EF for enteric CH_4 from goats for both low and high production systems the following steps were followed:

- Average goat weight (LW) for high and low production systems were estimated using global world information from Gerber *et al*. (2013). For high and low production systems it was estimated average weight values of 50 kg and 28 kg, respectively.
- Daily dry matter intake per animal was estimated as a function of animal weight using the equation from AFRC (1998).
- Using the equation from Fig 10B.2 we obtained kg CH_4/animal yr as a function of the previously estimated value of daily dry matter intake.

EF for Tier 1 resulted in 8.7 and 4.9 kg CH_4/head yr for high and low production systems, respectively. These values are both lower than those estimated in Vermorel *et al.* (2008) from French systems (11.9 kg CH_4/head yr^{-1}) and that for high production systems is similar to that proposed by Lassey (2012) for New Zealand goat herd.

Considering the data analysed, a Y_m of 5.5 percent has been chosen. No clear evidence was found to develop Y_m factors separately as a function of diet quality or production system.

In order to develop default values for N excretion rates (for Table 10.19) the following steps were followed:

Average goat weight (LW) for each global region were estimated using global world information from GLEAM FAO.

Daily N intake per animal and day was estimated as a function of average goat weight using the relationship developed from this database relating goat weight and N intake (Fig 10B.4) (R^2=0.48; P<0.00001).

Daily N excretion rate was subsequently calculated using the relationship also found using this database relating daily N intake and daily N excretion (Fig 10B.5) (R^2=0.89; P<0.00001) and transforming values to excretion rates espressed as kg N $(1000 \text{ kg animal mass})^{-1}$) day^{-1}.

Figure 10B.4 (New) Daily N intake per animal expressed in relation to animal weight.

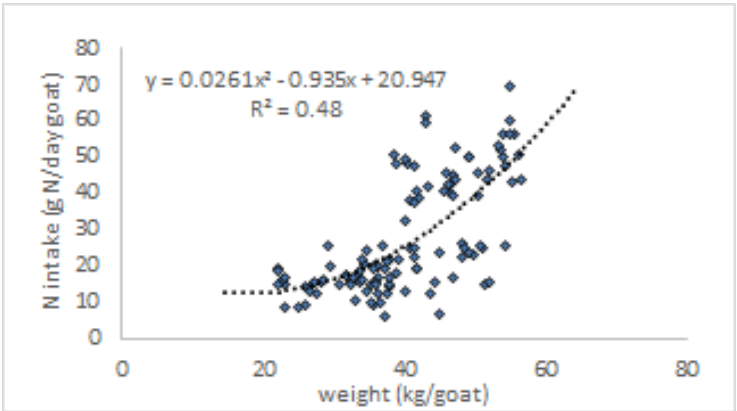
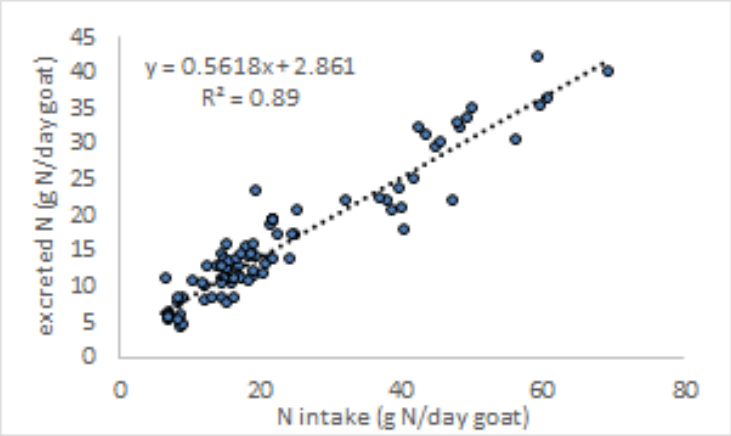


Figure 10B.5 (New) **Daily N excretion output per animal expressed in relation to daily N intake.**



In order to develop default values for volatile solids (VS) excretion rates (for Table 10.14A) we calculated daily VS excretion from goats for each world region according to equation 10.24. Gross energy intake was derived based on DM intake using the conversion factor 18.45 MJ/kg DM. We assumed that digestibility of the feed was 50 and 60 percent for developing and developed countries, respectively. The ash content of the feed was assumed to be 8 percent. We assumed the animal weights for each region based on information from FAO work: GLEAM FAO.

10B.4 Feed intake estimates using a simplified Tier 2 method

Prediction of DMI for cattle based on body weight and estimated dietary net energy concentration (NE_{ma}) or digestible energy values (DE percent):

Several studies have shown that dry matter intake (DMI) is highly and positively related to methane emissions. In some cases it has been reported that up to 92 percent of the variability in enteric methane emissions could be explained by DMI alone (Charmley *et al*. 2016). Most models developed to predict enteric methane emissions usually include either DMI or some form of feed intake. There are a number of models already developed with the objective of predicting DMI and these could be used in conjunction with emission factors to estimate enteric methane emissions in a Tier 2 approach. Appuhamy *et al*. (2016) evaluated 40 prediction equations using data that included measured DMI and feed quality attributes from North America, Europe and Australia/New Zealand. The best performing models in each region were then re-evaluated using calculated DMI and compared with estimates that used measured DMI. They evaluated several DMI prediction equations including the Cornell Net Carbohydrate and Protein System (CNCPS, Fox *et al*. 1992) as modified by Arnerdal (2005), National Research Council (NRC 2001) (developed based on North America cows), Lindgren *et al*. (2001) and Arnerdal (2005) (developed using data from cows in Europe), and Vazquez and Smith (2000) model (developed from Australia/New Zealand data). Appuhamy *et al*. (2016) reported that models using estimated DMI predicted enteric methane emissions just as good as the measured data and concluded that enteric methane emissions from dairy cows can be predicted successfully with estimated DMI, particularly using the modified CNCPS model. Appuhamy *et al*. (2018) further evaluated the comprehensive (IPCC-CMP) and simplified (IPCC-SMP) IPCC models (IPCC 2006) to predict DMI as well as the modified CNCPS and NRC (2001) models to predict DMI using an independent data. The modified CNCPS relying on BW and fat corrected milk yield (Eq. 1) more accurately predicted DMI (RMSPE = 14.1 percent) than NRC (RMSPE = 19.4 percent), IPCC-SMP (RMSPE = 16.9 percent), and IPCC-CMP (RMSPE = 23.4 percent). Overall, the results demonstrated that DMI of dairy cows can be predicted successfully using information such as milk yield, milk fat content, and body weight (BW) that are routinely available in dairy farms.

$$\text{DMI (kg/d)} = 0.0185 * \text{BW (kg)} + 0.305 * \text{fat corrected milk (kg/d)} \quad \text{Eq [1]}$$

A simplified approach can also be used to estimate DMI of beef cattle, updated based on the most recent methodologies as described by NASEM (2017). For growing and finishing cattle, equations are:

Calves

$$\text{DMI (kg/d)} = (BW^{0.75} * (0.2435 * NE_{mf} - 0.0466 * NE_{mf}^2 - 0.1128)) / NE_{mf} \quad \text{Eq. [2]}$$

Yearlings

$$\text{DMI (kg/d)} = (BW^{0.75} * (0.2435 * NE_{mf} - 0.0466 * NE_{mf}^2 - 0.0869)) / NE_{mf} \quad \text{Eq. [3]}$$

Feedlot cattle (high grain diets)

Steers: $\text{DMI (kg/d)} = 3.830 + 0.0143 * BW * 0.96$ Eq. [4]

Heifers: $\text{DMI (kg/d)} = 3.184 + 0.01536 * BW * 0.96$ Eq. [5]

Where: BW = body weight (kg), NE_{mf} = Mcal/kg feed DM Eq. [6]

Mature Cows

Forage type	Digestibility	Forage DMI Capacity (kg/day), % of BW (kg)	
		Non-lactating	Lactating
Low quality	<52	1.8	2.2
Average quality	52-59	2.2	2.5
High quality	>59	2.5	2.7

10B.5 Basis for Changes to MCF Calculations for Liquid/Slurry

The following briefly summarizes the *2006 IPCC Guidelines* approach and improvements included in the current approach.

2006 IPCC Guidelines Model for Liquid/Slurry:

The *2006 IPCC Guidelines* MCF for liquid slurry was based on the following relationship:

MCF = *f*

where *f* was calculated with the following temperature-dependent Arrhenius function, derived from Mangino *et al*. (2001), which is based on Safley & Westerman (1990):

$f = EXP[(Ea\times(T_2-T_1))/(R\times T_2\times T_1)]$

where,

f is a dimensionless fraction (0 to 1). Originally, Safley & Westerman (1990) used *f* to design an anaerobic digestion system at a lower temperature (T_2) based on known performance of a digester at a warmer temperature (T_1).

Ea is the activation energy. Originally, Safley and Westerman used Ea = 15175 cal/mol, based on an earlier study. Mangino *et al*. (2001) continued to use 15175 cal/mol.

T_2 is the variable temperature (K). Defined by Safley & Westerman (1990) as the unknown anaerobic digester temperature. Mangino *et al*. (2001) defined T_2 as the monthly temperature of the anaerobic lagoon (assuming equality with monthly average air temperature). The *2006 IPCC Guidelines* defined T_2 as the annual average temperature of a region.

T_1 is the reference temperature (K). Defined by Safley & Westerman (1990) as 30 °C (303.16 K). Mangino *et al*. (2001) and the *2006 IPCC Guidelines* use the same value.

R is the gas constant 1.987 cal k^{-1} mol^{-1}.

The reasons for modification of MCF, though the Methane conversion factor (MCF) remains an uncertain parameter.

First and foremost, in the *2006 IPCC Guidelines*, the MCF parameter violates a first-principle of inventory development: comparability. The use of an annual average temperature to calculate MCF systematically underestimates the annual MCF due to the mathematical principle known as Jensen's Inequality which applies to non-linear functions such as the Arrhenius equation (VanderZaag *et al*. 2018). Using this mathematical principle it can be shown that for a 1-month retention time, the annual average MCF calculated based on monthly temperature will always exceed the MCF calculated from the annual average temperature. Therefore, the *2006 IPCC Guidelines* MCF values are underestimates, and the level of underestimation is greatest for countries with large seasonal temperature extremes.

The model in the *2006 IPCC Guidelines* also used a management and design practices (MDP) factor which reduced the mass of VS entering the manure storage or lagoon. Since VS cannot simply vanish, there needs to be justification for altering the VS loading rate. In the modified method, the MCF calculation used an MDP = 1.0, which means we are assuming the VS Excretion rates are correct, and that VS Excreted enters the liquid manure storage. MDP factors may be used in specific cases such as when solid-liquid separation systems are used, whereby VS is removed from the liquid system and transferred to a solid system. However in most cases the use of MDP factor is indicative of an inaccurate B0 or VS input into the manure storage system.

For the sake of completeness, it is worth pointing out that the quantity of VS entering liquid storage could be greater than VS excreted (implied MDP >1.0). For instance, the use of straw bedding results in additional VS entering the liquid storage. Another example is waste milk (from treated cows, or from cleaning milking systems) on dairy farms which adds VS to the storage. Secondly, it is well known that the retention time of liquid manure in storage is a critical parameter in determining MCF, and the *2006 IPCC Guidelines* state "both temperature and retention time play an important role in the calculation of MCF". However, the *2006 IPCC Guidelines* calculations of MCF (Table 1), give very little focus to retention time. Previous *Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories (GPG2000)* recommended that future MCFs be modelled accounting for the storage period (Zeeman & Gerbens 2000). Furthermore, the work of Safley & Westerman (1990) showed that the same amount of VS destruction can be achieved by longer retention time at lower temperature compared with shorter retention time at higher temperature. Furthermore the suggestion to use formula 1 for batch-fed storage/digesters that is currently in *2006 IPCC Guidelines* would not result in a value that is comparable to the default annual temperature values, because this equation would inherently require inclusion of retention time.

Recent year-round field studies in climates where the annual average air temperature was <10°C have reported MCFs in the range of 0.61 (Wightman & Woodbury 2016) , ≥0.57 (Balde *et al*. 2016a) at liquid/slurry dairy manure storages, and greater for anaerobic lagoons (Leytem *et al*. 2017). Controlled studies at or around 20°C without added inoculum reported MCF of 55 percent over 165 d (VanderZaag *et al*. 2010) and 32 percent over 150-d (Masse *et al*. 2008). Another study showed the MCF increased non-linearly with the duration of storage (Le Riche *et al*. 2016). Previous IPCC Guidance reported an MCF of 39 percent, 45 percent, and 72 percent for liquid/slurry for Cool, Temperate, and Warm climates, respectively (Zeeman & Gerbens 2000). They also stated that liquid/slurry storage tanks were considered to have ≥6 month retention time. Therefore, the interaction between retention time and temperature has long been recognized, but the calculation of MCFs has not been fully transparent about how this important interaction has been handled (or how it should be handled by practitioners) and therefore has made comparability with measurements challenging.

Thirdly, the single temperature time step given in the IPCC guidelines suggests a level of certainty that is simply not supported by the experimental results, considering the approach being used.

TABLE 10B.6 *2006 IPCC GUIDELINES* TABLE OF MCF VALUES FOR LIQUID/SLURRY (TABLE 10.17)

TABLE 10.17
MCF VALUES BY TEMPERATURE FOR MANURE MANAGEMENT SYSTEMS

System[a]		MCFs by average annual temperature (°C)																			Source and comments
		Cool					Temperate											Warm			
		≤ 10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	≥ 28	
Liquid/Slurry	With natural crust cover	10%	11%	13%	14%	15%	17%	18%	20%	22%	24%	26%	29%	31%	34%	37%	41%	44%	48%	50%	Judgement of IPCC Expert Group in combination with Mangino *et al.* (2001) and Sommer (2000). The estimated reduction due to the crust cover (40%) is an annual average value based on a limited data set and can be highly variable dependent on temperature, rainfall, and composition. When slurry tanks are used as fed-batch storage/digesters, MCF should be calculated according to Formula 1.
	Without natural crust cover	17%	19%	20%	22%	25%	27%	29%	32%	35%	39%	42%	46%	50%	55%	60%	65%	71%	78%	80%	Judgement of IPCC Expert Group in combination with Mangino *et al.* (2001). When slurry tanks are used as fed-batch storage/digesters, MCF should be calculated according to Formula 1.

Proposed Changes:

The proposed change is to use a spreadsheet model to calculate MCF using monthly temperature in each IPCC climate region, and for a specific liquid manure retention time (e.g. the table below). Therefore, this approach produces MCF values that account for both temperature and retention time, while leaving the users to decide which retention time is appropriate for their manure management systems. The spreadsheet model *<Vol4_Ch10_MCF_Calculation-Spreadsheet>* for calculation of country-specific MCFs is available at *https://www.ipcc-nggip.iges.or.jp/public/2019rf/pdf/4_Volume4/Vol4_Ch10_%20MCF_Calculation-Spreadsheet.xlsx*.

TABLE 10B.7 (NEW)
MCFS CALCULATED FOR EACH RETENTION TIME AND CLIMATE (SELECTED IPCC CLIMATE REGIONS SHOWN)

RETENTION TIME	Tropical Montane	Tropical[1] Wet	Tropical[1] Moist	Tropical[1] Dry	Warm Temperate Moist	Warm Temperate Dry	Cool Temperate Moist	Cool Temperate Dry
1 Month	0.25	0.38	0.36	0.42	0.13	0.15	0.06	0.08
3 Month	0.43	0.61	0.57	0.62	0.24	0.28	0.12	0.16
4 Month	0.50	0.67	0.64	0.68	0.29	0.32	0.15	0.19
6 Month	0.59	0.76	0.73	0.74	0.37	0.41	0.21	0.26
12 Month	0.73	0.80	0.80	0.80	0.55	0.64	0.31	0.42
T_{avg} C	21.5	25.9	25.2	25.6	13.9	14.0	4.6	5.8

[1] Note that an upper limit MCF of 80% has been imposed for consistency with the anaerobic lagoon MCFs at high temperatures and long retention times

Changes in liquid/slurry MCF, compared to the 2006 IPCC Guidelines are summarized below:

#1 – Timestep:

Monthly temperature (proposed) instead of annual average temperature (IPCC 2006)

Methane emissions are non-linearly related to temperature, therefore Jensen's inequality states that the use of the average temperature will lead to systematic underestimation. As a result, monthly average air temperature is proposed for the calculation of MCF, rather than annual average temperature. Therefore, it is proposed that MCF for liquid/slurry be calculated using the Mangino *et al*. (2001) spreadsheet model, with the regional climate data from the IPCC defined climate regions. Additional details below.

#2 – Retention Time:

Several retention times (proposed) instead of 1-month implied retention time (IPCC 2006)

Retention time is a crucial parameter determining the extent of methane emissions and the quantity of VS in storage at any given time, therefore affecting the MCF. The *2006 IPCC Guidelines* used a 1-month retention time for all liquid/slurry systems by using MCF = *f*, based on an annual average temperature. Using a 1-month retention time is unrealistic, since the majority of liquid/slurry storages are meant for storage over several months or more. Therefore, it is proposed to calculate MCF based on five retention times: 1 month, 3 months, 4 months, 6 months, and 12 months.

Proposed "*good practice*" in the case of countries that do not have information on retention times is to use the six month retention time.

#3 – Activation Energy (Ea):

Updated Ea value (19347 cal/mol proposed) instead of 15175 cal/mol (IPCC 2006)

Recent research from Petersen *et al*. (2016) and Elsgaard *et al*. (2016) propose a new Ea value of 81 kJ/mol = 19347 cal/mol. It is proposed to use this updated value.

#4 – Reference Temperature (T_1):

Updated T1 value (308.16 proposed) instead of 303.16 K (IPCC 2006)

The value of T_1 used by *2006 IPCC Guidelines* and Mangino *et al*. (2001) is directly taken from Safley & Westerman (1990). The original intent of Safley and Westerman was comparing performance of a known and unknown anaerobic digester performance. In Mangino *et al*. (2001) and the *2006 IPCC Guidelines* the value of T1 defines the temperature at which *f* = 1.0, therefore T1 defines the temperature at which the B_0 will be reached in one month. There is considerable literature on laboratory methods for incubating manure to measure methane potential (e.g. BMP, B_0) and it is customary for the temperature of these incubations to be ca. 35°C, rather than 30°C. With a temperature of 35°C it would be reasonable to expect the B_0 to nearly be reached in 30 days (i.e. one month) (e.g. Owen *et al*. 1979; Pham *et al*. 2013). Therefore, it is proposed to change T_1 to 308.16 K (=35 + 273.16).

#5 – Manure Temperature (T_2):

Manure temperature lagging behind T_{air} (proposed) instead of equal T_{air} (IPCC 2006)

Most of the time, manure temperature does not equal air temperature. The temperature of liquid manure tends to lag behind air temperature. While models for manure temperature do exist (Rennie *et al*. 2017) this is too complex for the general guidelines. As a pragmatic alternative, a 1-month lag is proposed, i.e., set $T_2 = T_{air}$ from the previous month. It has also been shown (Rennie *et al*. 2018) that manure storages which are emptied once per year at the end of the growing season before winter stay cooler than air temperature during the summer. Therefore, only in the case of once per year emptying (i.e. 12 month retention time), a downward temperature shift of 3°C has also been applied.

#6 – VS carryover after emptying:

After manure is removed, 5 percent remains (proposed), instead of complete emptying (IPCC 2006)

It has been shown in several studies that farms do not completely empty liquid/slurry storages due to the practical challenge of doing so at the farm-scale (Balde *et al*. 2016b). Therefore, it is proposed that 5 percent of VS is retained in storage after emptying, rather than 0 percent (i.e. completely clean) assumption implied in the *2006 IPCC Guidelines* calculations. It is noteworthy that the IPCC 2000 *Good Practice* Guide (Zeeman & Gerbens 2000) mention approximately 15 percent of the manure storage cannot be emptied.

10B.6 Revision of methane from dung deposited onto pasture range and paddocks (Table 10.17)

Dataset

Cai *et al*. (2017) included 26 data, however some of these were omitted due to incomplete information to allow an estimation of methane conversion factor (MCF) and/or emission factors on the basis of volatile solids (VS) content. Therefore, the number of values retained was 20. Our review of the literature identified a further 25 suitable values (Carran *et al*. 2003; Saggar *et al*. 2003; Sherlock *et al*. 2003b; Sherlock *et al*. 2003a; Kelly *et al*. 2016), resulting in a total of 45 data values spanning six countries (Table 10B.8). Data were available for dairy cattle (25), beef cattle (9), sheep (8) and yaks (3). Data was assessed for suitability, in terms of length of study, sufficient replication and inclusion of key manure characteristics to allow estimation of the emission factors (g CH_4/kg VS; Table 10B.9) and MCF (percent; Table 10.17). Some studies also presented emissions on the basis of mass of CH_4 emitted per unit of faecal dry matter (FDM). Therefore, we have also supplied emission factors using these units (g CH_4/kg FDM) for countries with access to total FDM (Table 10B.9).

TABLE 10B.8 (NEW)
REGIONAL DISTRIBUTION OF DATA USED TO DERIVE MCF AND METHANE EF FROM EXCRETION VOLITILE SOLIDS DATA ON PRP

Country	Cattle	Sheep	Total
Australia	13		13
Brazil	4		4
China	3	2	5
Japan	5		5
New Zealand	6	6	12
UK	6		6
Total	**37**	**8**	**45**

Emission factors

Methane conversion factors (MCF) and emission factors were estimated for both cattle and sheep, where yaks were grouped with cattle (Table 10B.9). For estimating MCFs and emission factors based on VS content, ash content of dung is required. We estimated dung ash content to be 17.9 percent for pasture-fed sheep, beef cattle and dairy cattle (Fries *et al*. 1982; Karn 1991; Waghorn *et al*. 1999; Andueza *et al*. 2017). Data from a UK study (Defra, 2014) suggested that the IPCC B_0 values were appropriate for cattle, we therefore assumed the IPCC values for sheep were also reasonable estimates. For yaks, we used the IPCC default B_0 value for buffalo (0.100).

There was no significant difference in values for cattle and sheep regardless of the method of representing methane emissions ($P > 0.05$). For the refinement of the *2006 IPCC Guidelines* we therefore suggest an aggregated value is used. We also explored the possibility of disaggregating EF values by climatic zones, however the limited size of the dataset did not support this. Therefore, an aggregated value regardless of temperature is suggested for the refinement.

When adopting a Tier 2 approach, the MCF must be used in conjunction with a single B_0 value of 0.19 m^3 CH_4 kg^{-1} of VS excreted to ensure consistency with the Tier 1 emission factor provided in Table 10.14.

TABLE 10B.9 (NEW)
METHANE CONVERSION FACTOR (MCF) AND METHANE EMISSION FACTORS (PER KG FAECAL DRY MATTER (FDM)) AND VOLATILE SOLIDS (VS) FOR CATTLE AND SHEEP

Livestock species	MCF (%) Average, (Std Dev)	EF (g CH_4/kg FDM) Average, (Std Dev)	EF (g CH_4/kg VS) Average, (Std Dev)
Cattle	0.46 (0.38)	0.49 (0.42)	0.59 (0.51)
Sheep	0.52 (0.40)	0.53 (0.42)	0.65 (0.51)
Average	**0.47 (0.38)**	**0.50 (0.42)**	**0.60 (0.51)**

10B.7 Estimation of default values for MCFs, EFs for direct N_2O emissions, NH_3 and N_2 volatilized as well as NO_3 leached from solid storage and composting systems

Methodologies

The estimation of updated MCF values, EF for direct N_2O emissions and NO_3 leaching and N_2 from both (i) solid storage and (i) two composting systems (static pile and passive windrow) are based on an extensive meta-analysis of 50 peer-reviewed research articles involving 304 observations and published in open access by Pardo *et al*. (2015). In this study it was quantified the response of GHG emissions, NH_3 emissions, and total N losses to different solid waste management strategies (conventional solid storage, turned composting, forced aerated composting, covering, compacting, addition/substitution of bulking agents and the use of additives).

For solid storage, new treatments have been proposed to be incorporated in the *2019 Refinement*: covering/compacted (both treatments had similar effects on GHG emissions), addition/substitution of bulking agents and the use of additives. In the *2006 IPCC Guidelines for National GHG inventories* default emission factors for solid storage were based on expert IPCC judgement and a single study (Amon *et al*. 2001). In Pardo *et al*. (2015) the estimation of MCF values and EF for direct N_2O emissions from solid storage (without treatment) is based on data from 30 studies at the farm level.

For the new treatments, MCF values and EFs for direct N_2O emissions have been based on:

- 9 studies for compacting and covering;
- 11 studies for addition/substitution of bulking agents;
- 6 studies for use of additives.

For the rest of the management systems, MCF values and EF for direct N_2O emissions have been based on:

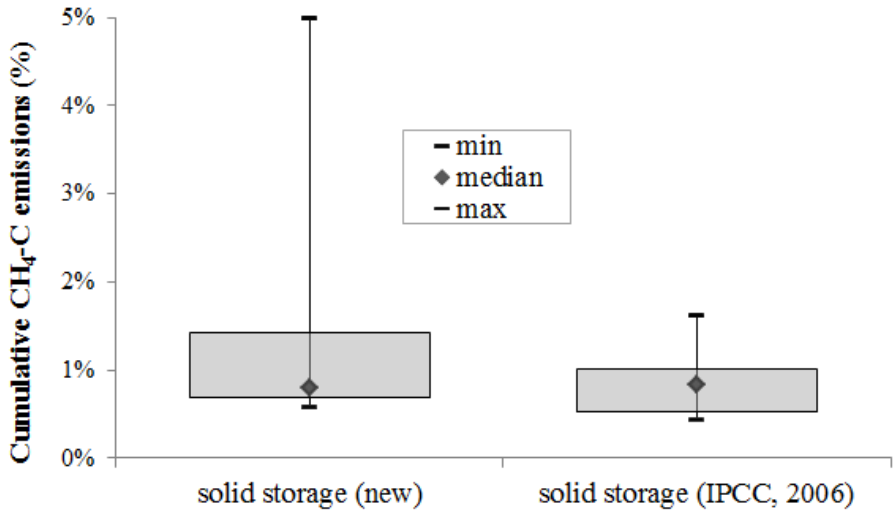
- 22 studies for solid storage;
- 6 studies for composting-static piles (Forced aeration);
- 11 studies for composting-Passive windrow (infrequent turning).

Based on the *2006 IPCC Guidelines* climate zone classification two factors were defined: Temperature, which involved two categories (i) Warm temperate and (ii) Cool temperate; and annual rainfall rate, including (i) Dry, (ii) Moist and (iii) Wet conditions.

CH_4 MCF

For the absolute CH_4-C emission values, Pardo *et al*. (2015) used untreated solid storage as a reference system. They compared estimated percent C lost as CH_4 using the *2006 IPCC Guidelines* method (IPCC 2006 MCF) with the values obtained at the different studies (Figure 10B.6).

Figure 10B.6 (New) Comparison between ranges of CH_4-C emissions observed in collected studies in Pardo *et al.* (2015) (new) with estimations for the same studies according to the *2006 IPCC Guidelines* methodology. Figure adapted from Pardo *et al.* (2015).



For untreated solid storage systems Pardo *et al*. (2015) showed that overall values were within the *2006 IPCC Guidelines* range for CH_4 emissions (Figure 10B.6) and confirmed that the differences between cold and temperate conditions were in agreement with those indicated by the *2006 IPCC Guidelines* not shown here, Figure S3b in Pardo *et al*. (2015). There were not enough studies under warm conditions and therefore, the assumption is to keep the same values indicated by the *2006 IPCC Guidelines*.

Values for new solid storage treatments and composting (static pile and passive windrow) are estimated using the reference value from the untreated solid storage system and the relative differences observed in Pardo *et al*. (2015).

For the new treatments, covering or compacted solid storage resulted in emissions in the same range as in solid storage not shown here, Figure 2b in Pardo *et al*. (2015) and estimated reduction of 75 percent and 50 percent was observed due to bulking agent addition and additives, respectively not shown here, Figure 2b in Pardo *et al*. (2015). The differences amongst climatic zones were assumed to be in the same proportion as that found for untreated solid storage systems.

Both composted static piles and static windrows were estimated to produce 50 percent of the CH_4 emitted from solid storage not shown here, Figure 2b in Pardo *et al*. (2015), which results in consistently greater values than those indicated by the *2006 IPCC Guidelines*. As a difference to the *2006 IPCC Guidelines*, CH_4 emissions were found to be temperature dependent for both composting systems (*2006 IPCC Guidelines* did not indicate temperature differences for static piles).

N_2O EF3 (Table 10.21)

According to the data examined in Pardo *et al*. (2015), there was no evidence to assume a lower EF for solid storage systems (0.005 kg N_2O–N kg^{-1} N excreted) than for passive windrow composting (0.01 kg N_2O–N kg−1N excreted). In fact, an EF of 0.5 percent (0.005kg N_2O-N kg initial N^{-1}) and 1 percent (0.01kg N_2O-N kg initial N^{-1}) were found for composting-passive windrow and solid storage, respectively.

Composting static pile, in contrast to the *2006 IPCC Guidelines*, was found to emit greater N_2O emissions than passive windrows (not shown here, Fig. 3a in Pardo *et al*. 2015).

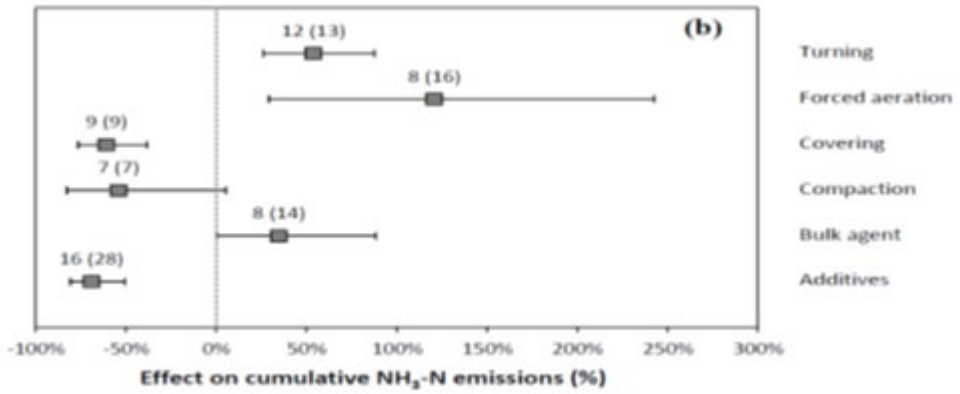
For the different treatments of solid storage, whereas Pardo *et al*. (2015) found no different effect on N_2O after compaction or covering, for both the addition of bulking agents or additives, a reduction of about 50 percent compared with conventional solid storage was observed not shown here, Figure 2a in Pardo *et al*. (2015).

NH_3 losses

For solid storage and composting relative values compared to solid storage reflect results obtained from meta-analysis by Pardo *et al*. (2015) (Fig 10B.7). Ammonia and NO_x default values in Table 10.22 for conventional solid manure storage and other systems defined both in IPCC Guidelines and EMEP/EEA (2016) have been taken from current EMEP/EEA air pollutant emission inventory guidebook 2016. EFs from EMEP/EEA (2016) values, which are expressed per TAN excreted and for each of the phases of the manure management, have been re-

calculated to be expressed as a funtion of total N excreted considering the mass balance flow between the different manure management phases prior to manure application (housing, yards and storage). For other categories not present in EMEP/CORINAIR (2016), first for stages prior to storage, we have estimated percent N lost using default EMEP/CORINAIR EFs for conventional manure storage and assuming no N_2O or N_2 losses, and subsequently, during storage, we used the relative effect between solid storage and the alternative solid storage categories (e.g. composting) (Fig 10B.7) as the basis to estimate NH_3+NO_x EF during storage.

Figure 10B.7 (New) Effect on cumulative NH_3-N emissions of different solid storage and composting methods compared with conventional solid storage. Figure adapted from Pardo *et al.* (2015)



NO_3 leaching and N_2 losses

Nitrate leaching/run-off has been estimated from the database from Pardo *et al*. (2015). For solid storage and composting some of the studies included measurements of N leaching (15), some of which estimated N_2 from the total N balance, but only one included measurements of N_2 (Moral *et al*. 2012). As a median value about 3 percent is estimated to be lost as NO_3 leaching/run-off (range: 0-38 percent). This value is subject to large uncertainty. In fact these trials may not represent common practices where the efficiency of collection of excreta N is much lower and can lead to as great as 50 percent losses (e.g. Lekasi *et al*. 2001; Rufino *et al*. 2007). Nitrogen (N_2) losses, have only been, to our knowledge, measured by Moral *et al*. (2012) (12 percent) and even though they could be estimated as a result of an N balance from trials where all N flows except N_2 have been measured, the results are very uncertain (0-55 percent). For N_2, an estimated median value of 12 percent was found; coinciding with the measured value by Moral *et al*. (2012). Systems that do not percolate but are subject to large water input will have greater N_2 losses and lower NO_3 leaching-runoff. The opposite effect will be expected with rainy areas with no containment and large possibilities for run-off/leaching. Values must be considered with large caution.

A further summary review was carried out to identify run-off/leaching values from dry lots and manure pack. As observed in the *2006 IPCC Guidelines* runoff and leaching values varied greatly citing ranges of 3 to 6 percent of N excreted (Eghball & Power 1994) or 5 to 19 percent (Bierman *et al*. 1999). In humid environments losses can be significant reaching 22-25 percent (Uusi-Kämppä 2002). However, uncovered holding and feeding pens without runoff containment tend to be in drier climates simply due to challenges in moisture control in more humid environments. Furthermore, considerable numbers of cattle are raised in drier climates and as a result considerably more studies exist looking at runoff from feedlots and drylots. Likewise recent attempts have been made to attempt to model these losses to the environment (Kizil *et al*. 2006; Williams et al. 2006). These studies tend to place the range of runoff loss between 1 percent and roughly 7 (Kizil *et al*. 2006; Erickson & Klopfenstein 2010; Vadas & Powell 2013). It is proposed the value of 3.5 percent with an uncertain range of 0 to 7 percent be considered as a default leaching factor for open, uncovered, uncontained drylots and bedded pack to provide a Tier 1 estimate of the fraction of N excreted lost to the environment.

Inventory compilers must be careful to consider that this refers to N lost to the environment surrounding the pens or leached into the soil. If runoff is captured and returned to agricultural fields these losses must not be considered. In humid environments, in cases where manure is left exposed to rainfall, inventory compilers should consider the use of the upper bounds of the leaching fraction and furthermore to consider the development of a country specific leaching fraction.

Review of the effect of slurry store solid covers and natural crust on emissions of CH_4 and N_2O

The review found 18 papers dealing with the impact of solid covers or natural crusts on CH_4 and/or N_2O emissions from slurry stores. 11 of them were suitable to be included here to deduce emission factors (Amon *et al*. 2006; Clemens *et al*. 2006; Guarino *et al*. 2006; Amon *et al*. 2007; VanderZaag *et al*. 2008; VanderZaag *et al*. 2009; Aguerre *et al*. 2012; Nielsen *et al*. 2013; Hou *et al*. 2015; Matulaitis *et al*. 2015; Misselbrook *et al*. 2016).

For CH_4 emissions from Liquid/Slurry, the *2006 IPCC Guidelines* state that by judgement of the IPCC Expert Group, a reduction of 40 percent due to crust cover may be applied when a thick, dry, crust is present. The new review carried our within the *2019 Refinement* confirms this judgement (VanderZaag *et al*. 2008; Aguerre *et al*. 2012; Nielsen *et al*. 2013). A solid cover reduces CH_4 emissions by 25 to 50 percent (range: 0 to 90 percent) (Amon *et al*. 2006; Clemens *et al*. 2006; Guarino *et al*. 2006; Amon *et al*. 2007; VanderZaag *et al*. 2008; VanderZaag *et al*. 2009; Hou *et al*. 2015; Matulaitis *et al*. 2015; Misselbrook *et al*. 2016).

For N_2O emissions from Liquid/Slurry with natural crust cover a detailed literature review carried out during the *2019 Refinement* revealed only very few new datasets on the measurement of N_2O emissions from manure stores and the influence of crusting. These datasets agree that N_2O emissions increase when a crust is formed, but do not give concrete numbers on the level of increase (VanderZaag *et al*. 2008; Aguerre *et al*. 2012).

For N_2O emissions from Liquid/Slurry with a cover a detailed literature review carried out during the *2019 Refinement* revealed only few new datasets on the measurement of N_2O emissions from manure stores. These datasets encompass a large range from a 50 percent reduction to a 100 percent increase in N_2O emissions when slurry stores are covered. The *2019 Refinement* therefore suggest to use the emission factor of crust cover (Amon *et al*. 2006; Clemens *et al*. 2006; Guarino *et al*. 2006; Amon *et al*. 2007; VanderZaag *et al*. 2009; Hou *et al*. 2015; Misselbrook *et al*. 2016).

References

Section 10.2 Livestock Population and Feed Characterisation

REFERENCES NEWLY CITED IN THE *2019 REFINEMENT*

AFRC (1995) *Energy and protein requirements of ruminants. An advisory manual prepared by the AFRC Technical Committee on Response to Nutrients*. Wallingford, UK: CAB International. pp 159.

AFRC (1998) *The Nutrition of Goats*. Wallingford: CAB International. pp 118.

Animut G., Puchala R., Goetsch A.L., Patra A.K., Sahlu T., Varel V.H., Wells J. (2008) Methane emission by goats consuming different sources of condensed tannins. *Animal feed science and technology* **144**: 228-241.

Arnerdal S. (2005) *Predictions for voluntary dry matter intake in dairy cows. Thesis*. Department of Animal Nutrition and Management, Swedish University of Agricultural Sciences.

Fox D.G., Sniffen C.J., O'connor J.D., Russell J.B., Van Soest P.J. (1992) A Net Carbohydrate and Protein System for Evaluating Cattle Diets: III. Cattle Requirements and Diet Adequacy. *Journal of Animal Science* **70**: 3578-3596.

IPCC, FAO, IFAD (2015) *Emerging activities to combat climate change – use of FAO data and IPCC GHG Inventory Guidelines for Agriculture and Land Use*. In: *Report of the joint FAO-IPCC-IFAD Expert Meeting*, Eds. Tubiello, F.N., Neeff, T., Tanabe, K., Baasansuren, J., Fukuda, M.. M.. Report of the joint FAO-IPCC-IFAD Expert Meeting, Pub. IGES, Japan.

MacLeod M., Vellinga T., Opio C., Falcucci A., Tempio G., Henderson B., Makkar H., Mottet, A., Robinson, T., Steinfeld, H., Gerber, P. (2017) Invited review: A position on the Global Livestock Environmental Assessment Model (GLEAM). *animal* **12(2)**: 1-15.

National Academies of Sciences, Engineering and Medicine (2016) *Nutrient Requirements of Beef Cattle: Eighth Revised Edition*. Washington, DC: The National Academies Press. pp 494.

Nousiainen J., Rinne M., Huhtanen P. (2009) A meta-analysis of feed digestion in dairy cows. 1. The effects of forage and concentrate factors on total diet digestibility. *Journal of Dairy Science* **92**: 5019-5030.

REFERENCES COPIED FROM THE 2006 IPCC GUIDELINES

AAC (1990) *Feed Standards for Australian Livestock Ruminants. Commonwealth Scientific and Industrial Research Organization (CSIRO) Publications*. East Melbourne, Victoria, Australia: Australian Agricultural Council.

AFRC (1990) *Nutritive Requirements of Ruminant Animals: Energy. Rep. 5*. Wallingford, UK: CAB International

Bamualim A., Kartiarso (1985) Nutrition of draught animals with special reference to Indonesia. In: *Draught Animal Power for Production. Australian Centre for International agricultural Research (ACIAR), Proceedings Series No. 10*, ed. JW Copland. Canberra, A.C.T., Australia: ACIAR.

FAO, IDF, IFCN (2014) *World mapping of animal feeding systems in the dairy sector*. Rome, Italy: Food and Agriculture Organization of the United Nations, International Dairy Federation, IFCN Dairy Research Network. pp 160.

Johnson, D. E. 1986. Climatic stress and production efficiency. Limiting the Effects of Stress on Cattle. Western Regional Res. Pub. #009 and Utah Agric. Exp. Sta. Res. Bull. 512:17-26.

Gibbs M.J., Conneely D., Johnson D., Lassey K.R., Ulyatt M.J. (2002) CH_4 emissions from enteric fermentation. in: *Background Papers: IPCC Expert Meetings on Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories*, pp. 297-320. Hayama, Kanagawa, Japan: IPCC-NGGIP, Institute for Global Environmental Strategies (IGES).

Gibbs M.J., Johnson D.E. (1993) Livestock Emissions. In: *International Methane Emissions*. Washington, D.C., U.S.A: US Environmental Protection Agency, Climate Change Division.

Ibrahim M.N.M. (1985) Nutritional status of draught animals in Sri Lanka. In: *Draught Animal Power for Production. ACIAR (Australian Centre for International Agricultural Research) Proceedings Series No. 10*, ed. JW Copland. Canberra, A.C.T., Australia: ACIAR.

Jurgens M.H. (1988) *Animal Feeding and Nutrition, Sixth Edition*. Dubuque, Iowa, U.S.A.: Kendall/Hunt Publishing Company.

Lawrence P.R. (1985) A review of nutrient requirements of draught oxen. In: *Draught Animal Power for Production. ACIAR (Australian Centre for International Agricultural Research) Proceedings Series No. 10*, ed. JW Copland. Canberra, A.C.T., Australia: ACIAR.

NRC (1989) *Nutrient Requirements of Dairy Cattle, 6th Ed.* Washington, D.C. U.S.A: National Academy Press.

NRC (1996) *Nutrient Requirements of Beef Cattle, 7th Revised Ed.* Washington, DC: The National Academies Press.

NRC (2001) *Nutrient Requirements of Dairy Cattle: Seventh Revised Edition, 2001*. Washington, DC: The National Academies Press. pp. 408.

Section 10.3 Methane Emissions from Enteric Fermentation

REFERENCES NEWLY CITED IN THE *2019 REFINEMENT*

Aguerre M.J., Wattiaux M.A., Powell J.M., Broderick G.A., Arndt C. (2011) Effect of forage-to-concentrate ratio in dairy cow diets on emission of methane, carbon dioxide, and ammonia, lactation performance, and manure excretion. *Journal of Dairy Science* **94**: 3081-3093.

Ahirwar R.R., Singh, A., Qureshi, M.I. (2010) A study of managemental practices in Water buffalo (Bubalus Bubalis) in India. *Buffalo Bulletin* **29**: 43-51.

Alemu A.W., Dijkstra J., Bannink A., France J., Kebreab E. (2011) Rumen stoichiometric models and their contribution and challenges in predicting enteric methane production. *Animal feed science and technology* **166-67**: 761-778.

Ali A., Abdel-Razek A.K., Derar R., Abdel-Rheem H., Shehata S. (2009) Forms of Reproductive Disorders in Cattle and Buffaloes in Middle Egypt. *Reproduction in Domestic Animals* **44**: 580-586.

Anjum M.I., Azim A., Jabbar M.A., Anwar M., Mirza I.H. (2012) Age and Weight at Puberty in Nili-Ravi Buffalo Heifers Reared on Three Dietary Energy Restriction Periods followed by Compensatory Growth. *Pakistan Veterinary Journal* **32**: 367-371.

Appuhamy J.A., France J., Kebreab E. (2016) Models for predicting enteric methane emissions from dairy cows in North America, Europe, and Australia and New Zealand. *Glob Chang Biol* **22**: 3039-3056.

Azary M., Manafiazar G., Razagzadeh S., Amini-jabalkandi J. (2007) Comparing fattening performance of Azeri buffalo, native and crossbred (native* Holstein) male calves in west Azerbaijan - Iran. *Italian Journal of Animal Science* **6**: 1152-1255.

Baldwin R.L. (1995) Dynamic models of ruminant digestion. In: *Modelling Ruminant Digestion and Metabolism*, pp. 300-318. London: Chapman & Hall.

Bannink A., van Schijndel M.W., Dijkstra J. (2011) A model of enteric fermentation in dairy cows to estimate methane emission for the Dutch National Inventory Report using the IPCC Tier 3 approach. *Animal feed science and technology* **166-167**: 603-618.

Baron V.S., Flesch T.K., Doce R.R., Wilson J.D., Basarab J.A. (2017) Enteric methane emission from winter-grazed beef cows. *American Society of Agronomy, Crop Science Society of America, Soil Science Society of America International Annual Meeting, Nov. 2-5, Long Beach, CA. Abstract* **256**: 5.

Beauchemin K.A., McGinn S.M. (2005) Methane emissions from feedlot cattle fed barley or corn diets. *Journal of Animal Science* **83**: 653-661.

Beauchemin K.A., McGinn S.M. (2006a) Enteric methane emissions from growing beef cattle as affected by diet and level of intake. *Can. J. Anim. Sci.* **86**: 401-408.

Beauchemin K.A., McGinn S.M. (2006b) Methane emissions from beef cattle: Effects of fumaric acid, essential oil, and canola oil. *Journal of Animal Science* **84**: 1489-1496.

Beauchemin K.A., McGinn S.M., Martinez T.F., McAllister T.A. (2007) Use of condensed tannin extract from quebracho trees to reduce methane emissions from cattle. *Journal of Animal Science* **85**: 1990-1996.

Benchaar C., Hassanat F., Gervais R., Chouinard R.Y., Petit H.V., Masse D.I. (2014) Methane production, digestion, ruminal fermentation, nitrogen balance, and milk production of cows fed corn silage- or barley silage-based diets. *Journal of Dairy Science* **97**: 961-974.

Bernardes O. (2007) Bubalinocultura no Brasil: situação e importância econômica. *Rev Bras Reprod Anim, Belo Horizonte* **31**: 293-298.

Boadi D.A., Wittenberg K.M. (2002) Methane production from dairy and beef heifers fed forages differing in nutrient density using the sulphur hexafluoride (SF6) tracer gas technique. *Canadian Journal of Animal Science* **82**: 201-206.

Boadi D.A., Wittenberg K.M., Scott S.L., Burton D., Buckley K., Small J.A., Ominski K.H. (2004) Effect of low and high forage diet on enteric and manure pack greenhouse gas emissions from a feedlot. *Canadian Journal of Animal Science* **84**: 445-453.

Borghese A. (2013) Buffalo livestock and products in Europe. *Buffalo Bulletin* **32**: 50-74.

Chaves A.V., Thompson L.C., Iwaasa A.D., Scott S.L., Olson M.E., Benchaar C., Veira D.M., MacAllister T.A. (2006) Effect of pasture type (alfalfa vs. grass) on methane and carbon dioxide production by yearling beef heifers. *Canadian Journal of Animal Science* **86**: 409-418.

Chawla A., Chawla N., Pant Y., Kandhari P. (2009) *Milk and Dairy Products in India – Production, Consumption and Exports. Report of Hindustan Studies & Services Ltd. and Infolitics*.

Chung Y.H., McGeough E.J., Acharya S., McAllister T.A., McGinn S.M., Harstad O.M., Beauchemin K.A. (2013) Enteric methane emission, diet digestibility, and nitrogen excretion from beef heifers fed sainfoin or alfalfa. *J. Anim. Sci.* **91**: 4861-4874.

Cruz L.C. (2007) Trends in buffalo production in Asia. *Italian Journal of Animal Science* **6**: 9-24.

Dezfuli B.T., Javaremi A.N., Abbasi M.A., Fayazi J., Chamani M. (2011) Economic weights of milk production traits for buffalo herds in the southwest of Iran using profit equation. *World Applied Sciences Journal* **15**: 1604-1613.

Doreau M., Werf H.M.G.v.d., Micol D., Dubroeucq H., Agabriel J., Martin Y.R.C. (2011) Enteric methane production and greenhouse gases balance of diets differing in concentrate in the fattening phase of a beef production system. *Journal of Animal Science* **89**: 2518-2528.

Dougherty H.C., Kebreab E., Evered M., Little B.A., Ingham A.B., Nolan J.V., Hegarty R.S., Pacheco D., McPhee M.J. (2017) The AusBeef model for beef production: I. Description and evaluation. *The Journal of Agricultural Science* **155**: 1442-1458.

Ellis J.L., Bannink A., France J., Kebreab E., Dijkstra J. (2010) Evaluation of enteric methane prediction equations for dairy cows used in whole farm models. *Global change biology* **16**: 3246-3256.

Ellis J.L., Dijkstra J., Bannink A., Kebreab E., Archibeque S., Benchaar C., Beauchemin K.A., Nkrumah J.D., France J. (2014) Improving the prediction of methane production and representation of rumen fermentation for finishing beef cattle within a mechanistic model. *Canadian Journal of Animal Science* **94**: 509-524.

Ellis J.L., Kebreab E., Odongo N.E., Beauchemin K., McGinn S., Nkrumah J.D., Moore S.S., et al. (2009) Modeling methane production from beef cattle using linear and nonlinear approaches. *Journal of Animal Science* **87**: 1334-1345.

Ellis J.L., Kebreab E., Odongo N.E., McBride B.W., Okine E.K., France J. (2007) Prediction of methane production from dairy and beef cattle. *Journal of Dairy Science* **90**: 3456-3467.

Ellis J.L., Qiao F., Cant J.P. (2006) Prediction of dry matter intake throughout lactation in a dynamic model of dairy cow performance. *Journal of Dairy Science* **89**: 1558-1570.

Ermetin O. (2017) Husbandry and Sustainability of Water Buffaloes in Turkey. *Food Science and Technology* **5**: 1673-1682.

Escobar-Bahamondes P., Oba M., Beauchemin K.A. (2016) An evaluation of the accuracy and precision of methane prediction equations for beef cattle fed high-forage and high-grain diets. *animal* **10(1)**: 68-77.

FAO (2005) *Buffalo production and research. REU Technical Series 67*. Rome, Italy: FAO regional office for Europe, inter-regional cooperative research network on buffalo (ESCORENA). pp. 178-179.

FAO (2017) *Global Livestock Environmental Assessment Model v2.0. Data reference year 2010. Revision 4, June 2017. Available at: http://www.fao.org/fileadmin/user_upload/gleam/docs/GLEAM_2.0_Model_description.pdf*. Rome, Italy: Food and Agriculture Oganization of the United Nations.

FAO, IDF, IFCN (2014) *World mapping of animal feeding systems in the dairy sector*. Rome, Italy: Food and Agriculture Organization of the United Nations, International Dairy Federation, IFCN Dairy Research Network. pp. 160.

Fiorentini G., Carvalho I.P.C., Messana J.D., Castagnino P.S., Berndt A., Canesin R.C., Frighetto R.T.S., Berchielli T.T. (2014) Effect of lipid sources with different fatty acid profiles on the intake, performance, and methane emissions of feedlot Nellore steers. *J. Anim. Sci.* **92**: 1613-1620.

Frei S., Dittmann M.T., Reutlinger C., Ortmann S., Hatt J.-M., Kreuzer M., Clauss M. (2015) Methane emission by adult ostriches (Struthio camelus). *Comparative Biochemistry and Physiology Part A: Molecular & Integrative Physiology* **180**: 1-5.

Gibbs M.J., Johnson D.E. (1993) Livestock Emissions. In: *International Methane Emissions*. Washington, D.C., U.S.A: US Environmental Protection Agency, Climate Change Division.

Gregorini P., Beukes P.C., Hanigan M.D., Waghorn G., Muetzel S., McNamara J.P. (2013) Comparison of updates to the Molly cow model to predict methane production from dairy cows fed pasture. *Journal of Dairy Science* **96**: 5046-5052.

Grice A.C., Campbell S., Breaden R., Bebawi F., Vogler W. (2008) *Habitat management guide—Rangelands: Ecological principles for the strategic management of weeds in rangeland habitats*. Adelaide: CRC for Australian Weed Management.

Habeeb A.A.M., Gad A.E., Atta M.A.A. (2016) Changes in Body Weight Gain and Blood Hormonal Levels in Relation to Change in Age of Egyptian Male Buffaloes Calves from Birthing to Puberty. *Advances in Applied Physiology* **1**: 43-48.

Hales, K E., Jaderborg J.P., Crawford G.I., DiCostanzo A., Spiehs M.J., Brown-Brandl T.M., Freetly H.C. (2015) Effects of dry-rolled or high-moisture corn with twenty-five or forty-five percent wet distillers' grains with solubles on energy metabolism, nutrient digestibility, and macromineral balance in finishing beef steers. *J. Anim. Sci* **93**: 4995-5005.

Hales K.E., Brown-Brandl T.M., Freetly H.C. (2014) Effects of decreased dietary roughage concentration on energy metabolism and nutrient balance in finishing beef cattle. *J. Anim. Sci.* **92**: 264-271.

Hales K.E., Cole N.A., MacDonald J.C. (2012) Effects of corn processing method and dietary inclusion of wet distillers grains with solubles on energy metabolism, carbon−nitrogen balance, and methane emissions of cattle. *J. Anim. Sci.* **90**: 3174-3185.

Hales K.E., Foote A.P., Brown-Brandl T.M., Freetly H.C. (2017) The effects of feeding increasing concentrations of corn oil on energy metabolism and nutrient balance in finishing beef steers. *J. Anim. Sci.* **95**: 939-948.

Hammond K.J., Humphries D.J., Crompton L.A., Green C., Reynolds C.K. (2015) Methane emissions from cattle: Estimates from short-term measurements using a Green Feed system compared with measurements obtained using respiration chambers or sulphur hexafluoride tracer. *Animal feed science and technology* **203**: 41-52.

Hart K.J., Martin P.G., Foley P.A., Kenny D.A., Boland T.M. (2009) Effect of sward dry matter digestibility on methane production, ruminal fermentation, and microbial populations of zero–grazed beef cattle. *J. Anim. Sci.* **87**: 3342-3350.

Hassan E.H., Abdel-Raheem S.M. (2013) Response of growing buffalo calves to dietary supplementation of caraway and garlic as natural additives. *World Applied Sciences Journal* **22**: 408-414.

Hassanat F., Gervais R., Julien C., Massé D.I., Lettat A., Chouinard P.Y., Petit H.V., Benchaar C. (2013) Replacing alfalfa silage with corn silage in dairy cow diets: Effects on enteric methane production, ruminal fermentation, digestion, N balance, and milk production. *Journal of Dairy Science* **96**: 4553-4567.

Hegarty R.S., Goopy J.P., Herd R.M., McCorkell B. (2007) Cattle selected for lower residual feed intake have reduced daily methane production. *J. Anim. Sci.* **85**: 1479-1486.

Hossein-zadeh N.G., Madad M., Shadparvar A.A., Kianzad D. (2012) An Observational Analysis of Secondary Sex ratio, Stillbirth and Birth Weight in Iranian Buffaloes (Bubalus bubalis). **14**: 1477-1484.

Huhtanen P., Ramin M., Udén P. (2015) Nordic dairy cow model Karoline in predicting methane emissions: 1. Model description and sensitivity analysis. *Livestock Science* **178**: 71-80.

Hünerberg M., McGinn S.M., Beauchemin K.A., Okine E.K., Harstad O.M., McAllister T.A. (2013) Effect of dried distillers' grains plus solubles on enteric methane emissions and nitrogen excretion from growing beef cattle. *J. Anim. Sci.* **91**: 2846-2857.

Ibrahim M.A.R. (2012) Water buffalo for our next generation in Egypt and in the world. *Scientific Papers, Series D. Animal Science* **55**: 183-192.

Intergovernmental Panel on Climate Change (IPCC) (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. Prepared by the National Greenhouse Gas Inventories Programme , Eggleston H.S., Buendia L., Miwa K., Ngara T. and Tanabe K. (eds). Published: IGES, Japan .

Jayasundara S., Ranga Niroshan Appuhamy J.A.D., Kebreab E., Wagner-Riddle C. (2016) Methane and nitrous oxide emissions from Canadian dairy farms and mitigation options: An updated review. *Canadian Journal of Animal Science* **96**: 306-331.

Jordan E., Kenny D., Hawkins M., Malone R., Lovett D.K., Mara F.P.O. (2006a) Effect of refined soy oil or whole soybeans on intake, methane output, and performance of young bulls. *J. Anim. Sci.* **84**: 2418-2425.

Jordan E., Lovett D.K., Monahan F.J., Callan J., Flynn B., Mara F.P.O. (2006b) Effect of refined coconut oil or copra meal on methane output and on intake and performance of beef heifers. *J. Anim. Sci.* **84**: 162-170.

Kamalzadeh A., Rajabbaigy M., Kiasat A. (2008) Livestock production systems and trends in livestock industry in Iran. *Journal of Agriculture and Social Sciences* **4**: 183-188.

Karakok S.G. (2007) Small scale cattle farmers and their sustainability in lowland villages of Adana province, Turkey. *Livestock Research for Rural Development* **19**.

Kebreab E., Johnson K.A., Archibeque S.L., Pape D., Wirth T. (2008) Model for estimating enteric methane emissions from United States dairy and feedlot cattle. *J Anim Sci* **86**: 2738-2748.

Kebreab E., Tedeschi L., Dijkstra J., Ellis J.L., Bannink A., France J. (2016) Modeling Greenhouse Gas Emissions from Enteric Fermentation. *Synthesis and Modeling of Greenhouse Gas Emissions and Carbon Storage in Agricultural and Forest Systems to Guide Mitigation and Adaptation* **6**: 173-195.

Kennedy P.M., Charmley E. (2012) Methane yields from Brahman cattle fed tropical grasses and legumes. *Animal Production Science* **52**: 225-239.

Khadda B.S., Lata K., Singh B., Kumar R. (2017) Study of buffalo husbandry practices in rural area of central Gujarat in India. *Buffalo Bulletin* **36**: 75-87.

Khan M.S., Ahmad N., Khan M.A. (2007) Genetic resources and diversity in dairy buffaloes of Pakistan. *Pakistan Veterinary Journal* **27**: 201-207.

Khan S., Qureshi M.S., Ahmad N., Durrani M.A.F.R., Younas M. (2008) Effect of Pregnancy on Lactation Milk Value in Dairy Buffaloes. *Asian Australas. J. Anim. Sci.* **21**: 523-531.

Ma H., Oxley L., Rae A., Fan C., Huang J., Rozelle S. (2012) The evolution of productivity performance on China's dairy farms in the new millennium. *J. Dairy Sci*. **95(12)**

Ma H., Rae A.N., Huang J., Rozelle S. (2007) Enhancing productivity on suburban dairy farms in China. *Agricultural Economics Research Review* **37**: 29-42.

Mc Geough E.J., O'Kiely P.O., Foley P.A., Hart K.J., Boland T.M., Kenny D.A. (2010a) Methane emissions, feed intake, and performance of finishing beef cattle offered maize silages harvested at 4 different stages of maturity. *J. Anim. Sci.* **88**: 1479-1491.

Mc Geough E.J., O'Kiely P.O., Hart K.J., Moloney A.P., Boland T.M., Kenny D.A. (2010b) Methane emissions, feed intake, performance, digestibility, and rumen fermentation of finishing beef cattle offered whole–crop wheat silages differing in grain content. *J. Anim. Sci.* **88**: 2703-2716.

McGinn S.M., Chung Y.H., Beauchemin K.A., Iwaasa A.D., Grainger C. (2009) Use of corn distillers' dried grains to reduce enteric methane loss from beef cattle. *Can. J. Anim. Sci.* **89**: 409-413.

Mills J.A.N., Dijkstra J., Bannink A., Cammell S.B., Kebreab E., France J. (2001) A mechanistic model of whole-tract digestion and methanogenesis in the lactating dairy cow: Model development, evaluation, and application. *Journal of Animal Science* **79**: 1584-1597.

Mills J.A.N., Kebreab E., Yates C.M., Crompton L.A., Cammell S.B., Dhanoa M.S., Agnew R.E. and France J. (2003) Alternative approaches to predicting methane emissions from dairy cows. *Journal of Animal Science* **81**: 3141-3150.

Nascimento C.F.M., Berndt A., Romero L.A., Meyer P.M., Frighetto R.T.S., Demarchi J.J.A.A., Rodrigues P.H.M. (2016) Methane emission of cattle fed Urochloa brizantha hay harvested at different stages. *J. Agric. Sci* **8(1)**: 163-174.

Naserian A.A., Saremi B. (2007) Water buffalo industry in Iran. *Italian Journal of Animal Science* **6**: 1404-1405.

Neglia G., Balestrieri A., Gasparrini B., Cutrignelli M.I., Bifulco G., Salzano A., Cimmino R., D'occhio M., Campanile J. (2014) nitrogen and Phosphorus Utilisation and Excretion in Dairy Buffalo Intensive Breeding. *Italian Journal of Animal Science* **13**: 3362.

Nielsen O.-K., Plejdrup M.S., Winther M., Nielsen M., Gyldenkærne S., Mikkelsen M.H., Albrektsen R., et al. (2018) *Denmark's National Inventory Report 2018. Emission Inventories 1990-2016 - Submitted under the United Nations Framework Convention on Climate Change and the Kyoto Protocol. Scientific Report from DCE – Danish Centre for Environment and Energy No. 272.*: Aarhus University, DCE – Danish Centre for Environment and Energy. pp. 851.

Niu M., Kebreab E., Hristov A.N., Oh J., Arndt C., Bannink A., Bayat A.R., et al. (2018) Prediction of enteric methane production, yield, and intensity in dairy cattle using an intercontinental database. *Global change biology* 1-22.

Pinares-Patiño C.S., Baumont R., Martin C. (2003) Methane emissions by Charolais cows grazing a monospecific pasture of timothy at four stages of maturity. *Can. J. Anim. Sci.* **83**: 769-777.

Pinares-Patino C.S., Ulyatt M.J., Lassey K.R., Barry T.N., Holmes C.W. (2003) Persistence of differences between sheep in methane emission under generous grazing conditions. *Journal of Agricultural Science* **140**: 227-233.

Radwan M.A.A. (2016) *Characterization of milk and veal production chains of buffalo under crop-livestock production system in Egypt. PhD thesis*. Department of Animal Production Faculty of Agriculture. Cairo University.

Ranjhan S.K. (2007) Buffalo as a social animal for humanity. *Italian Journal of Animal Science* **6**: 30-38.

Sabia E., Napolitano F., Claps S., Braghieri A., Piazzolla N., Pacelli C. (2015) Feeding, Nutrition and Sustainability in Dairy Enterprises: The Case of Mediterranean Buffaloes (Bubalus bubalis). In: *The Sustainability of Agro-Food and Natural Resource Systems in the Mediterranean Basin*, ed. A Vastola, pp. 57-64.

Soliman I. (2009) Present situation and future perspective of buffalo production in Africa. In: *6th Asian Buffalo Congress on 'Buffalo-prospective animal for milk and meat enterprises'. 27-30 October*.

Soysal M.I. (2013) Anatolian water buffaloes husbandry in Turkey. *Buffalo Bulletin* **32**: 293-309.

Soysal M.I., Tuna Y.T., Gurcan E.K., Ozkan E., Kok S., Castellano N., Cobanoglu O., et al. (2007) Anatolian water buffaloes husbandry in Turkey: preliminary results on somatic characterization. *Italian Journal of Animal Science* **6**: 1302-1307.

Staerfl S.M., Zeitz J.O., Kreuzer M., Soliva C.R. (2012) Methane conversion rate of bulls fattened on grass or maize silage as compared with the IPCC default values, and the long-term methane mitigation efficiency of adding acacia tannin, garlic, maca and lupine. *Agric. Ecosys. Env.* **148**: 111-120.

Swainson N., Muetzel S., Clark H. (2016) Updated predictions of enteric methane emissions from sheep suitable for use in the New Zealand national greenhouse gas inventory. *Animal Production Science* [Published online: 8 June 2016].

Troy S.M., Duthie C.A., Hyslop J.J., Roehe R., Ross D.W., Wallace R.J., Waterhouse A., Rooke J.A. (2015) Effectiveness of nitrate addition and increased oil content as methane mitigation strategies for beef cattle fed two contrasting basal diets. *J. Anim. Sci.* **93**: 1815-1823.

Vyas D., Alazzeh A., McGinn S.M., McAllister T.A., O M., Harstad, Holo H., Beauchemin K.A. (2016a) Enteric methane emissions in response to ruminal inoculation of Propionibacterium strains in beef cattle fed a mixed diet. *Animal Production Science* **56**: 1035-1040.

Vyas D., McGeough E.J., McGinn S.M., McAllister T.A., Beauchemin K.A. (2016b) Effect of Propionibacterium spp. on ruminal fermentation, nutrient digestibility, and methane emissions in beef heifers fed a high–forage diet. *Animal Production Science* **56**: 1035-1040.

Warner D., Bannink A., Hatew B., van Laar H., Dijkstra J. (2017) Effects of grass silage quality and level of feed intake on enteric methane production in lactating dairy cows. *Journal of Animal Science* **95**: 3687-3700.

Yang B., Zeng X.L.Q., Qin J., Yang C. (2007) Dairy buffalo breeding in countryside of China. *Italian Journal of Animal Science* **6**: 25-29.

Yilmaz O., Akin O., Yener S.M., Ertugrul M., Wilson R.T. (2012) The domestic livestock resources of Turkey: cattle local breeds and types and their conservation status. *Animal Genetic Resources/Ressources génétiques animales/Recursos genéticos animales* **50**: 65-73.

Yilmaz O., Wilson R.T. (2012) The domestic livestock resources of Turkey: Economic and social role, species and breeds, conservation measures and policy issues. *Livestock Research for Rural Development* **24**.

REFERENCES COPIED FROM THE 2006 IPCC GUIDELINES

Clark H., Brookes I., Walcroft A. (2003) *Enteric methane emissions from New Zealand ruminants 1999-2001 calculated using an IPCC Tier 2 approach. Report to the Ministry of Agriculture and Forestry.*: Note AL - Publisher Place etc missing.

Crutzen P.J., Aselmann I., Seiler W. (1986) Methane Production by Domestic Animals, Wild Ruminants, Other Herbivorous Fauna, and Humans. *Tellus* 38B: 271-284.

Johnson K., Huyler M., Westberg H., Lamb B., Zimmerman P. (1994) Measurement of Methane Emissions from Ruminant Livestock Using a SF6 Tracer Technique. *Environmental Science and Technology* 28: 359-362.

Johnson K.A., Johnson D.E. (1995) Methane emissions from cattle. *Journal of Animal Science* 73: 2483-2492.

Ulyatt M.J., Lassey K.R., Shelton I.D., Walker C.F. (2002a) Methane emission from dairy cows and wether sheep fed subtropical grass-dominant pastures in midsummer in New Zealand. *New Zealand Journal of Agricultural Research* 45: 227-234.

Ulyatt M.J., Lassey K.R., Shelton I.D., Walker C.F. (2002b) Seasonal variation in methane emission from dairy cows and breeding ewes grazing ryegrass/white clover pasture in New Zealand. *New Zealand Journal of Agricultural Research* 45: 217-226.

Ulyatt M.J., Lassey K.R., Shelton I.D., Walker C.F. (2005) Methane emission from sheep grazing four pastures in late summer in New Zealand. *New Zealand Journal of Agricultural Research* 48: 385-390.

Section 10.4 Methane Emissions from Manure Management

REFERENCES NEWLY CITED IN THE *2019 REFINEMENT*

Aguerre M.J., Wattiaux M.A., Powell J.M. (2012) Emissions of ammonia, nitrous oxide, methane, and carbon dioxide during storage of dairy cow manure as affected by dietary forage-to-concentrate ratio and crust formation. *J. Dairy Sci.* **95**: 7409-7416.

Amon B., Kryvoruchko V., Amon T., Zechmeister-Boltenstern S. (2006) Methane, nitrous oxide and ammonia emissions during storage and after application of dairy cattle slurry and influence of slurry treatment. *Agriculture, Ecosystems & Environment* **112**: 153-162.

Amon B., Kryvoruchko V., Fröhlich M., Amon T., Pöllinger A., Mösenbacher I., Hausleitner A. (2007) Ammonia and greenhouse gas emissions from a straw flow system for fattening pigs: Housing and manure storage. *Livestock Science* **112**: 199-207.

Balde H., VanderZaag A.C., Burtt S., Evans L., Wagner-Riddle C., Desjardins R.L., MacDonald J.D. (2016) Measured versus modelled methane emissions from separated liquid dairy manure show large model underestimates. *Agriculture Ecosystems & Environment* **230**: 261-270.

Cai Y., Chang S.X., Cheng Y. (2017) Greenhouse gas emissions from excreta patches of grazing animals and their mitigation strategies. *Earth-Science Reviews* **171**: 44-57.

Clemens J., Trimborn M., Weiland P., Amon B. (2006) Mitigation of greenhouse gas emissions by anaerobic digestion of cattle slurry. *Agriculture, Ecosystems & Environment* **112**: 171-177.

Dämmgen U., Amon B., Gyldenkærne S., Hutchings N.J., Klausing H.K., Haenel H.-D., Roesemann C. (2011) Reassessment of the calculation procedure for the volatile solids excretion rates of cattle and pigs in the Austrian, Danish and German agricultural emission inventories. *Landbauforschung Volkenrode* **61**: 115-126.

EEA (2016) *EMEP/EEA air pollutant emission inventory guidebook - 2016. Technical guidance to prepare national emission inventories*. Luxembourg: Publications Office of the European Union.

FAO (2017) *Global Livestock Environmental Assessment Model v2.0.* Data reference year 2010. Revision 4, June 2017.
Available at: *http://www.fao.org/fileadmin/user_upload/gleam/docs/GLEAM_2.0_Model_description.pdf*. Rome, Italy: Food and Agriculture Oganization of the United Nations.

Guarino A., Fabbri C., Brambilla M., Valli L., Navarotto P. (2006) Evaluation of simplified covering systems to reduce gaseous emissions from livestock manure storage. *Transactions of the Asabe* **49**: 737-747.

Hou Y., Velthof G.L., Oenema O. (2015) Mitigation of ammonia, nitrous oxide and methane emissions from manure management chains: a meta-analysis and integrated assessment. *Glob Chang Biol* **21**: 1293-1312.

Matulaitis R., Juskiené V., Juska R. (2015) The effect of floating covers on gas emissions from liquid pig manure. *Chilean Journal of Agricultural Research* **75**: 232-238.

Misselbrook T., Hunt J., Perazzolo F., Provolo G. (2016) Greenhouse gas and ammonia emissions from slurry storage: impacts of temperature and potential mitigation through covering (pig slurry) or acidification (cattle slurry). *Journal of Environmental Quality* **45**: 1520-1530.

Nielsen D.A., Schramm A., Nielsen L.P., Revsbech N.P. (2013) Seasonal methane oxidation potential in manure crusts. *Applied and environmental microbiology* 79: 407-410.

VanderZaag A.C., Gordon R.J., Glass V.M., Jamieson R.C. (2008) Floating covers to reduce gas emissions from liquid manure storages: a review. *Applied Engineering in Agriculture* **24**: 657.

VanderZaag A.C., Gordon R.J., Jamieson R.C., Burton D.L., Stratton G.W. (2009) Gas emissions from straw covered liquid dairy manure during summer storage and autumn agitation. *Transactions of the Asabe* **52**: 599.

REFERENCES COPIED FROM THE 2006 IPCC GUIDELINES

Sneath R.W., Phillips V.R., Demmers G.M., Burgess L.R., Short J.L. (1997) Long Term Measurements of Greenhouse Gas Emissions from UK Livestock Buildings. In: *Livestock Environment: Proceedings of the Fifth International Symposium. Bloomington MN. May 29-31 Bio-Engineering Division, Silsoe Research Institute, Wrest Park, Silsoe, Bedford, MK45 4HS.*

Section 10.5 N_2O Emissions from Manure Management

REFERENCES NEWLY CITED IN THE *2019 REFINEMENT*

Asman W.A.H., Sutton M.A., Schjorring J.K. (1998) Ammonia: emission, atmospheric transport and deposition. *New Phytologist* **139**: 27-48.

Boonsinchai N., Potchanakorn M., Kijparkorn S. (2016) Effects of protein reduction and substitution of cassava for corn in broiler diets on growth performance, ileal protein digestibility and nitrogen excretion in feces. *Animal feed science and technology* **216**: 185-196.

Chiba, L.I. (2009) Animal Nutrition Handbook, Arkansas University

du Toit C.J.L., van Niekerk W.A., Meissner H.H. (2013) Direct methane and nitrous oxide emissions of monogastric livestock in South Africa. *South African Journal of Animal Science* **43**: 362-3875.

EEA (2016) *EMEP/EEA air pollutant emission inventory guidebook - 2016. Technical guidance to prepare national emission inventories*. Luxembourg: Publications Office of the European Union.

FAO (2017) *Global Livestock Environmental Assessment Model v2.0*. Data reference year 2010. Revision 4, June 2017.
Available at: *http://www.fao.org/fileadmin/user_upload/gleam/docs/GLEAM_2.0_Model_description.pdf*. Rome, Italy: Food and Agriculture Oganization of the United Nations.

Gasco L., Rotolo L., Masoero G., Miniscalco B., Zoccarato I. (2014) Urine features used to survey nitrogen excretion in rabbits. *World Rabbit Sci.* **22**: 187-194.

MacLeod M., Gerber P., Mottet A., Tempio G., Falcucci A., Opio C., Vellinga T., Henderson B., Steinfeld H. (2013) *Greenhouse gas emissions from pig and chicken supply chains – A global life cycle assessment*. Food and Agriculture Organization of the United Nations (FAO), Rome.

Maertens L., Cavani C., Petracci M. (2005) nitrogen and phosphorus excretion on commercial rabbit farms: calculations based on the input-output balance. *World Rabbit Sci.* **13**: 1-16.

Ministry for the Environment (2018) *New Zealand's Greenhouse Gas Inventory 1990-2016. Fulfilling reporting requirements under the United Nations Framework Convention on Climate Change and the Kyoto Protocol*. Wellington, New Zealand: Ministry for the Environment.

Nielsen O.-K., Plejdrup M.S., Winther M., Nielsen M., Gyldenkærne S., Mikkelsen M.H., Albrektsen R., et al. (2018) *Denmark's National Inventory Report 2018. Emission Inventories 1990-2016 - Submitted under the United Nations Framework Convention on Climate Change and the Kyoto Protocol. Scientific Report from DCE – Danish Centre for Environment and Energy No. 272.*: Aarhus University, DCE – Danish Centre for Environment and Energy. pp. 851.

Poulsen H.D., Kristensen V.F. (1998) *Standard values for farm manure. A Revaluation of the Danish Standard Values concerning the nitrogen, Phosphorus and Potassium content of manure. Report n.7*. Tjele, Denmark: Animal Husbandry, Danish Institute of Agricultural Sciences, Ministry of Food, Agriculture and Fisheries.

Reis L.S., Oliveira T.C. (2008) Ostrich (Strutio camelus) Meat Protein Quality and Digestibility. *Brazilian Journal of Poultry Science* **10**: 185-188.

Shields R., Mahan D., Graham P. (1983) Changes in Swine Body Composition from Birth to 145 kg. *Journal of Animal Science* **57**: 43-54.

Velthof G.L. (2014) *Report Task 1 of Methodological studies in the field of Agro-Environmental Indicators. Lot 1 excretion factors. Final draft*. Wageningen.

Velthof G.L., Hou Y., Oenema O. (2015) nitrogen excretion factors of livestock in the European Union: a review. *J Sci Food Agric* **95**: 3004-3014.

Webb J. (2001) Estimating the potential for ammonia emissions from livestock excreta and manures. *Environmental Pollution* **111**: 395-406.

Webb J., Misselbrook T.H. (2004) A mass-flow model of ammonia emissions from UK livestock production. *Atmospheric environment* **38**: 2163-2176.

Williams C.M. (2013) Poultry waste management in developing countries. The role of poultry in human nutrition. **46**.

Xiccato G., Schiavon S., Gallo L., Bailoni L., Bittante G. (2005) nitrogen excretion in dairy cow, beef and veal cattle, pig, and rabbit farms in Northern Italy. *Italian Journal of Animal Science* **4**: 103-111.

REFERENCES COPIED FROM THE 2006 IPCC GUIDELINES

Bierman S., Erickson G.E., Klopfenstein T.J., Stock R.A., Shain D.H. (1999) Evaluation of nitrogen and organic matter balance in the feedlot as affected by level and source of dietary fiber. *Journal of Animal Science* 77: 1645-1653.

Döhler H., Eurich-Menden B., Dämmgen U., Osterburg B., Lüttich M., Bergschmidt A., Berg W., et al. (2002) *BMVEL/UBA-Ammoniak-Emissionsinventar der deutschen Landwirtschaft und Minderungsszenarien bis zum Jahre 2010. Texte 05/02*. Berlin, Germany: Umweltbundesamt.

Dustan A. (2002) Review of methane and nitrous oxide emission factors in cold climates. *Institutet for jordbruks- och miljoteknik, JTI-rapport, Lantbruk & Industri* 299.

Eghball B., Power J.F. (1994) Beef-Cattle Feedlot Manure Management. *Journal of Soil and Water Conservation* 49: 113-122.

Hutchings N.J., Sommer S.G., Andersen J.M., Asman W.A.H. (2001) A detailed ammonia emission inventory for Denmark. *Atmospheric environment* 35: 1959-1968.

Monteny G.J., Erisman J.W. (1998) Ammonia emission from dairy cow buildings: A review of measurement techniques, influencing factors and possibilities for reduction. *Netherlands Journal of Agricultural Science* 46: 225-247.

NRC (1996) *Nutrient Requirements of Beef Cattle, 7th Revised Ed.* Washington, DC: The National Academies Press.

Rotz C.A. (2004) Management to reduce nitrogen losses in animal production. *J. Anim. Sci.* 82 (E. Suppl): E119-E137.

References Annexes

REFERENCES NEWLY CITED IN THE *2019 REFINEMENT*

Annex 10A.1 Data underlying methane default emission factors for Enteric Fermentation, Volatile solids and nitrogen excretion and retention fractions for Cattle and Buffalo

(see References in Annex 10B.1)

Annex 10A.2 Additional data and information for the calculation of methane and nitrous oxide from Manure Management

FAO (2017) Global Livestock Environmental Assessment Model v2.0. Data reference year 2010. Revision 4, June 2017. Available at: http://www.fao.org/fileadmin/user_upload/gleam/docs/GLEAM_2.0_Model_description.pdf. Rome, Italy: Food and Agriculture Oganization of the United Nations.

MacLeod M., Vellinga T., Opio C., Falcucci A., Tempio G., Henderson B., Makkar H., Mottet A., Robinson T., Steinfeld H., Gerber, P. (2017) Invited review: A position on the Global Livestock Environmental Assessment Model (GLEAM). animal **12(2)**: 1-15.

Annex 10A.3 MCF Spreadsheet example for the calculation of a country or regions specific MCF

Intergovernmental Panel on Climate Change (IPCC) (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. Prepared by the National Greenhouse Gas Inventories Programme, eds. HS Eggleston, L Buendia, K Miwa, T Ngara, K Tanabe. Japan: IGES.

Annex 10A.4 Calculations of Methane Conversion Factors (MCFs) for biogas systems

Rösemann C., Haenel H.-D., Dämmgen U., Freibauer A., Wulf S., Eurich-Menden B., Döhler H., Schreiner C., Osterburg B. (2017) Calculation of gaseous and particulate emissions from German agriculture 1990 – 2015. Report on methods and data (RMD). Submission 2017. *Thünen Rep* **46**.

Annex 10A.5 Equations relating all direct and indirect N_2O emissions from manure along all stages in agricultural production for livestock

No references.

Annex 10.B Data and Explanatory Text for Development of New Parameters in the *2019 Refinement*

10B.1 Raw data used to compile Annex 10A.1 enteric fermentation Tier 1 emission factors, volatile solids and nitrogen excretion for cattle and buffalo

Abd El-Salam M.H., El-Shibiny S. (2011) A comprehensive review on the composition and properties of buffalo milk. *Dairy Science and Technology* **91**: 663-699.

Abd-Allah M., Elaref M.Y., Zanouny A.I. (2015) Influence of different managerial systems on performance and physiological responses of developing buffalo calves during fattening period. *Egyptian J. Anim. Prod* **52**: 1-9.

Abdel Rahman M.K. (2007) Sudanese cattle resources and their productivity. A review. *Agric. Rev* **28**: 305-308.

Abdelhadi O.M.A., Babiker S.A. (2009) Prediction of zebu cattle live weight using live animal measurements. *Livestock Research for Rural Development* **21**: 1-6.

Abera M. (2016) Reproductive and Productive Performances of Crossbred and Indigenous Dairy Cattle under Rural, peri-urban and Urban Dairy Farming Systems in West Shoa Zone, Oromia, Ethiopia. **43**.

Abraha S., Belihu K., Bekana M., Lobago F. (2009) Milk yield and reproductive performance of dairy cattle under smallholder management system in North-eastern Amhara Region, Ethiopia. *Trop Anim Health Prod.* **41**.

Addisu B., Mengistie T., Adebabay K., Getinet M., Asaminew T., Tezera M., Gebeyehu G. (2010) Milk yield and calf growth performance of cattle under partial suckling system at Andassa Livestock Research Centre, North West Ethiopia. *Livestock Research for Rural Development*. **22(8)**.

Adebambo O.A. (2001) The Muturu: A rare sacred breed of cattle in Nigeria. *Animal Genetic Resources Information* **31**: 27-36

Adesina K. (2012) Effect of Breed on the Composition of Cow Milk under Traditional Management Practices in Ado-Ekiti, Nigeria. *J. Appl. Sci. Environ. Manag.* **16**: 55-59.

Afzal M., Anwar M., Mirza M.A., Adrabi S.M.H. (2009) Comparison of Growth Rate of Male Buffalo Calves under Open Grazing and Stall Feeding System. *Pakistan Journal of Nutrition* **8**: 187-188.

Ageeb A.G., Hillers J.K. (1991) Production and reproduction characteristics of Butana and Kenana cattle of the Sudan. *World Animal Review* **2**: 49-56.

AGRI-IS (2017) An Information System on Animal Genetic Resources of India. URL http://14.139.252.116/agris/breed.aspx.

Ahamefule F.O., Ibeawuchi J.A., Okereke S.N., Anyanwu A.C. (2007) Reproductive Performance of White Fulani, N'Dama and their crossbred in a hot humid environment. *Journal of Animal and Veterinary Advances* **6**: 955-958.

Ahmad F., Jabbar M.A., Ahmad I., Afzal M. (2004) Comparative Fattening Potential and Carcass Evaluation of Simmental and Brown Swiss Crossbred Calves. *International Journal of Agriculture &Biology* **6**.

Ahmad I., Fiaz M., Manzoor M.N., Ahmad T., Yaqoob M., Jo I.H. (2013) Comparative Growth Performance of Calves of Different Cattle Breeds Under a Feedlot Fattening System. *Journal of Animal Science and Technology* **55**: 539-543.

Ahmed Hassan J.Z. (2010) Identification and Evaluation Dairy cattle Feeding System and their Effects on Milk Yield and Composition in Abasseya Locality, Sudan. University of Kordofan.

Ahmed M.I.A., Zubeir I.E.M.E. (2013) Husbandry Practices and Hygiene in Dairy Farms in Khartoum State, Sudan. *U of K. J. Vet. Med. & Anim. Prod* **4**: 16-35.

Akbaş Y., Alçiçek A., Önenç A., Güngör M. (2006) Growth curve analysis for body weight and dry matter intake in Friesian, Limousin x Friesian and Piemontese x Friesian cattle. *Arch.Tierz., Dummerstorf*.

Albarrán-Portillo B., Rebollar-Rebollar S., García-Martínez A., Rojo-Rubio R., Avilés-Nova F., Arriaga-Jordán C.M. (2015) Socioeconomic and productive characterization of dual-purpose farms oriented to milk production in a subtropical region of Mexico. *Tropical Animal Health and Production* **47**: 519-523.

Albertini T.Z., Medeiros S.R., Torres Júnior R.A.A., Zocchi S.S., Oltjen J.W., Strathe A.B., Lanna D.P.D. (2012) A methodological approach to estimate the lactation curve and net energy and protein requirements of beef cows using nonlinear mixed-effects modeling. *Journal of Animal Science* **90**: 3867-3878.

Alejandrino A.L., Asaada C.O., Malabayabasb B., De Veraa A.C., Herreraa M.S., Deocarisa C.C., Ignacioa L.M., et al. (1999) Constraints on dairy cattle productivity at the smallholder level in the Philippine. *Preventive Veterinary Medicine* **38**: 167-178.

Alemayehu M., Wondatir Z., Gojjam Y., Gebriel K.W. (2013) Evaluation of friesian x boran crossbred and Ethiopian Highland Zebu oxen with a reciprocal work effect on carcass characteristics. **1**: 1-7.

Ali A., Abdel-Razek A.K., Derar R., Abdel-Rheem H., Shehata S. (2009) Forms of Reproductive Disorders in Cattle and Buffaloes in Middle Egypt. *Reproduction in Domestic Animals* **44**: 580-586.

Ali I.E., Ishag I.A., Ibrahim F.H., Magzoob A., Ahmed M.-k.A., Angus R. (2015) Impact of Genetic and Non-Genetic Factors on Birth Weight of Crossbred Red Angus and Simmental with Local Cattle. **2**: 80-84.

Alsiddig M.A., Babiker S.A., Galal M.Y., Mohammed A.M. (2010) Phenotypic Characterization of Sudan Zebu Cattle (Baggara Type). *Research Journal of Animal and Veterinary Sciences,* 10-17.

Amaral T.B., Corrêa E.S., Costa F.P. (2005) *Suplementação Alimentar de Baças de Cria: Quando e Por que Fazer? Campo Grande: Embrapa Gado de Corte. (Documentos, n. 156)*.

Amerkhanov K., Polovinko L., Kalashnikov N., Kayumov F. (2016) Characteristics of the genetic material in breeding high-productive type «Voznesenovsky» of the Kalmyk cattle. *Bulletin of meat breeding* **4**: 15-21.

Ancco E. (2015) *Efecto de la sincronización y resincronización de celo sobre la preñez en vacas Brown Swiss utlizando progestágenos en la Estación Experimental Agraria Illpa*, Peru: Universidad Nacional del Altiplano.

Andrade V.J.d., Garcia S.K. (2005) Padrões raciais e registro de bubalinos. Breed characterization and registry in water buffaloes (Bubalus bubalis). *Rev Bras Reprod Anim, Belo Horizonte* **259**: 39-45.

Andrighetto C., Jorge A.M., Gomes M.I.F.V., Hoch A., Piccinin A. (2005) Efeito da Monensina Sódica sobre a Produção e Composição do Leite, a Produção de Mozzarela e o Escore de Condição Corporal de Búfalas Murrah. *R. Bras. Zootec.* **34**: 641-649.

Anitha A., Rao K.S., Suresh J., Moorthy P.R.S., Reddy Y.K. (2011) Body condition score (bcs) system in murrah buffaloes. *Buffalo Bulletin* **30**: 79-99.

Anjum M.I., Azim A., Jabbar M.A., Anwar M., Mirza I.H. (2012) Age and Weight at Puberty in Nili-Ravi Buffalo Heifers Reared on Three Dietary Energy Restriction Periods followed by Compensatory Growth. *Pakistan Veterinary Journal* **32**: 367-371.

Anjum M.I., Azim A., Jabbar M.A., Nadeem M.A., Mirza I.H. (2012) Effect of Low Energy Followed by High Energy Based Total Mixed Diets on Growth Rate , Blood Haematology and Nutrient Digestibility in Growing Buffalo Heifers. *Pakistan Journal of Zoology* **44**: 399-408.

Appuhamy J.A., France J., Kebreab E. (2016) Models for predicting enteric methane emissions from dairy cows in North America, Europe, and Australia and New Zealand. *Glob Chang Biol* **22**: 3039-3056.

Ariff O.M., Sharifah N.Y., Hafidz A.W. (2015) Status of beef industry of Malaysia. *Mal. J. Anim. Sci* **18**: 1-21.

Ashour G., Omran F.I., Yousef M.M., Shafie M.M. (2007) Effect of thermal environment on water and feed intakes in relationship with growth of buffalo calves. *Egyptian J. Anim. Prod* **44**: 25-33.

Asimwe L., Kimambo A.E., Laswai G.H., Mtenga L.A., Weisbjerg M.R., Madsen J., Mushi D.E. (2015) Growth performance and carcass characteristics of Tanzania Shorthorn Zebu cattle finished on molasses or maize grain with rice or maize by-products. *Livestock Science* **182**: 112-117.

Atanasov A.S., Dineva J.D., Yotov S.A. (2012) Ultrasonic evaluation of uterine involution in Bulgarian Murrah buffalo after administration of oxytocin. *Animal Reproduction Science* **133**: 71-76.

Australian Government Department of Climate Change (2007) *Australian Methodology for the estimation of Greenhouse Gas Emissions and Sinks 2006. Agriculture.* (National Greenhouse Gas Inventory Committee, Australian Government: Canberra).

Azary M., Manafiazar G., Razagzadeh S., Amini-jabalkandi J. (2007) Comparing fattening performance of Azeri buffalo, native and crossbred (native* Holstein) male calves in west Azerbaijan - Iran. *Italian Journal of Animal Science* **6**: 1152-1255.

Azaubaeva G.S. (2008) nitrogen and energy metabolism, milk productivity of cows due to change in diet ration. *Agrarian Bulletin of the Urals* **3**: 41-43.

Bakharev A.A. (2012) Milk productivity and milk content of beef breed cows. *Agricultural policy of the Russian Federation* **9**: 57-59.

Bannink A., van Schijndel M.W., Dijkstra J. (2011) A model of enteric fermentation in dairy cows to estimate methane emission for the Dutch National Inventory Report using the IPCC Tier 3 approach. *Animal feed science and technology* **166-167**: 603-618.

Bannink A., Warner D., Hatew B., Ellis J.L., Dijkstra J. (2016) Quantifying effects of grassland management on enteric methane emission. *Animal Production Science* **56**: 409-416.

Barajas Merchan J.L., Hernández Cerón J., García Alfonso A., Martínez Bárcenas E., Juárez López N.O., Bedolla Alva M.A., De la Sota R.L. (2017) Endometritis subclínica y tasa de gestación en vacas lecheras en México. *Revista Mexicana de Ciencias Pecuarias* **9**: 135.

Barrantes C. (2000) *Efecto de la forma de presentación física del alimento y el uso de insumos grasos sobre el crecimiento de terneros Holstein en crianza intensiva. Tesis Ing. Zootecnista*, Perú: UNALM. Perú.

Bartl K., Mayer A.C., Gómez C.A., Muñoz E., Hess H.D., Holmann F. (2009) Economic evaluation of current and alternative dual-purpose cattle systems for smallholder farms in the central Peruvian highlands. *Agricultural Systems* **101**: 152-161.

Basarab J.A., Okine E.K., Baron V.S., Marx T., Ramsey P., Ziegler K., Lyle K. (2005) Methane emissions from enteric fermentation in Alberta's beef cattle population. *Canadian Journal of Animal Science* **85**: 501-512.

Bashir H.H.A., El Zubeir I.E.M. (2013) Milk Production and Reproduction Performance of Baggara Cattle Raised Under Extensive and Semi- Extensive Systems in South Kordofan State, Sudan. *J. Anim. Prod. Adv.* **3**: 192-202.

Basra M.J., Nisa M., Khan M.A., Riaz M., Tuqeer N.A., Saeed M.N. (2003) Nili-Ravi Buffalo III. Energy and Protein Requirements of 12 – 15 Months Old Calves. *International Journal of Agriculture&Biology* **5**: 382-383.

Batosarnma J.A. (2006) Potential and application of reproduction technologies of water buffaloes in Indonesia. In: *Proc. International Seminar on Artificial Reproductive Biotechnologies for Buffaloes 2006*. Bogor, Indonesia.

Becoña G. (2012) *Emisiones de gases de efecto invernadero en sistemas de cría vacuna del Uruguay. Tesis de Maestria.* Facultad de Agronomía, Uruguay.

Behnke R., Osman H.M. (2012) The contribution of livestock to the Sudanese economy. In: *IGAD LPI Working Paper*, Addis Ababa, Ethiopia: IGAD Livestock Policy Initiative.

Beldman A., Junfei B., Binbin C., Zhijun C., Xiangming D.W.F., Huiyuan G., Pei G., et al. (2014) White paper on China dairy. In: Sino-Dutch Dairy Development Centre.

Berthouly C. (2008) *Characterisation of the cattle , buffalo and chicken populations in the Northern Vietnamese province of Ha Giang*, Paris, France: Ecole Doctorale: ED 435 Agriculture, Alimentation, Biologie, Environnements et Santé, AgroParistech. pp. 263.

Birthal P., Parthasarathy Rao P. (2002) Technology options for sustainable livestock production in India. In: *Workshop on Documentation, Adoption, and Impact of Livestock Technologies in India*, eds. P Birthal, P Parthasarathy Rao.

Blench R. (1999) Traditional Livestock Breeds: Geographical Distribution and Dynamics in Relations to the Ecology of West Africa. *Overseas Development Institute Portland House Stag Place London, SW1E 5DP* Working Paper 122: 1-69.

Borghese A. (2010) *Development and perspective of Buffalo and Buffalo market in Europe and Near East*, Buones Aires.

Borghese A. (2013) Buffalo livestock and products in Europe. *Buffalo Bulletin* **32**: 50-74.

Boro P., Naha B.C., Prakash C., Madkar A., Kumar N., Kumari A., Channa G.P. (2016) Genetic and Non-Genetic Factors Affecting Milk Composition in Dairy Cows. *International journal of advanced biological research* **6**: 170-174.

Bradfield M., Ismail T. (2012) *Meat Value Chain Assessment of the Livestock Sector in Pakistan. USAID Agribusiness Project (UAP)*, ed. CNFA.

Breeding survey book (2013) *Estimated Livestock Population Breed Wise Based on Breed Survey 2013*, New Delhi: Department of Animal Husbandry, Dairying & Fisheries, Government of India.

Cândido E.P., Pimenta Filho E.C., Gonzaga Neto S., Santos E.M., Moura J.F.P. (2015) Análise dos Sistemas de Produção de Bovinos Leiteiros do Cariri Oriental da Paraíba. *Revista Científica de Produção Animal* **17**: 7-17.

Capper J.L. (2011) The environmental impact of beef production in the United States: 1977 compared with 2007. *Journal of Animal Science* **89**: 4249-4261.

Carabao situation report (2017) *Carabao situation report*, Republic of the Philippines: Philippine statistics authority.

Cardoso C.J.T., Da Silva K.C., Anache N.A., Rodrigues W.B., De Lima A.C.B., Ferreira M.G.C.R., Sterza F.A.M., et al. (2017) *Supplementation with protected FAT in the dairy buffalo cows pregnancy rate. Proceedings of the 31st Annual Meeting of the Brazilian Embryo Technology Society (SBTE); Cabo de Santo gostinho, PE, Brazil, August 17th to 19th, 2017*.

Cardoso E.C., Vale W.G., McDowel L.R., Wilkinson N.S., Simão Neto M., Veiga J.B., Lourenço Jr. J.B. (1997) Seasonal Variation of Selenium, Crude Protein, and In Vitro Organic Matter Digestibility of Brachiaria humidicola from Marajó Island. *Brazil. Commun. Soil Sci. Plant Anal.* **28**: 1683-1691.

Cardoso R.B., Pedreira M.d.S., Rech C.L.d.S., Silva H.G.d.O., Rech J.L., Schio A.R., Aguiar L.V., et al. (2017) Produção e composição química do leite de vacas em lactação mantidas a pasto submetidas à diferentes sistemas alimentares. *Revista Brasileira de Saúde e Produção Animal* **18**: 113-126.

Carriquiry M., Espasandín A., Soca P., Astessiano A.L., Casal A., Guitérrez V., Laporta J., et al. (2013) Metabolismo de la vaca de carne y su cría en pastoreo de campo nativo: un enfoque endócrino-molecular. In: Montevideo, Uruguay: Instituto Nacional de Investigación Agropecuaria (Uruguay).

Castro J.C.M., Rivera J.C., Zavaleta J.A. (2012) Redalyc Characteristics of the production and marketing of bovine milk in double purpose systems in Dobladero, Veracruz. *Revista Mexicana de Agronegocios* **16**: 816-824.

CBAT (2017) Cattle Breeders' association of Turkey (CBAT). URL http://cbat.org/.

Çelikeloğlu K., Erdoğan M., Koçak S., Zemheri F., Tekerli M. (2015) The effect of environmental factors and Growth Hormone Receptor gene polymorphism on growth curve and live weight parameters in buffalo calves. *Araşt. Enst. Derg* **55**: 45-49.

Central Statistical Agency (2017) Agricultural Sample Survey 2016/17 [2009 e.c.] Volume II. Report on Livestock and Livestock Characteristics (Private Peasant Holdings). *Statistical Bulletin* **585**: 1-194.

Chabo R.G., Koka D.C., Oageng T. (2003) Milk Yield During the First Four Months of Lactation and Cow Productivity of Brahman and Tuli Beef Cattle in South-East Botswana. *Journal of Agriculture and Rural Development in the Tropics and Subtropics* **104**: 65-70.

Chang H.-L., Huang Y.-C. (2003) *The relationship between indigenous animals and humans in APEC region*, Taiwan: The Chinese Society of Animal Science. pp 186.

Chashnidel Y., Pirsaraei A., Yousef-Elahi M. (2007) Comparison of daily weight gain and fattening characteristics between buffalo and Holstein male calves with different diets. *Italian Journal of Animal Science* **6**: 1199-1201.

Chavez H. (2010) *Efecto de maíz extruido en la alimentación de terneros destetados. Tesis Ing. Zootecnista, Universidad Nacional Agraria La Molina*, Perú: UNALM. Perú.

Cheng P. (1984) *Livestock breeds of China. FAO Animal Production and Health Paper 46*, Rome, Italy: FAO. pp. 1-217.

Chowdhry N.R. (2007) *Production system analysis of Tharparkar cattle in its breeding tract. PhD Thesis*: Deemed University, National Dairy Research Institute, Karnal, Haryana, India.

Ciudad de México Financiera Rural (2009) Bovino y sus derivados. URL http://www.gbcbiotech.com/bovinos/industria/Bovino%20y%20sus%20derivados%20Financiera%20Rural%202012.pdf.

Coelho K.O., Machado P.F., Coldebella A., Cassoli L.D., Corassin C.H. (2004) Determinação do perfil físico-químico de amostras de leite de búfalas, por meio de analisadores automáticos. *Ciência Animal Brasileira, Goiânia* **5**: 167-170.

Condor R.D., Valli L., De Rosa G., Di Francia A., De Lauretis R. (2008) Estimation of the methane emission factor for the Italian Mediterranean buffalo. *animal* **2**: 1247-1253.

Corbet N.J., Shepherd R.K., Burrow H.M., van der Westhuize J., Strydom P.E., Bosman D.J. (2006) Evaluation of Bonsmara and Belmont Red cattle breeds in South Africa. 1. Productive performance. *Australian Journal of Experimental Agriculture* **46**: 99-212.

Cruz L. (2012) Transforming swamp buffaloes to producers of milk and meat through crossbreeding and backcrossing. *JAPS, Journal of Animal and Plant Sciences* **22**: 157-168.

Cruz L.C. (2007) Trends in buffalo production in Asia. *Italian Journal of Animal Science* **6**: 9-24.

Cui D., Wang X., Wang L., Wang X., Zhang J., Qin Z., Li J., Yang Z. (2014) The administration of Sheng Hua Tang immediately after delivery to reduce the incidence of retained placenta in Holstein dairy cows. *Theriogenology* **80**: 645-650.

Cunha C.S., Lopes N.L., Veloso C.M., Jacovine L.A.G., Tomich T.R., Pereira L.G.R., Marcondes M.I. (2016) Greenhouse gases inventory and carbon balance of two dairy systems obtained from two methane-estimation methods. *Science of the Total Environment* **571**: 744-754.

da Cunha D.N.F.V., Pereira J.C., de Campos O.F., Gomes S.T., Braga J.L., Martuscello J.A. (2010) Simulation of Holstein and Jersey profitability by varying milk price payment system. *R. Bras. Zootec.*

Dahiya S.S., Singh P. (2013) Nutritional and other management practices for optimum semen production in buffalo bulls. *Buffalo Bulletin* **32**: 277-284.

Dairy NZ, LIC (2018) URL www.dairynz.co.nz/dairystatistics.

Dairy Technical Working Group (2015) Review of the methods and data used to estimate dairy cattle emissions in the national inventory. A report to Department of the Environment, Australia.

Damé M.C.F., de Lima C.T.S., Marcondes C.R., Ribeiro M.E.R., Garner A.D.V., dos Santos C.d.S. (2010) *Produção e Qualidade de Leite de Bubalinos no Rio Grande do Sul: dados preliminares*, Pelotas, RS: Empresa Brasileira de Pesquisa Agropecuária; Embrapa Clima Temperado; Ministério da agricultura, Pecuária e abastecimento.

Das A., Das D., Goswami R.N., Bhuyan D. (2004) Growth performance of swamp buffaloes of assam from birth to 12 months of age. *Buffalo Bulletin* **23**: 84-89.

Deb G.K., Nahar T.N., Duran P.G., Presicce G.A. (2016) Safe and Sustainable Traditional Production: The Water Buffalo in Asia. *Frontiers in Environmental Science* **4**: 1-7.

Dekeba A., Ayalew W., Hedge P.B., Taddese Z. (2006) Performance of the Abernosa Ranch in the Production of Ethiopian Boran X Holstein Crossbreed Dairy Heifers in Ethiopia. *Ethiopial Journal of Animal Production* 33-55.

Department of Veterinary Services (2013) Malaysian Livestock Breeding Policy, 2013. In: Ministry of Agriculture and Agro-based Industry Malaysia.

Deshetti M.B., Teggi M.Y., Gadd G.M., Sadashivanagowda S.N.O. (2016) Economics of dairy enterprise under stall-fed condition in Vijayapura and Bagalakote Districts of Karnataka, India. *Eco. Env. & Cons.*

Dezfuli B.T., Mashayekhi B., Kordnejad E., Mansori H., Alboshoke N. (2010) *Designing special weight tape for Khuzestani buffaloes*, Ahwaz, Islamic Republic of Iran: Agriculture and Natural Resources Research Center of Khuzestan.

Dezfuli B.T., Javaremi A.N., Abbasi M.A., Fayazi J., Chamani M. (2011) Economic weights of milk production traits for buffalo herds in the southwest of Iran using profit equation. *World Applied Sciences Journal* **15**: 1604-1613.

Dhanda O.P. *Buffalo Production Scenario in India : Opportunities and Challenges*.

Dhingra S., Mehta R., Krishnaswamy S. (2017) AFOLU Emissions. Version 2.0 dated September 28, 2017, from GHG platform India: GHG platform - India-2005-2013 National Estimates - 2017 URL http://ghgplatform-india.org/data-and-emissions/afolu.html.

Dimov K., Tzankova M. (2003) Study of the Feeding Behaviour and Conversion of Feed in Buffalo Calves on Diets Different in Structure. **22**: 20-23.

Dinh V.C. (2007) *Overview of Beef Production in Vietnam*, Ho Chi Minh City: Agriculture Publishing House.

Djaja W. (2011) An Introduction Study on Characteristic of Body Length , Withers Height , and Body Weight of Murrah Female Buffalo in Deli Serdang and Serdang Bedagai County , North Sumatra Province. *Lucrări Ştiinţifice, Seria Zootehnie* **55**: 213-216.

Djajanegara A., Diwyanto K. (2002) Development Strategies for Genetic Evaluation of Beef Production in Indonesia. In: *Development Strategies for Genetic Evaluation for Beef Production in Developing Countries*. Proceedings of an International Workshop held in Khon Kaen Province, Thailand, July 23–28 2001, eds. J Allen, A Na-Chiangmai, p. 180.

Dong L.F., Zhang W.B., Zhang N.F., Tu Y., Diao Q.Y. (2017) Feeding different dietary protein to energy ratios to Holstein heifers: effects on growth performance, blood metabolites and rumen fermentation parameters. *Journal of Animal Physiology and Animal Nutrition* **101**: 30-37.

Dong R.L., Zhao G.Y., Chai L.L., Beauchemin K.A. (2014) Prediction of urinary and fecal nitrogen excretion by beef cattle. *J Anim Sci* **92**: 4669-4681.

Dong S.-W., Shi-Dong Z., Dong-Sheng W., Hui W., Xiao-Fei S., Ping Y., Zuo-Ting Y., et al. (2015) Comparative proteomics analysis provide novel insight into laminitis in Chinese Holstein cows. *BMC Veterinary Research* **11**.

dos Santos C.L.R., dos Santos Júnior J.B., da Cunha M.C., Nunes S.R.F., Bezerra D.C., de Souza Torres Júnior J.R., Chaves N.P. (2016) Nível tecnológico e organizacional da cadeia produtiva da bubalinocultura de corte no estado do Maranhão. *Arq. Inst. Biol* **83**.

Du Toit C., Meissner H., Van Niekerk W. (2013) Direct methane and nitrous oxide emissions of South African dairy and beef cattle. *South African Journal of Animal Science* **43**: 320.

Dunin I., Sharkaev V., Kochetkov A. (2011) Performance results of beef cattle production branch in the Russian Federation. *Dairy and Beef Cattle Breeding* **5**: 2-5.

Edea Z., Dadi H., Kim S.-W., Dessie T., Lee T., Kim H., Kim J.-J., et al. (2013) Genetic diversity, population structure and relationships in indigenous cattle populations of Ethiopia and Korean Hanwoo breeds using SNP markers. *Frontiers in Genetics* **4**: 1-9.

El-Asheeri A. K. (2012) Economic return of fattening Baladi and buffalo calves under prevailing system in Egypt. *J.Animal and Poultry Prod., Mansoura Univ* **3**: 21-28.

Elrshied I., Ishag A.I. (2015) Body Weight and Growth Rate of Crossbred (F1) Beef Cattle (Red Angus and Simmental with Local Cattle). Presentation. University OF Khartoum Faculty OF Animal Production.

Engida E., Guthiga P., Karugia J. (2015) The Role of Livestock in the Tanzanian Economy: Policy Analysis Using a Dynamic Computable General Equilibrium Model for Tanzania. In: *International Conference of Agricultural Economics*, Italy.

Essien A. (2003) Heterosis for birth weight in N'Dama F1 crossbred calves in South western Nigeria. Livestock Research for Rural Development. **15**.

Ethiopia F.D.R.o. (2011) *Agricultural Sample Survey 2010/11 [2003 E.C.] Volume II. Report on Livestock and Livestock Characteristics (Private Peasant Holdings)*, Addis Ababa, Ethiopia: Federal Democratic Republic of Ethiopia Central Statistical Agency.

Euclides V.P.B., Medeiros S.R.d. (2003) Principais Gramíneas Cultivadas no Brasil. 43.

FAO (2003) Report on Domestic Animal Genetic Resources in China. Country Report for the Preparation of the First Report on the State of the World's Animal Genetic Resources. In: Bejing, China: FAO.

FAO (2005) *Buffalo production and research. REU Technical Series 67*, Rome, Italy: FAO regional office for Europe, inter-regional cooperative research network on buffalo (ESCORENA). pp. 178-179.

FAO (2016) Global Agro-Ecological Zones (GAEZ), Version 3. URL http://gaez.fao.org/.

FAO (2017) *Global Livestock Environmental Assessment Model v2.0. Data reference year 2010. Revision 4, June 2017. Available at: http://www.fao.org/fileadmin/user_upload/gleam/docs/GLEAM_2.0_Model_description.pdf*, Rome, Italy: Food and Agriculture Organization of the United Nations.

FAO (2017) World Animal Review. URL http://www.fao.org/docrep/004/X6512E/X6512E22.htm\#ch22.

FAO, IAEA (2011) Genetic characterization of indigenous cattle breeds in Zambia - which way forward?

FAO, IDF, IFCN (2014) *World mapping of animal feeding systems in the dairy sector*, Rome, Italy: Food and Agriculture Organization of the United Nations, International Dairy Federation, IFCN Dairy Research Network. pp. 160.

FAOSTAT (2017) *http://www.fao.org/faostat/en/*.

Farmer E., Mbwika J. (2012) End Market Analysis of Kenyan Livestock and Meat: A Desk Study. *USAID* 1-35.

Fatahnia F., Rowghani E., Hosseini A.R., Darmani Kohi H., Zamiri M.J. (2010) Effect of different levels of monensin in diets containing whole cottonseed on milk production and composition of lactating dairy cows. *Iranian Journal of Veterinary Research, Shiraz University*.

Feedipedia (2015) Feedipedia Animal feed resources information system. URL https://feedipedia.org/.

FICCI (2014) *Overview of the Indian Buffalo Meat Value Chain*, New Delhi, India: Federation of Indian Chamber of Commerce and Industry.

Fick J. (2016) Detailed methodologies for agricultural greenhouse gas emissions calculation. Version 3. In: *MPI Technical Paper*.

Flores E.B., Maramba J.F., Aquino D.L., Abesamis A.F., Cruz A.F., Cruz L.C. (2007) Evaluation of milk production performance of dairy buffaloes raised in various herds of the Philippine Carabao Center. *Ital.J.Anim.Sci.* **6**: 295-298.

Furaeva N.S. (2013) Current state of pedigree base of a cattle of the Yaroslavl breed and prospect of its development. *Agricultural bulletin of Yaroslavl region* **21**: 21-30.

Gami R., Thakur S.S., Mahesh M.S. (2017) Protein Sparing Effect of Dietary Rumen Protected Lysine Plus Methionine in Growing Murrah Buffaloes (Bubalus bubalis). *Proceedings of the National Academy of Sciences, India Section B: Biological Sciences* **87**: 885-891.

Gao Z., Maa W., Zhu G., Roelcke M. (2013) Estimating farm-gate ammonia emissions from major animal production systems in China. *Atmospheric environment* **79**: 20-28.

Gao Z., Yuan H., Maa W., Liu X., Desjardins R.L. (2011) Methane emissions from a dairy feedlot during the fall and winter seasons in Northern China. *Environmental Pollution* **159**: 1183-1189.

Garcia O., Hemme T., Nho L.T., Huong Tra H.T. (2006) The economics of milk production in Hanoi, Vietnam, with particular emphasis on small-scale producers. *A Living from Livestock* 54.

Garg M.R., Sherasia P.L., Bhanderi B.M., Phondba B.T., Shelke S.K., Makkar H.P.S. (2013) Effects of feeding nutritionally balanced rations on animal productivity, feed conversion efficiency, feed nitrogen use efficiency, rumen microbial protein supply, parasitic load, immunity and enteric methane emissions of milking animals under field conditions. *Animal feed science and technology* **179**: 24-35.

Garg M.R., Sherasia P.L., Phondba B.T., Makkar H.P.S. (2018) Greenhouse gas emission intensity based on lifetime milk production of dairy animals, as affected by ration-balancing program. *Animal Production Science* **58**: 1027.

Gayirbegov D., Mandjiev D. (2013) The effect of feeding type on metabolism and growth energy of bulls of kalmyk breed. *Dairy and Beef Cattle Breeding* **7**: 31-32.

Gebre Mariam S., Amare S., Baker D., Solomon A., Davies R. (2013) Study of the Ethiopian live cattle and beef value chain. ILRI Discussion Paper 23.

Gerber P., Vellinga T., Opio C., Steinfeld H. (2011) Productivity gains and greenhouse gas emissions intensity in dairy systems. *Livestock Science* **139**: 100-108.

Gerrits W.J.J., Dijkstra J., Bannink A. (2014) *Methaanproductie bij witvleeskalveren. Livestock Research Report 813*, Wageningen, Netherlands: Wageningen UR (University & Research centre) Livestock Research.

Gioi P.V., Graser H.-U., Van Duc N., Them T.T., Thong T.T., Van Trung N., Trung D.D., et al. (2012) Variance and covariance components of Lactation Milk Yield, Body Weight and Calving Interval for Vietnamese purebred Holstein Friesian Cattle under intensive systems.

Golubkov A.I., Dunin I.M., Adzhibekov K.K., Lazovaya G.S., Chekushkin A.M. (2015) Milk productivity of the red-motley breed cows of different intrabreed types. *Bulletin of Krasnoyarsk state agricultural university* **10**: 189-196.

Gonçalves O. (2008) *Características de criações de búfalos no Brasil e a contribuição do marketing no agronegócio bubalino: Pirassununga, SP*. Tese. Faculdade Zootecnia e engenharia de alimentos da Universidade de São Paulo, 2008.

Goncharova N., Kibkalo L. (2011) Efficiency of cultivation of bull- calves on meat. *Dairy and Beef Cattle Breeding* **3**: 20-21.

Goncharova N.A., Kibkalo L.I., Zerebilov N.I. (2009) Feedlot efficiency of growing beef cattle. *Bulletin of Krasnoyarsk state agricultural university* **3**: 70-74.

Gonzalez Gonzalez O.J. (2011) *Buffalo bulls for meat production: Feeding and Meat Quality*, Napoli, Italy: University of Naples Federico II Faculty of Veterinary Medicine.

Goopy J.P., Onyango A.A., Dickhoefer U., Butterbach-Bahl K. (2018) A new approach for improving emission factors for enteric methane emissions of cattle in smallholder systems of East Africa – Results for Nyando, Western Kenya. *Agricultural Systems* **161**: 72-80.

Gren O.V. (2013) The fodder nutrients digestibility when feeding lactation cows with «Biokoretron-forte». *Bulletin of Krasnoyarsk state agricultural university* **1**: 88-90.

Groeneveld E., Mostert B.E., Rust T. (1998) The covariance structure of growth traits in the Afrikaner beef population. *Livestock Production Science* **55**: 99-107.

Gubaidullin N., Tagirov H., Iskhakov R. (2011) Productive qualities of thoroughbred and hybrid bulls. *Dairy and Beef Cattle Breeding* **S1**: 25-26.

Gunawan A., Jakaria (2011) Genetic and Non-Genetics Effect on Birth, Weaning, and Yearling Weight of Bali Cattle. *Journal of Animal Science and Technology* **34**: 93-98.

Gupta S.K., Singh P., Shinde K.P., Lone S.A., Kumar N., Kumar A. (2016) Strategies for attaining early puberty in cattle and buffalo: A review. *Agricultural Reviews* **37**: 160-167.

Gwaza D.S., Momoh O.M. (2016) Endangered indigenous cattle Breeds of Nigeria a case for their conservation and management. *World Scientific News* **30**: 68-88.

Habeeb A.A.M., Gad A.E., Atta M.A.A. (2016) Changes in Body Weight Gain and Blood Hormonal Levels in Relation to Change in Age of Egyptian Male Buffaloes Calves from Birthing to Puberty. *Advances in Applied Physiology* **1**: 43-48.

Haile A., Joshi B.K., Ayalew W., Tegegne A., Singh A. (2011) Genetic evaluation of Ethiopian Boran cattle and their crosses with Holstein Friesian for growth performance in central Ethiopia. *Journal of Animal Breeding and Genetics* **128**: 133-140.

Halala H. (2015) Review of Beef Cattle Value Chain in Ethiopia. *Industrial Engineering Letters* **5**: 11-23.

Hammond K.J., Crompton L.A., Bannink A., Dijkstra J., Yáñez-Ruiz D.R., O'Kiely P., Kebreab E., et al. (2016) Review of current in vivo measurement techniques for quantifying enteric methane emission from ruminants. *Animal feed science and technology* **219**: 13-30.

Han B.-Z., Meng Y., Li M., Yang Y.-X., Ren F.-Z., Zeng Q.-K., Robert Nout M.J. (2007) A survey on the microbiological and chemical composition of buffalo milk in China. *Food Control* **18**: 742-746.

Han X.P., Hubbert B., Hubbert M.E., Reinhardt C.D. (2016) Overview of the Beef Cattle Industry in China: The widening Deficit between Demand and Output in a Vicious Circle. *J Fisheries Livest Prod* **4**.

Haren H.I.H., Idris H. (2015) Performance of Three Breeds of Sudanese Cattle. In: *The 6th International Seminar on Tropical Animal Production. Integrated Approach in Developing Sustainable Tropical Animal Production*, Yogyakarta, Indonesia.

Hassan E.H., Abdel-Raheem S.M. (2013) Response of growing buffalo calves to dietary supplementation of caraway and garlic as natural additives. *World Applied Sciences Journal* **22**: 408-414.

Haysanov D.P. (2011) The milk yield of cows according to their genotype, feeding level and technology content. *Bulletin of Krasnoyarsk state agricultural university* **4**: 102-106.

Hieu Vu N., Lambertz C., Gauly M. (2016) Factors Influencing Milk Yield, Quality and Revenue of Dairy Farms in Southern Vietnam. *Asian Journal of Animal Sciences* **10**: 290-299.

Hossein-zadeh N.G., Madad M., Shadparvar A.A., Kianzad D. (2012) An Observational Analysis of Secondary Sex ratio , Stillbirth and Birth Weight in Iranian Buffaloes (Bubalus bubalis). **14**: 1477-1484.

Hu Z., Zhang D. (2003) China's pasture resources. In: *Transhumant Grazing Systems in Temperate Asia*, eds. JM Suttie, SG Reynolds. FAO.

Huai Q., Jun L. (1995) Water buffalo and yak production in China. *Bulletin d'Information sur les Ressources Genetiques Animales (FAO/PNUE); Boletin de Informacion sobre Recursos Geneticos Animales (FAO/PNUMA)*.

Huai Q., Zhiyong J., Zhijie C. (1993) A survey of cattle production in China. *World review animal* **76**.

Huhn S., Guimaráes M.C.d.F., Nascimento C.N.B.d., Carvalho L.O.D.d.M., Moreira E.D., Lourenço Junior J.d.B. (1982) Estudo comparativo da composição química do leite de zebuínos e bubalinos. *Boletim de pesquisa EMBRAPA/CPATU* **36**: 1-16.

Hussein H.A., Abdel-Raheem S.M. (2013) Effect of feed intake restriction on reproductive performance and pregnancy rate in Egyptian buffalo heifers. *Tropical Animal Health and Production* **45**: 1001-1006.

Huuskonen A. (2017) Effects of skim milk and whey-based milk replacers on feed intake and growth of dairy calves. *Journal of Applied Animal Research* **45**: 480-484.

IBGE (2017) URL https://www.ibge.gov.br/.

Ibrahim M.A.R. (2012) Water buffalo for our next generation in Egypt and in the world. *Scientific Papers, Series D. Animal Science* **55**: 183-192.

Ichinohe T., Orden E.A., del Barrio A.N., Lapitan R.M., Fujihara T., C. C.L., Kanai Y. (2014) Comparison of voluntary feed intake, rumen passage and degradation kinetics between crossbred Brahmam cattle (Bos indicus) and swamp buffaloes (Bubalus bubalis) fed a fattening diet based on corn silage. *Animal Science Journal* **75**: 533-540.

Ilatsia E.D., Migose S.A., Muhuyi W.B., Kahi A.K. (2011) Sahiwal cattle in semi-arid Kenya: genetic aspects of growth and survival traits and their relationship to milk production and fertility. *Tropical Animal Health and Production* **43**: 1575-1582.

Ilichev E., Nazarova A., Polishchuk S., Inozemtsev V. (2011) Diet digestibility and nutrient balance with the addition of cobalt and copper nanopowders to the calves' rations. *Dairy and Beef Cattle Breeding* **5**: 27-29.

International Livestock Centre for Africa (1977) *Evaluation and comparisons of productivities of indigenous cattle in Africa: The Maure and Peul breeds at the Sahelian station Niono Mali*, Addis Ababa: International Livestock Centre for Africa.

Intergovernmental Panel on Climate Change (IPCC) (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories, Prepared by the National Greenhouse Gas Inventories Programme*, eds. HS Eggleston, L Buendia, K Miwa, T Ngara, K Tanabe. Japan: IGES.

Işik M., Gül M. (2016) Economic and social structures of water buffalo farming in Muş province of Turkey. *Revista Brasileira de Zootecnia* **45**: 400-408.

Ismail A.B., Sulaiman Y.R., Ahmed F.A., Ali H.A. (2014) Effect of summer supplementary feeding on cattle performance in low rainfall grassland savanna, south Darfur, Sudan. *Open Journal of Animal Sciences* **4**: 337-343.

Ítavo L.C.V., Euclides Filho K., Torres Júnior R.A.d.A., Ítavo C.C.B.F., Nogueira É., Dias A.M. (2014) Efficiency of calf production of cows from two genetic groups. *Revista Brasileira de Zootecnia* **43**: 390-394.

Jaayid T.A., Yousief M.Y., Hamed F.H., Owaid J.M. (2011) Body and Udder Measurements and Heritability and their Relationship to the Production of Milk in the Iraqi Buffalo. **7**: 553-564.

Jabbar M.A., Fiaz M., Gilani A.H., Naseer T. (2009) Comparative Performance of Calves of Buffalo and Different Breeds of Cattle on Feed Lot Fattening. 401-407.

Jayasundara S., Ranga Niroshan Appuhamy J.A.D., Kebreab E., Wagner-Riddle C. (2016) Methane and nitrous oxide emissions from Canadian dairy farms and mitigation options: An updated review. *Canadian Journal of Animal Science* **96**: 306-331.

Jha A.K., Singh K., Sharma C., Singh S.K., Gupta P.K. (2011) Assessment of Methane and Nitrous Oxide Emissions from Livestock in India. *J Earth Sci Climat Change* **1**: 107.

Jorge A.M., Andrighetto C., Strazza M.R.B., Correa R.C., Kasburgo D.G., Piccinin A., Victória C., et al. (2005) Correlações entre o California Mastitis Test e a Contagem de células somáticas do leite de búfalas Murrah. *Rev. bras. zootec.* **34**: 2039-2045.

Jorge A.M., Gomes M.I.F.V., Halt R.C. (2002) Efeito da Utilização da Somatotropina Bovina Recombinante (bST) sobre a Produção de Leite em Búfalas. *R. Bras. Zootec.* **31**: 1230-1234.

Kahi A.K., Wasike C.B., Rewe T.O. (2006) Beef Production in the Arid and Semi-Arid Lands of Kenya. *Outlook on Agriculture* **35**: 217-225.

Kalnickij B.D., Haritonov E.L. (2008) Determination of the dairy cows protein diet standards for the first phase of lactation. *Achievements of Science and Technology of AICis* **10**: 18-22.

Kamalzadeh A., Rajabbaigy M., Kiasat A. (2008) Livestock production systems and trends in livestock industry in Iran. *Journal of Agriculture and Social Sciences* **4**: 183-188.

Kanai E.T., Zagi I. (2013) Phenotypic characterization of white Fulani (Bunaji) and Bunaji x Friesian breed of cattle from National Animal Production Research Institute (NAPRI) cattle herd from Nigeria. **1**: 215-219.

Kara N.K., Galic A., Koyuncu M. (2014) Comparison of Milk Yield and Animal Health in Turkish Farms with Differing Stall Types and Resting Surfaces. *Asian-Australasian Journal of Animal Sciences* **28**: 268-272.

Karakok S.G. (2007) Small scale cattle farmers and their sustainability in lowland villages of Adana province, Turkey. *Livestock Research for Rural Development* **19**.

Kashoma I.P.B., Luziga C., Werema C.W., Shirima G.A., Ndossi D. (2011) Predicting body weight of Tanzania shorthorn zebu cattle using heart girth measurements. *Livestock Research for Rural Development* **23**: 4-8.

Kayastha R.B., Zaman G., Goswami R.N. (2008) Studies on the birth weight of indigenous cattle of Assam. *Indian J. Anim. Res.* **42**: 230.

Kenyanjui M.B., Sheikh-Ali M., Ghaffar A. (2009) Observations on cattle dairy breeds in Pakistan; need to curb unseen economic losses through control of mastitis and endemic diseases. *Journal of Agriculture and Environment for International Development* **103**: 155-172.

Khan D.A. (2011) Crossbreeding Cattle Breeding Policy and Action Plan. Report of FAnGR Pakistan.

Khan M., Nomani A., Salman M. (2016) Impact of Beef Ban on Economy and Meat Processing Industry of India: A Complete Value Chain Analysis. *Management Studies and Economic Systems* **2**: 325-334.

Khan M.J., Peters K.J., Uddin M.M. (2009) Feeding Strategy For Improving Dairy Cattle Productivity In Small Holder Farm In Bangladesh. *Bangladesh Journal of Animal Science* **38**: 67-85.

Khan R., Ahmad S., Kaleem K., Shahid M., Irshad M., Rizwan M., Muhammad D., et al. (2010) Growth Rate of Various Indigenous Bovine Breed Fed on Shandar Wanda at Livestock Research and Development Station Surezai Peshawar. **5**: 35-38.

Khan S., Qureshi M.S., Ahmad N., Durrani M.A.F.R., Younas M. (2008) Effect of Pregnancy on Lactation Milk Value in Dairy Buffaloes. *Asian Australas. J. Anim. Sci.* **21**: 523-531.

Khare A., Baghel R.P.S. (2010) Effects of strategic dietary supplementation of buffaloes on economics of their milk production. *Buffalo Bulletin* **29**: 12-20.

Khattab H.M., El-Basiony A.Z., Hamdy S.M., Marwan A.A. (2011) Immune response and productive performance of dairy buffaloes and their offspring supplemented with black seed oil. *Iranian Journal of Applied Animal Science* **1**: 227-234.

Koçyiğit R., Aydin R., Yanar M., Güler O., Diler A., Avci M., Özyürek S., et al. (2014) Effects of Weaning Ages on the Growth, Feed Conversion Efficiency and Some Behavioral Traits of Brown Swiss x Eastern Anatolian Red Calves. *Journal of Agricultural Sciences*.

Kolling G.J., Stivanin S.C.B., Gabbi A.M., Machado F.S., Ferreira A.L., Campos M.M., Tomich T.R., et al. (2018) Performance and methane emissions in dairy cows fed oregano and green tea extracts as feed additives. *Journal of Dairy Science* **101**: 4221-4234.

Kostenko V.I., Pyrozhenko Y.V. (2012) Methodology for GHG emissions estimation from cattle enteric fermentation in conditions of Ukraine. *Scientific journal* **179**: 183-193.

Kouazounde J.B., Gbenou J.D., Babatounde S., Srivastava N., Eggleston S.H., Antwi C., Baah J., et al. (2015) Development of methane emission factors for enteric fermentation in cattle from Benin using IPCC Tier 2 methodology. *animal* **9**: 526-533.

Kubkomawa H.I. (2017) Indigenous Breeds of Cattle, their Productivity, Economic and Cultural Values in Sub-Saharan Africa: A Review. *International Journal of Research Studies in Agricultural Sciences* **3**: 27-43.

Kumar D.S., Prasad J.R., Rao E.R. (2011) Effect of dietary inclusion of yeast culture (Saccharomyces cerevisiae) on growth performance of graded murrah buffalo bull calves. *Buffalo Bulletin* **30**: 63-66.

Kumar R., Dass R.S. (2006) Effect of niacin supplementation on growth, nutrient utilization and blood biochemical profile in male buffalo calves. *Asian-Australasian Journal of Animal Sciences* **19**: 1422-1428.

Kurwijila L.R., Bennett A. (2011) Dairy Development - Institutions in East Africa. Lessons learned and options. 36-39.

Kusnadi U., Praharani L. (2009) Profile of Buffalo Farms and Performance in Banten province, West Java. 210-214.

Lam V. (2011) Milk Production on Smallholder Dairy Cattle Farms in Southern Vietnam. Uppsala Swedish University of Agricultural Sciences.

Lambertz C., Panprasert P., Holtz W., Moors E., Jaturasitha S., Wicke M., Gauly M. (2014) Carcass characteristics and meat quality of swamp buffaloes (bubalus bubalis) fattened at different feeding intensities. *Asian-Australasian Journal of Animal Sciences* **27**: 551-560.

Landes M., Cessna J., Kuberka L., Jones K. (2017) India's Dairy Sector: Structure, Performance, and Prospects. *Economic Research Service/USDA*.

Lapitan R.M., del Barrio A.N., Katsube O., Ban-Tokuda T., Orden E.A., Robles A.Y., Cruz L.C., et al. (2008) Comparison of fattening performance in Brahman grade cattle (Bos indicus) and crossbred water buffalo (Bubalus bubalis) fed on high roughage diet. *Animal Science Journal* **79**: 76-82.

Legesse G., Beauchemin K.A., Ominski K.H., McGeough E.J., Kroebel R., MacDonald D., Little S.M., et al. (2016) Greenhouse gas emissions of Canadian beef production in 1981 as compared with 2011. *Animal Production Science* **56**: 153-168.

Leontev V., Burmistrov V., Linkevich R., Asaynin V., Lavrova A. (2013) Comparative evaluation of limousin bull growth and slaughter quality in the JSC "Zavolzhskoe" farm, in Tver region. *Dairy and Beef Cattle Breeding* **2**: 18-19.

Levakhin V., Azhmuldinov E., Ibraev A., Babicheva I., Poberukhin M. (2011) Influence of structure and quality of rations on meat productivity of young animals. *Dairy and Beef Cattle Breeding* **6**: 31-32.

Li Q., Wang Y., Tan L., Leng J., Lu Q., Tian S., Shao S., et al. (2018) Effects of age on slaughter performance and meat quality of Binlangjang male buffalo. *Saudi Journal of Biological Sciences* **25**: 248-252.

Lima D.M., Abdalla Filho A.L., Lima P.d.M.T., Sakita G.Z., Silva T.P.D.e., McManus C., Abdalla A.L., et al. (2018) Morphological characteristics, nutritive quality, and methane production of tropical grasses in Brazil. *Pesquisa Agropecuária Brasileira* **53**: 323-331.

Lima T.C.C., Rangel A.H.N., Macêdo C.S., Araújo T.P.M., Lima Junior D.M., Murmann L., Novaes L.P. (2014) Composição e qualidade do leite e do soro do leite de búfalas no estado do Rio Grande do Norte. *Acta Veterinaria Brasílica* **8**: 25-30.

Litovchenko V. (2012) Growth and productivity of meat from calves simmental genotypes in Southern Ural. *Dairy and Beef Cattle Breeding* **6**: 16-18.

Loculan D. (2002) Genetic Evaluation of Beef Production in the Philippines. In: *Development Strategies for Genetic Evaluation for Beef Production in Developing Countries. Proceedings of an International Workshop held in Khon Kaen Province, Thailand, July 23–28 2001*, eds. J Allen, A Na-Chiangmai. Canberra: Australian Centre for International Agricultural Research.

Lukuyu B., Gachuiri C.K., Lukuyu M., Lusweti C., Mwendia S. (2012) Feeding dairy cattle in East Africa. *East Africa Dairy Development Project* 1-112.

Lukuyu M.N., Gibson J.P., Savage D.B., Duncan A.J., Mujibi F.D.N., Okeyo A.M. (2016) Use of body linear measurements to estimate liveweight of crossbred dairy cattle in smallholder farms in Kenya. *SpringerPlus* **5**: 63.

Ma H., L. , Oxley A., C. R., Fan J., Huang, S. R. (2012) The evolution of productivity performance on China's dairy farms in the new millennium. *J. Dairy Sci*.

Ma H., Rae A.N., Huang J., Rozelle S. (2007) Enhancing productivity on suburban dairy farms in China. *Agricultural Economics* **37**: 29-42.

MAAR. (2013) Overview on China's animal husbandry. In: Ministry of agriculture and rural affairs on the People's Republic of China.

Macedo M.P., Wechsler F.S., Ramos A.d.A., Amaral J.B.d., Souza J.C.d., Resende F.D.d., Oliveira J.V.d. (2001) Composição físico-química e produção de leite de búfalas da raça Mediterrâneo no Oeste do estado de São Paulo. *Revista Brasileira de Zootecnia, Viçosa* **30**: 1084-1088.

Machado Filho L.C., D'Ávila L.M., da Silva Kazama D.C., Bento L.L., Kuhnen S. (2014) Productive and Economic Responses in Grazing Dairy Cows to Grain Supplementation on Family Farms in the South of Brazil. *Animals* **4**: 463-475.

Maeda E.M., Zeoula L.M., Geron L.J.V., de Best J., Prado I.N., Martins E.N., Kazama R. (2007) Digestibilidade e características ruminais de dietas com diferentes níveis de concentrado para bubalinos e bovinos. *R. Bras. Zootec.* **36**: 716-726.

Mahakur K., Panda P., Das B.C., Nayak G.D. (2017) Study on morphometric traits of different genetic groups of adult cattle in Jajpur district of Odisha. *Indian Res. J. Ext. Edu., Special issue on Veterinary Research & Extension* 16–19.

Mahmoudzadeh H., Fazaeli H. (2009) Growth response of yearling buffalo male calves to different dietary energy levels. **33**: 447-454.

Mahmoudzadeh H., Fazaeli H., Kordnejad I., Mirzaei H.R. (2007) Response of male buffalo calves to different levels of energy and protein in finishing diets. *Pakistan journal of biological sciences* **10**: 1398-1405.

Mai H.M., Irons P.C., Kabir J., Thompson P.N. (2012) A large seroprevalence survey of brucellosis in cattle herds under diverse production systems in northern Nigeria. *BMC Vet. Res.* **8**: 144.

Mamaev I.I., Mironova I.V., Dolzhenkova G.M., Kosilov, V.I. (2017) Productive qualities of young black-spotted cattle and their double-and-triple cross hybrids. *Bulletin of Orenburg State Agrarian University* **1**: 128-130.

Manafiazar G., Mohsenourazary A., Afsharihamidi B., Mahmoodi B. (2007) Comparison carcass traits of Azeri buffalo, native and crossbred (native * Holstein) male calves in west Azerbaijan-Iran. *Italian Journal of Animal Science* **6**: 1167-1170.

Mandefro A., Duguma G., Mirkena T., Dadi H. (2017) Evaluation of alternative breeding plans for two indigenous cattle breeds of Ethiopia. *Livestock Science* **205**: 122-128.

Manoj M. (2009) *Evolving multi-trait selection criteria using body weights and first lactation traits in Sahiwal cattle. MSc thesis*: National Dairy Research Institute, Karnal (Deemed university). pp. 253.

Mapiye C., Chimonyo M., Dzama K., Hugo A., Strydom P.E., Muchenje V. (2011) Fatty acid composition of beef from Nguni steers supplemented with Acacia karroo leaf-meal. *Journal of Food Composition and Analysis* **24**: 523-528.

Marai I.F.M., Daader A.H., Soliman A.M., El-Menshawy S.M.S. (2009) Non-genetic factors affecting growth and reproduction traits of buffaloes under dry management housing (in sub-tropical environment) in Egypt. *Livestock Research for Rural Development* **21**: 1-10.

Marai I.F.M., Farghaly H.M., Nasr A.A., Abou-Fandoud E.I., Mohamed I.A.S (2001) Buffalo Cow Productive , Reproductive and Udder Traits and Stayability under Sub-tropical Environmental Conditions of Egypt. 1-14.

Mariani P., Vizentin W.W., Lipinski L., Saporski Segui M., Weiss R.R., Ernandes Kozicki L., Breda J.C., et al. (2009) Avaliação do ganho de peso ajustado para 205 dias em bezerros da raça nelore e mestiç nelore x red angus, submetidos ao desmame temporário. *Revista Acadêmica: Ciência Animal* **7**: 407.

Martojo H. (2012) Indigenous Bali Cattle is Most Suitable for Sustainable Small Farming in Indonesia. *Reprod. Dom. Anim.* **47**: 10-14.

Masama E., Kusina N.T., Sibanda S., Majoni C. (2003) Reproduction and Lactation performance of cattle in a smallholder dairy system in Zimbabwe. *Tropical Animal Health and Production* **35**: 117-129.

Mata e Silva B.C., Lopes F.C.F., Pereira L.G.R., Tomich T.R., Morenz M.J.F., Martins C.E., Gomide C.A.M., et al. (2017) Effect of sunflower oil supplementation on methane emissions of dairy cows grazing Urochloa brizantha cv. marandu. *Animal Production Science* **57**: 1431.

McManus C., Louvandini H., Carneiro H.C., Lima P.R.M., Neto J.B. (2011) Production indices for dual purpose cattle in central Brazil. *Revista Brasileira de Zootecnia* **40**: 1576-1586.

Medeiros S.R., Oliveira D.E., Aroeira L.J.M., McGuire M.A., Bauman D.E., Lanna D.P.D. (2010) Effects of dietary supplementation of rumen-protected conjugated linoleic acid to grazing cows in early lactation. *Journal of Dairy Science* **93**: 1126-1137.

Mekonnen A., Haile A., Dessie T., Mekasha Y. (2012) On farm characterization of Horro cattle breed production systems in western Oromia, Ethiopia. *Livestock Research for Rural Development* **24**: 7.

Meyer K., Graser H.U., Na-Chiangmai A. (2000) Estimates of genetic parameters for growth and skeletal measurements in Thai swamp buffalo. *Animal Science* **70**: 399-406.

MFAL (2011) *Domestic animal genetic resources in the Republic of Turkey*, Ankara, Turkey: Ministry of Food Agriculture and Livestock, General directorate of agricultural research and policy.

Mingala C.N., Villanueva M.A., Cruz L.C. (2017) River and swamp buffaloes: history, distribution and their characteristics. In: *The Buffalo (Bubalus bubalis) - Production and Research*, ed. GA Presicce. Bentham Science Publishers.

Ministerio de Ganadería A.y.P.d.U. (2017) Annuario estadístico agropecuario, vigésima edicion. URL http://www.mgap.gub.uy/sites/default/files/diea-anuario2017web01a.pdf.

Ministry of Livestock and Fisheries Development of Tanzania (2014) *Basic data for livestock and fisheries sectors 2013*, Tanzania: Ministry of Livestock and Fisheries Development.

Ministry of Livestock and Fisheries Development of Tanzania. (2015) Tanzania livestock modernisation initiative. In: Tanzania: Ministry of livestock and fisheries development.

Mlote N. (2013) Estimating technical efficiency of small scale beef cattle fattening in the lake zone in Tanzania. *Journal of Development and Agricultural Economics* **5**: 197-207.

Moaeen-ud-Din M., Bilal G. (2017) Effects of breed, various environmental and maternal factors on growth traits in cattle. *JAPS, Journal of Animal and Plant Sciences* **27**: 1415-1419.

Modernel P., Astigarraga L., Picasso V. (2013) Global versus local environmental impacts of grazing and confined beef production systems. *Environmental Research Letters* **8**.

Moran J. (2012) *Rearing Young Stock on Tropical Dairy Farms in Asia*: CSIRO Publishing. pp. 296.

Morsy T.A., Kholif A.E., Kholif S.M., Kholif A.M., Sun X., Salem A.Z.M. (2016) Effects of Two Enzyme Feed Additives on Digestion and Milk Production in Lactating Egyptian Buffaloes. *Annals of Animal Science* **16**: 209-222.

Mpofu N. (1996) Conservation of the Tswana cattle breed in Botswana. *AGRI* **20**: 17-26.

Msanga Y.N., Mwakilembe P.L., Sendalo D. (2012) The indigenous cattle of the Southern Highlands of Tanzania: Distinct phenotypic features, performance and uses. *Livestock Research for Rural Development* **24**: 1-7.

Muhuyi W.B., Lokwaleput I., Ole Sinkeet S.N. (1999) Conservation and utilisation of the Sahiwal cattle in Kenya. *Animal Genetic Resources Information* **26**: 35-44.

Mulliniks J.T., Edwards S.R., Hobbs J.D., McFarlane Z.D., Cope E.R. (2017) Post-weaning feed efficiency decreased in progeny of higher milk yielding beef cows. *animal* 1-5.

Muriuki H.G. (2011) Dairy development in Kenya. *Food and Agriculture Organization of the United nations*, pp 1-52.

Musa A.M., Elamin K.M., Mohammed S.A., Abdalla H.O. (2011) Morphometric Traits As Indicators for Body Weight in Sudanese Kenana Cattle. *Online Journal of Animal and Feed Research* **1**: 218-222.

Mwambene P.L., Chawala A., Illatsia E., Das S.M., Tungu B., Loina R. (2014) Selecting indigenous cattle populations for improving dairy production in the Southern Highlands and Eastern Tanzania. *Livestock Research for Rural Development* **26**.

Mwambene P.L., Katule A.M., Chenyambuga S.W., Mwakilembe P.A.A. (2012) Fipa cattle in the southwestern highlands of Tanzania: morphometric and physical characteristics. *Animal Genetic Resources/Ressources génétiques animales/Recursos genéticos animales* **51**: 15-29.

Mwanyumba P.M., Wahome R.W., MacOpiyo L., Kanyari P. (2015) Livestock herd structures and dynamics in Garissa County, Kenya. *Pastoralism* **5**: 26.

Myburgh J., Osthoff G., Hugo A., de Wit M., Nel K., Fourie D. (2012) Comparison of the milk composition of free-ranging indigenous African cattle breeds. *South African Journal of Animal Science* **42**: 1-14.

MZH (2016) *Livestock of Bulgaria. Statistical report N307*: Ministry of Agriculture, Food and Forestry of Republic of Bulgaria.

MZH (2017) *Livestock of Bulgaria. Statistical report N326*: Ministry of Agriculture, Food and Forestry of Republic of Bulgaria.

Nahar S., Islam A.F.M.F., Hoque M.A., Bhuiyan A.K.F.H. (2016) Animal performance of indigenous Red Chittagong cattle in Bangladesh. *Animal Sciences* **38**: 177-182.

Nanda A.S., Nakao T. (2003) Role of buffalo in the socioeconomic development of rural Asia: Current status and future prospects. *Animal Science Journal* **74**: 443-455.

Naserian A.A., Saremi B. (2007) Water buffalo industry in Iran. *Italian Journal of Animal Science* **6**: 1404-1405.

National Bureau of Animal Genetic Resources (2017) An Information System on Animal Genetic Resources of India. URL http://14.139.252.116/agris/breed.aspx.

Neglia G., Balestrieri A., Gasparrini B., Cutrignelli M.I., Bifulco G., Salzano A., Cimmino R., et al. (2014) nitrogen and Phosphorus Utilisation and Excretion in Dairy Buffalo Intensive Breeding. *Italian Journal of Animal Science* **13**: 3362.

Nekrasov R., Varenikov M., Chabaev M., Anisova N., Anikin A., Pisarev V., Turchina V. (2013) Balancing of the metabolic energy level in the high productive cow rations during the early lactation. *Dairy and Beef Cattle Breeding* **3**: 9-13.

Nell A.J. (2006) *Quick scan of the livestock and meat sector in Ethiopia: issues and opportunities.*, Wageningen: Wageningen University and Research Centre. pp. 1-38.

Nell A.J., Schiere H., Bol S. (2014) Quick scan Dairy Sector Tanzania. *Dutch Ministry of Economic Affairs (Dept. of European Agricultural Policy and Food Security; DG Agro)*.

Nha P.T., Thu N.V., Preston T.R. (2008) A field investigation of performance and economic efficiency of working buffaloes in the Mekong Delta. **20**: 2-5.

Nikolov V. (2011) *Livestock breeds in the Republic of Bulgaria*: Executive Agency on Selection and Reproduction in Animal Breeding. pp. 111.

Niu M., Kebreab E., Hristov A.N., Oh J., Arndt C., Bannink A., Bayat A.R., et al. (2018) Prediction of enteric methane production, yield, and intensity in dairy cattle using an intercontinental database. *Global change biology* 1-22.

Nosyreva Yu N., Tokareva V.F. (2014) Influence of multifunctional supplement “Fungistat gpk” on nutrition digestibility given to lactating cows of black-and-white. *Bulletin of Irkutsk State Agrarian University named after Ezhevskiy* **62**: 72-75.

Nouala F.S., Akinbamijo O.O., Bosso N.A., Agyemang K. (2003) The comparative performance of N'Dama and N'Dama crossbred cows under two supplementation levels in The Gambia. *Livestock Research for Rural Development* **15**: 19-28.

Nweze B.O., Ekwe O.O., Alaku S.O., Omeje I. (2012) Productivity of two indigenous nigerian cattle breeds and their crossbred under range grazing management. *World J Life Sci. and Medical Research* **2**: 1-7.

Oliveira A.G.d., Oliveira V.S.d., Santos G.R.D.A., Santos A.D.F., Sobrinho D.C.D.S., Oliveira F.L.d., Santana J.A., et al. (2014) Desempenho de vacas leiteiras sob pastejo suplementadas com níveis de concentrado e proteína bruta. *Semina: Ciências Agrárias* **35**: 3287.

Oliveira R.L., Ladeira M.M., Barbosa M.A.A.F., Matsushita M., Santos G.T., Bagaldo A.R., Oliveira R.L. (2009) Composição química e perfil de ácidos graxos do leite e muçarela de búfalas alimentadas com diferentes fontes de lipídeos. *Arq. Bras. Med. Vet. Zootec.* **61**: 736-744.

Olorunnisomo O.A. (2013) Milk production in Sokoto Gudali cows fed legume or elephant grass ensiled with cassava peel. *Livestock Research for Rural Development* **25**: 11.

Ominski K.H., Boadi D.A., Wittenberg K.M., Fulawka D.L., Basarab J.A. (2007) Estimates of enteric methane emissions from cattle in Canada using the IPCC Tier-2 methodology. *Canadian Journal of Animal Science* **87**: 459-467.

Onono J.O., Wieland B., Rushton J. (2013) Productivity in different cattle production systems in Kenya. *Tropical Animal Health and Production* **45**: 423-430.

Osman A.H. (1985) Meat production potential of Western Baggaga Cattle in the Sudan. In: *Evaluation of large ruminants for the tropics*, p. 178. Rockhampton, Queensland, Australia: CSIRO.

Özlütürk A., Yanar M., Tüzemen N., Kopuzlu S. (2006) Calving and preweaning growth performance traits of calves sired by Charolais, Simmental and Eastern Anatolian Red Bulls. *Turkish Journal of Veterinary and Animal Sciences* **30**: 257-263.

Pajuelo Montalvo F. (2008) Evaluación de dos niveles de proteína sobrepasante en el alimento de vacas a inicio de lactación. In: Universidad Nacional Agraria La Molina, Lima (Perú). Escuela de Postgrado

Pajuelo Montalvo F.E. (2003) *Evaluación técnica económica de la recría de vacunos en el establo San Isidro - Cañete. Tesis Ing. Zootecnista. Tesis, Universidad National Agraria La Molina*, Perú: UNALM, Perú.

Panandam J.M., Raymond A.K. (2005) Development of the Mafriwal Dairy Cattle of Malaysia.

Pathak H., Upadhyay R.C., Muralidhar M., Bhattacharyya P., Venkateswarlu B. (2013) *Measurement of greenhouse gas emission from crop, livestock and aquaculture*, New Delhi: Indian Agricultural Research Institute. pp. 101.

Pathak N.N. (2005) Comparison of feed intake, digestibility of nutrients and performance of cattle (B. indicus and B. indicus × B. taurus crosses) and buffaloes (Swamp and Indian). In: *Coping with feed scarcity in smallholder livestock systems in developing countries*, eds. AA Ayantunde, S Fernández-Rivera, G McCrabb, p. 306. Animal Sciences Group, Wageningen UR, Wageningen, The Netherlands; University of Reading, Reading, UK; ETH (Swiss Federal Institute of Technology), Zurich, Switzerland; ILRI (International Livestock Research Institute), Nairobi, Kenya.

Patra A.K. (2012) Estimation of methane and nitrous oxide emissions from Indian livestock. *Journal of Environmental Monitoring* **14**: 2673.

Peeva T., Nikolov P., Nikolova T., Penchev P., Ilieva Y. (2013) Breeding program of the Bulgarian Murrah buffalo. *Buffalo Bulletin* **32**: 236-243.

Peeva T., Penchev P., Maya Y. (2011) The Bulgarian Murrah -a genetic resource for Bulgarian livestock husbandry. *Agricultural science* **III**: 11-16.

Peres A.A.d.C., Carvalho C.A.B.d., Carvalho M.I.d.A.B., Vasquez H.M., Silva J.F.C.d., Clipes R.C., Morenz M.J.F. (2012) Production and quality of milk from Mantiqueira dairy cows feeding on Mombasa grass pasture and receiving different sources of roughage supplementation. *Revista Brasileira de Zootecnia* **41**: 790-796.

Phillippines Statistics Authority (2017) *Cattle situation report. January-June 2017*: Republic of the Philippines, Phillippines Statistics Authority.

Phomsouvanh A. (2002) Country Report: Lao PDR. In: *Development Strategies for Genetic Evaluation for Beef Production in Developing Countries. Proceedings of an International Workshop held in Khon Kaen Province, Thailand, July 23–28 2001*, eds. J Allen, A Na-Chiangmai. Canberra: Australian Centre for International Agricultural Research.

Pickering A., Wear S. (2013) *Detailed methodologies for agricultural greenhouse gas emission calculation Version 2. MPI Technical Paper No: 2013/27*: Ministry for Primary Industries, New Zealand Government.

Pico B.A., Neser F., van Wyk J.B. (2004) Genetic parameters for growth traits in South African Brahman cattle. *South African Journal Of Animal Science* **34**: 44-46.

Porter V., Alderson L., Hall S.J.G., Sponenberg D.P. (2016) *Mason's World Encyclopedia of Livestock Breeds and Breeding: 2 volume pack*: CABI publishing.

Prabowo A. (2012) Effect of dietary phosphorus level on performance of grazing water buffaloes in Lampung, Indonesia. In: *International Conference on Livestock Production and Veterinary Technology 2012*, pp. 139-144.

Pracht V. (2013) Effect of growth rate of holsteinized heifers of kholmogorskaya breed on subsequent milk performance. *Dairy and Beef Cattle Breeding* **5**: 31-32.

Premasundera A.S. (2002) Cattle and Buffalo Production and Breeding in Sri Lanka. In: *Development Strategies for Genetic Evaluation for Beef Production in Developing Countries. Proceedings of an International Workshop held in Khon Kaen Province, Thailand, July 23–28 2001*, eds. J Allen, A Na-Chiangmai. Canberra: Australian Centre for International Agricultural Research.

Presicce G.A. (2011) The Buffalo (Bubalus bubalis) - Production and Research. In: Bentham Science Publishers.

Primavesi O., Frighetto R.T.S., Pedreira M.D.S., Lima M.A.d., Berchielli T.T., Barbosa P.F. (2004) Metano entérico de bovinos leiteiros em condições tropicais brasileiras. *Pesquisa Agropecuária Brasileira* **39**: 277-283.

Prusty S., Kundu S.S., Mondal G., Sontakke U., Sharma V.K. (2016) Effect of energy and protein levels on nutrient utilization and their requirements in growing Murrah buffaloes. *Tropical Animal Health and Production* **48**: 807-815.

Putra W.P.B., Sumadi, Hartatik T., Saumar H. (2015) Relationship between body weight and body measurements of Aceh cattle. *Mal. J. Anim. Sci.* **18**: 35-43.

Qiao G., Shao T., Yang X., Zhu X., Li J., Lu Y. (2013) Effects of Supplemental Chinese Herbs on Growth Performance, Blood Antioxidant Function and Immunity Status in Holstein Dairy Heifers Fed High Fibre Diet. *Italian Journal of Animal Science* **12**: 1-20.

Qin G., Yang C., Tan Z., Huang J., Li H. (2013) Preliminary Results on the Growth Performance of F1 Mediterranean Buffalo Offspring Crossed In China. **32**: 750-754.

Qingkun Z., Bingzhuang Y., Jianghua S., Jing Q. (2002) Current Situation and Development Trend of Beef Industry in China. In: *Development Strategies for Genetic Evaluation for Beef Production in Developing Countries. Proceedings of an International Workshop held in Khon Kaen Province, Thailand, July 23–28 2001*, eds. J Allen, A Na-Chiangmai, p. 180. Canberra: Australian Centre for International Agricultural Research.

Queiroz M.F.S., Berchielli T.T., Morais J.A.S., Messana J.D., Malheiros E.B., Ruggieri A.C. (2011) Digestibilidade e parâmetros ruminais de bovinos consumindo brachiaria brizantha cv. marandu. *Arch. Zootec.* **60**: 997-1008.

Quispe J., Belizario C., Apaza E., Maquera Z., Quisocala V. (2016) Productive performance of Brown Swiss cattle in peruvian high plains. *Rev. investig. Altoandin.* **18**.

Radwan M.A.A. (2016) *Characterization of milk and veal production chains of buffalo under crop-livestock production system in Egypt. PhD thesis*: Department of Animal Production Faculty of Agriculture. Cairo University.

Rahman A., Islam M., Khan S., Ahmad A., Khattak T.A., Rahman A., Uddin S., Zeb K. (2012) Dressing Percentage and offal production of various breeds of Zebu cattle slaughtered at the Peshawar Abattoir. *Sarhad J. Agric.* **28**: 655-659.

Rahman S.M.A., Bhuiyan M.S.A., Bhuiyan A.K.F.H. (2015) Effects of genetic and non-genetic factors on growth traits of high yielding dairy seed calves and genetic parameter estimates. *J. Adv. Vet. Anim. Res.* **2**: 450-457.

Rakwadi E., Nsoso S.J., Gondwe T.N., Banda J.W. (2016) Estimates of phenotypic and genetic parameters and responses to selection in growth traits in three beef cattle breeds raised under ranch conditions in Botswana. *Botswana Journal of Agriculture and Applied Sciences* **11**: 2-10.

Ramírez-Restrepo C.A., Van Tien D., Duc N.L., Herrero M., Dinh P.L., Van D.D., Thi Hoa S.L., et al. (2017) Estimation of methane emissions from local and crossbreed beef cattle in Daklak province of Vietnam. *Asian-Australas J. Anim. Sci.* **30**: 1054-1060.

Ranjhan S.K. (2007) Buffalo as a social animal for humanity. *Italian Journal of Animal Science* **6**: 30-38.

Raphaka K. (2008) Estimation of genetic and non-genetic parameters for growth traits in two beef cattle breeds in Botswana. South Africa: University of Stellenbosch.

Rassi L.F., Araujo V.C., De Fariae e Vasconcellos B., Nascente F.X., Schwabacher V.G., Moreira P.C. (2009) Correlação entre produções parciais e totais de leite em um rebanho bubalino. *Estudos. Goiânia/GO.* **36**: 1135-1139.

Rege J.E.O. (1999) The state of African cattle genetic resources I. Classification framework and identification of threatened and extinct breeds. *Animal Genetic Resources Information* **25**: 1-25.

Reis J.C.L. (1998) *Pastagens em terras baixas*, Pelotas: Embrapa.

Restle J., Pacheco P.S., Moletta J.L., Brondani I.L., Cerdótes L. (2003) Grupo genético e nível nutricional pós-parto na produção e composição do leite de vacas de corte. *Revista Brasileira de Zootecnia* **32**: 585-597.

Rewe T.O., Indetie D., Ojango J.M.K., Kahi A.K. (2006) Economic values for production and functional traits and assessment of their influence on genetic improvement in the Boran cattle in Kenya. *Journal of Animal Breeding and Genetics* **123**: 23-36.

Rezende M.P.G.d., Ferraz P.C., Carneiro P.L.S., Malhado C.H.M. (2017) Phenotypic diversity in buffalo cows of the Jafarabadi, Murrah, and Mediterranean breeds. *Pesq. agropec. bras., Brasília* **52**: 663-669.

Ribeiro R.S., Terry S.A., Sacramento J.P., Silveira S.R.E., Bento C.B.P., da Silva E.F., Mantovani H.C., et al. (2016) Tithonia diversifolia as a Supplementary Feed for Dairy Cows. *PLOS ONE* **11**.

Riedel S., Meyer M., Schlecht E., Hülsebusch C., Schiborra A. (2012) Swamp buffalo keeping – an out-dated farming activity: A case study in smallholder farming systems in Xishuangbanna, Yunnan Province, PR China. *Journal of Agriculture and Rural Development in the Tropics and Subtropics* **113**: 137-145.

Rodrigues V.C., Andrade I.F., Gonçalves T.M., Sousa J.C.D., Inácio Neto A., Rezende C.A.P., Paiva P.C.A., et al. (2001) Desempenho comparativo de bubalinos e bovinos em confinamento. *Ciênc. agrotec., Lavras* **25**: 396-407.

Rodriguez Y. (2018) *Influencia de la alimentación en la composición de la leche en vacunos de crianza intensiva en la cuenca de Lima. Tesis Ing. Zootecnista*, Peru: UNALM. Perú.

Rojas R., Gómez N. (2005) Índice productivos y reproductivos del bovino Criollo en el departamento de Puno. *Arch. Zootec.* **54**: 571-574.

Rosa A.N., Lôbo R.B., Oliveira H.N., Bezerra L.A.F., Borjas A.R. (2001) Peso Adulto de Matrizes em Rebanhos de Seleção da Raça Nelore no Brasil. *Rev. bras. zootec.* **30**: 1027-1036.

Roy D., Kumar V., Kumar M., Sirohi R., Singh Y., Singh J.K. (2016) Effect of feeding Azolla pinnata on growth performance, feed intake, nutrient digestibility and blood biochemical's of Hariana heifers fed on roughage based diet. *Indian J Dairy Sci* **69**: 190-196.

Ruiz L., Sandoval R. (2014) Relationship between conventional reproductive parameters and parameters of reproductive efficiency of the dairy farming of Lima. *Spermova* **4**: 58-60.

RUSSTAT (2016) *Preliminary results of All-Russian Agricultural Census of 2016*, Moskow: Federal State Statistics Service of the Russian Federation. pp. 290.

Sabia E., Napolitano F., De Rosa G., Terzano G.M., Barile V.L., Braghieri A., Pacelli C. (2014) Efficiency to reach age of puberty and behaviour of buffalo heifers (Bubalus bubalis) kept on pasture or in confinement. *animal* **8**: 1907-1916.

Sadeghi-Sefidmazgi A., Moradi-Shahrbabak M., Nejati-Javaremi A., Miraei-Ashtiani S.R., Amer P.R. (2012) Breeding objectives for Holstein dairy cattle in Iran. *Journal of Dairy Science* **95**: 3406-3418.

Saha A., Garcia O., Hemme T. (2004) The Economics of Milk Production in Orissa, India, with Particular Emphasis on Small-Scale Producers. *PPLPI Working Paper No. 16*.

Saha D., Gupta R.S., Singh Baghel R.P., Khare A. (2012) Efficiency of utilization of dietary energy for milk production in lactating crossbred cattle (Bos Indicus). *Veterinary Research Forum* **3**: 213-216.

Said R., Bryant M.J., Msechu J.K.K. (2003) The survival, growth and carcase characteristics of crossbred beef cattle in Tanzania. *Tropical Animal Health and Production* **35**: 441-454.

Salako A.E. (2014) Asymptotic nonlinear regression models for the growth of White Fulani and N ' dama cattle in Nigeria. **26**.

Sambhaji N.M. (2013) *Studies on Morphometric Characteristics of Red Kandhari cattle in Parbhani District. MSc thesis*: College of agriculture. India. pp. 125.

Samorukov Y., Bychkov A., Chernov V., Andrianov V., Potepalova V., Marzanov N. (2013) About breeds in dairy cattle breeding. *Dairy and Beef Cattle Breeding* **1**: 21-23.

Samorukov Y., Kalyazina T., Marzanov N. (2013) About the breeds in dairy farming. *Dairy and Beef Cattle Breeding* **6**: 3-5.

Sanh V. (2007) Use of large bulls to improve the body weight of local small sized buffalo. *Italian Journal of Animal Science* **6**: 389-392.

Santos N.B.L., Jaeger S.M.P.L., Bagaldo A.R., Rocha N.B., Araújo F.L., Santos A.T.S. (2014) Consumo, Digestibilidade dos Nutrientes, Desempenho e Comportamento Ingestivo de Bezerros Bubalinos Desmamados Alimentados com Resíduo Úmido de Cervejaria. *Rev. Cient. Prod. Anim* **16**: 104-117.

Santos S.A., Valadares Filho S.d.C., Detmann E., Valadares R.F.D., Ruas J.R.d.M., Amaral P.d.M. (2011) Different forage sources for F1 Holstein×Gir dairy cows. *Livestock Science* **142**: 48-58.

Sarkar U., Gupta A.K., Sarkar V., Mohanty T.K., Raina V.S., Prasad S. (2006) Factors affecting test day milk yield and milk composition in dairy animals. *J. Dairying Foods and H.S.* **25**: 129-132

Scholtz M.M., Theunissen A. (2010) The use of indigenous cattle in terminal cross-breeding to improve beef cattle production in Sub-Saharan Africa. *Animal Genetic Resources/Ressources génétiques animales/Recursos genéticos animales* **46**: 33-39.

Şekerden Ö. (2013) Growth Traits of Anatolian and Anatolian x Italian Crossbred Buffalo Calves Under the Village Conditions. *Buffalo Bulletin* **32**: 632-636.

Sgroi S.A. (2017) *Application of urea-molasses blocks in the peruvian andes: formulation, management and effects on criollo heifers. Master's thesis*, Montpellier, France: Montpellier SupAgro.

Shahin K.A., Abdallah O.Y., Fooda T.A., Kawther A.M. (2010) Selection indexes for genetic improvement of yearling weight in Egyptian buffaloes. *Archiv fur Tierzucht* **53**: 436-446.

Shahzad M.A., Tauqir N.A., Ahmad F., Nisa M.U., Sarwar M., Tipu M.A. (2011) Effects of feeding different dietary protein and energy levels on the performance of 12-15-month-old buffalo calves. *Trop Anim Health Prod* **43**: 685-694.

Sharkaev V., Kochetkov A. (2012) Results of the complex estimation of dairy cattle in the Russian Federation. *Dairy and Beef Cattle Breeding* **8**: 9-12.

Sharkaeva G. (2012) Use of imported cattle in the territory of the Russian Federation. *Dairy and Beef Cattle Breeding* **1**: 12-14.

Sharkaeva G. (2013) Monitoring of the cattle imported in the Russian Federation. *Dairy and Beef Cattle Breeding* **1**: 14-16.

Sharma V.C., Mahesh M.S., Mohini M., Datt C., Nampoothiri V.M. (2014) Nutrient utilisation and methane emissions in Sahiwal calves differing in residual feed intake. *Archives of Animal Nutrition* **68**: 345-357.

Shekhar C., Thakur S.S., Shelke S.K. (2010) Effect of exogenous fibrolytic enzymes supplementation on milk production and nutrient utilization in Murrah buffaloes. *Tropical Animal Health and Production* **42**: 1465-1470.

Sheppard S.C., Bittman S., Donohoe G., Flaten D., Wittenberg K.M., Small J.A., Berthiaume R., et al. (2015) Beef cattle husbandry practices across Ecoregions of Canada in 2011. *Canadian Journal of Animal Science* **95**: 305-321.

Sheveleva O.M., Bakharev A.A. (2013) The formation of beef cattle breeding industry with the use of French breeds in the conditions of northern Zauralye. *Agrarian Bulletin of the Urals* **114**: 23-25.

Shevkhuzhev A.F., Dubrovin A.I., Ulimbasheva R.A. (2015) The behavioural reactions of bull-calves caused by technology of their growth. *Bulletin of Saint-Petersburg State Agrarian University* **41**: 100-104.

Shirima E., Nsiima L., Mwilawa A., Temu J., Michael S., Mlau D. (2016) Evaluation of Slaughter and Carcass Characteristics from Indigenous Beef Cattle in Six Abattoirs of Tanzania. *Journal of Scientific Research and Reports* **10**: 1-8.

Shittu A., Junaidu A.U., Chafe U.M., Magaji A.A., Faleke O.O., Salihu M.D., Jibril A., et al. (2008) A survey on current milk production and pricing in Sokoto state, Nigeria. *Sokoto Journal of Veterinary Sciences* **7**: 53-58.

Siegmund-Schultze M., Lange F., Schneiderat U., Steinbach J. (2012) Performance, management and objectives of cattle farming on communal ranges in Namibia. *Journal of Arid Environments* **80**: 65-73.

Silva J.A., Silva C.G.M., Sousa D.D.P., Paula N.F.d., Carvalho A.P.D.S., Macedo B.G., Costa Júnior W.S.d., et al. (2017) Supplementation strategies for dairy cows kept in tropical grass pastures. *Semina: Ciências Agrárias* **38**: 401.

Simbrasil Modelos de produção de leite à pasto.
URL http://simentalsimbrasil.org.br/biblioteca/modelos_de_producao_de_leite_a_pasto.pdf.

Simões A.R.P., Silva R.M.D., Oliveira M.V.M.D., Cristaldo R.O., Brito M.C.B. (2009) Avaliação econômica de três diferentes sistemas de produção de leite na região do Alto Pantanal Sul-mato-grossense. *Agrarian* **2**: 153-167.

Singal J.S. (2001) Effect of feeding bypass protein and improved managemental practices on growth performance of Murrah Buffalo heifers. PhD Thesis, Chaudhary Charan Singh Haryana Agricultural University.

Singh K. (2002) Beef Production in India. In: *Development Strategies for Genetic Evaluation for Beef Production in Developing Countries. Proceedings of an International Workshop held in Khon Kaen Province, Thailand, July 23–28 2001*, eds. J Allen, A Na-Chiangmai. Canberra: Australian Centre for International Agricultural Research.

Singh S., Kundu S.S., Kushwaha B.P., Maity S.B. (2009) Dietary energy levels response on nutrient utilization, nitrogen balance and growth in Bhadawari buffalo calves. *Livestock Research for Rural Development* **21**: 6-11.

Singh S., Kushwaha B.P., Maity S.B., Singh K.K., Das N. (2015) Effect of dietary protein on intake, nutrients utilization, nitrogen balance, blood metabolites, growth and puberty in growing Bhadawari buffalo (Bubalus bubalis) heifers. *Tropical Animal Health and Production* **47**: 213-220.

Singh S., Kushwaha B.P., Nag S.K., Bhattacharya S., Gupta P.K., Mishra A.K., Singh A. (2012) Assessment of enteric methane emission of Indian livestock in different agro-ecological regions. *Current Science* **102**: 1017-1027.

Sirohi A.S., Pandey H.N., Singla M. (2012) Effects of milking frequency on feed intake, body weight and haemato-biochemical changes in crossbred cows. *Journal of Applied Animal Research* **40**: 63-68.

Sivarajasingam S. (1987) Improvement and conservation of buffalo genetic resources in Asia. In: *Proceedings of the 2nd Meeting of the FAO/UNEP Expert Panel with Proceedings of the EAAP/PSAS Symposium on Small Populations of Domestic Animals*, ed. J Hodges, Rome, Italy: Food and Agriculture Organization of the United Nations.

Skunmun P., Chantalakhana C., Pungchai R., Poondusit T., Prucsasri P. (2002) Comparative Feeding of Male Dairy, Beef Cattle and Swamp Buffalo I. Economics of Beef Production. *Asian-Australasian Journal of Animal Sciences* **15**: 878-883.

Sodhi M., Mukesh M., Prakash B., Mishra B.P., Sobti R.C., Singh K.P., Singh S., et al. (2007) MspI allelic pattern of bovine growth hormone gene in Indian Zebu cattle (Bos indicus) breeds. *Biochemical Genetics* **45**: 145-153.

Soliman I. (2009) Present situation and future perspective of buffalo production in Africa. In: *6th Asian Buffalo Congress on 'Buffalo-prospective animal for milk and meat enterprises'. 27-30 October*.

Somapala K.C. (2002) Cattle and Buffalo Breeding in Sri Lanka. In: *Development Strategies for Genetic Evaluation for Beef Production in Developing Countries. Proceedings of an International Workshop held in Khon Kaen Province, Thailand, July 23–28 2001*, eds. J Allen, A Na-Chiangmai. Canberra: Australian Centre for International Agricultural Research.

Sontakke U.B., Kaur H., Tyagi A.K., Kumar M., Hossain S.A. (2014) Effect of feeding rice bran lyso-phospholipids and rumen protected fat on feed intake, nutrient utilization and milk yield in crossbred cows. *Indian Journal of Animal Sciences*.

Soysal M.I. (2013) Anatolian water buffaloes husbandry in Turkey. *Buffalo Bulletin* **32**: 293-309.

Soysal M.I., Gurcan E.K., Genc S., Aksel M. (2015) The Comparison of Growth Curve with Different Models in Anatolian Buffalo. *Journal of Tekirdag Agricultural Faculty* **12**: 57-61.

Soysal M.İ., Tuna Y.T., Gürcan E.K., İlçesi İ.S., Köyünde D., Yetiştiriciliği M., Bir Ü. (2005) An Investigation on the Water Buffalo Breeding in Danamandira Village of Silivri District of Istanbul Province of Turkey. *Journal of Tekirdag Agricultural Faculty* **2**: 73-78.

Soysal M.I., Tuna Y.T., Gurcan E.K., Ozkan E., Kok S., Castellano N., Cobanoglu O., et al. (2007) Anatolian water buffaloes husbandry in Turkey: preliminary results on somatic characterization. *Italian Journal of Animal Science* **6**: 1302-1307.

Spek J.W., Dijkstra J., van Duinkerken G., Hendriks W.H., Bannink A. (2013) Prediction of urinary nitrogen and urinary urea nitrogen excretion by lactating dairy cattle in northwestern Europe and North America: A meta-analysis. *Journal of Dairy Science* **96**: 4310-4322.

Stackhouse-Lawson K.R., Rotz C.A., Oltjen J.W., Mitloehner F.M. (2012) Carbon footprint and ammonia emissions of California beef production systems. *Journal of Animal Science* **90**: 4641-4655.

Statistical Centre of Iran (2011) *Selected Results of Livestock Survey*. Statistical Centre of Iran.

Statistics Botswana (2016) *Annual Agricultural Survey report 2014*. Annual Agricultural Survey report 2014. Agricultural Statistics Section. Ministry of Agriculture Department of Research. Botswana.

Statistics NZ (2018) Livestock Numbers by Regional Council.
URL http://nzdotstat.stats.govt.nz/wbos/Index.aspx?DataSetCode=TABLECODE7423.

Statistics NZ (2018) Livestock survey 2015.
URL http://archive.stats.govt.nz/browse_for_stats/industry_sectors/agriculture-horticulture-forestry/AgriculturalProduction_final_HOTPJun15final.aspx.

Stein J., Ayalew W., Rege J.E.O., Mulatu W., Malmfors B., Dessie T., Philipsson J. (2009) Livestock keeper perceptions of four indigenous cattle breeds in tsetse infested areas of Ethiopia. *Tropical Animal Health and Production* **41**: 1335-1346.

Strous E.E.C. (2010) *Population Structure and Reproduction Aspects in a Traditional Farming System in Mpumalanga Province, RSA*, Utrecht, Netherlands: Faculty Veterinary Medicine, Utrecht University. pp. 1-48.

Strydom P.E. (2008) Do indigenous Southern African cattle breeds have the right genetics for commercial production of quality meat? *Meat Science* **80**: 86-93.

Strydom P.E., Frylinck L., van der Westhuizen J., Burrow H.M. (2008) Growth performance, feed efficiency and carcass and meat quality of tropically adapted breed types from different farming systems in South Africa. *Australian Journal of Experimental Agriculture* **48**: 599.

Strydom P.E., Naude R.T., Smith M.F., Scholtz M.M., van Wyk J.B. (2000) Characterisation of indigenous African cattle breeds in relation to meat quality traits. *Meat Science* **55**: 79-88.

Suryanto B., Arifin M., Rianto E. (2002) Potential of swamp buffalo development in Central Java. Indonesia. *Buffalo Bulletin* **21**.

Sutarno A.D.S. (2015) Review: Genetic diversity of local and exotic cattle and their crossbreeding impact on the quality of Indonesian cattle. *Biodiversitas* **16**: 327-354.

Taneja V.K. (1999) Dairy breeds and selection. In: *Smallholder dairying in the tropics*, eds. L Falvey, C Chantalakhana, p. 462. Nairobi, Kenya: International Livestock Research Institute.

Tariq M., Younas M., Khan A.B., Schlecht E. (2013) Body measurements and body condition scoring as basis for estimation of live weight in Nili-Ravi buffaloes. *Pak Vet J* **33**: 325-329.

Tasdemir S., Urkmez A., Inal S. (2011) Determination of body measurements on the Holstein cows using digital image analysis and estimation of live weight with regression analysis. *Computers and Electronics in Agriculture* **76**: 189-197.

Tauqir N.A., Shahzad M.A., Nisa M., Sarwar M., Fayyaz M., Tipu M.A. (2011) Response of growing buffalo calves to various energy and protein concentrations. *Livestock Science* **137**: 66-72.

Tefera M. (2013) Atlas of Biogeography and Biodiversity of Indigenous Domestic and Wild Mammals of Ethiopia.

Tegegne A., Gebremedhin B., Hoekstra D., Belay B., Mekasha Y. (2013) *Smallholder dairy production and marketing systems in Ethiopia: IPMS experiences and opportunities for market-oriented development. IPMS (Improving Productivity and Market Success) of Ethiopian Farmers Project* ed. ILRI. Nairobi: International Livestock Research Institute (ILRI).

Teixeira A.M., Jayme D.G., Sene G.A., Fernandes L.O., Barreto A.C. (2013) Desempenho de vacas Girolando mantidas em pastejo de Tifton 85 irrigado ou sequeiro (Performance of crossbred Holstein x Zebu cows rotationally grazing in Tifton 85 pasture irrigated or rainfed). *Arq. Bras. Med. Vet. Zootec* **65**: 1447-1453.

Tekeev M., Chomaev A. (2011) Housing and rearing technology of replacement young cattle stock. *Dairy and Beef Cattle Breeding* **5**: 18-19.

Temoso O., Villano R., Hadley D. (2016) Evaluating the productivity gap between commercial and traditional beef production systems in Botswana. *Agricultural Systems* **149**: 30-39.

Teodoro R.L., Madalena F.E. (2002) Evaluation of crosses of Holstein, Jersey or Brown Swiss sires x Holstein-Friesian/Gir dams. 2. Female liveweights. *Genetics and Molecular Research* **1**: 25-31.

Teodoro R.L., Madalena F.E. (2005) Evaluation of crosses of Holstein, Jersey or Brown Swiss sires x Holstein-Friesian/Gir dams. 3. Lifetime performance and economic evaluation. *Genetics and Molecular Research* **4**: 84-93.

Tesfa A., Kumar D., Abegaz S., Mekuriaw G., Bimerew T., Kebede A., Bitew A., et al. (2016) Growth and reproductive performance of fogera cattle breed at Andassa livestock research center. *Livestock Research for Rural Development* **28**: 1-17.

Thanh V.T.K. (2014) Differences in protein nutrition in Swamp buffaloes compared to Yellow Cattle. *Buffalo Bulletin* **33**: 362-369.

Theunissen A., Scholtz M., Neser F., MacNeil M. (2013) Crossbreeding to increase beef production: Additive and non-additive effects on fitness traits. *South African Journal of Animal Science* **44**: 335.

Thombre B.M., Shikalga R.N.S., Bainwad D.V. (2015) Performance and Colour Pattern of Khillar Cattle on Organized Farm. IOSR Journal of Agriculture and Veterinary Science. **8***(***4)**: 04-05 // DOI: 10.9790/2380-08420405.

Tomar S.K., Sharma R.L. (2002) Fodder and feeding practices of cattle and sheep in Kashmir (India). *Tropical Agricultural Research and Extension* **5**: 1-5.

Tonhati H., Cerón-Muñoz M.F., Hurtado-Lugo N.A., Aspilcueta-Borquis R.R., Baldi F., Albuquerque L.G. (2009) Possibilidade de avaliação genética para bubalinos leiteiros na América do Sul. Simpósio de Búfalos das Américas. In: *Europe and America's Buffalo Symposium, 4. Pedro Leopoldo, MG, Brazil*.

Tonhati H., Cerón-Muñoz M.F., de Oliveira J.A., Duarte J.M.C., Furtado T.P., Tseimazides S.P. (2000) Parâmetros Genéticos para a Produção de Leite, Gordura e Proteína em Bubalinos. *Revista Brasileira de Zootecnia* **29**: 20151-20156.

Turkish Statistical Institute (2017) http://www.turkstat.gov.tr/Start.do.

Tuyen D.K. (2009) Buffalo Production Situation in Vietnam and Development Plan to 2020. Ministry of Agriculture and Rural Development, pp 1-15.

Tzankova M., Dimov K. (2003) Digestibility of rations with different contents of urea in the concentrate mixture consumed by weaned buffalo calves. *Buffalo Bulletin* **22**.

Ulaş D. (2016) Fat depression in milk obtained from Simmental and native (Yerli Kara) cows in first month of postpartum period. *Int. J. Biosci.* **9**: 125-128.

USDA (2015) *Live animals and animal products trade: Turkey, GAIN report*: USDA Foreign Agricultural Service.

Ustuner H., Yalcintan H., Orman A., Ardicli S., Ekiz B., Gencoglu H., Kandazoglu O. (2016) Effects of initial fattening age on carcass characteristics and meat quality in Simmental bulls imported from Austria to Turkey. *South African Journal of Animal Science* **47**: 194.

Van Sanh M. (2007) Use of large bulls to improve the body weight of local small sized buffalo. *Italian Journal of Animal Science* **6**: 389-392.

Verruma M.R., Salgado J.M. (1994) Análise química do leite de búfala em comparação ao leite de vaca. *Scientia Agricola* **51**: 131-137.

WAAP (2007) *A Review on Developments and Research in Livestock Systems. WAAP book of the year*, eds. A Rosati, A Tewolde, C Mosconi.

Waldrip H.M., Todd R.W., Cole N.A. (2013) Prediction of nitrogen excretion by beef cattle: A meta-analysis. *Journal of Animal Science* **91**: 4290-4302.

Waldron S., Erwidodo, Nuryati Y. (2015) The Indonesian Beef Industry. In: *Regional Workshop on Beef markets and trade in Southeast Asian and China*, Ben Tre, Vietnam.

Wanapat M., Rowlinson P. (2007) Nutrition and feeding of swamp buffalo: feed resources and rumen approach. *Italian Journal of Animal Science* **6**: 67-73.

Wang C., Liu J.-X., Paul H., Makkar S., Wei N.-B., Xu Q.-M. (2014) Production level, feed conversion efficiency, and nitrogen use efficiency of dairy production systems in China. *Trop Anim Health Prod* **46**: 669-673.

Wang G., Hua L., Squires V. (2017) Development impacts on beef and mutton production from the pastoral and agro-pastoral systems in China and the economic and cultural factors that influence it. *Livestock Research for Rural Development* **29**.

Wattiaux M.A., Frank G.G., Mark Powell J., Wu Z., Guo Y. (2002) *Agriculture and dairy production systems in China: an overview and case studies*: Babcock Institute.

Widiawati Y., Rofiq M.N., Tiesnamurti B. (2016) Methane Emission Factors for Enteric Fermentation in Beef Cattle using IPCC Tier-2 Method in Indonesia. *JITV* **21**: 101-111.

Wurzinger M., Ndumu D., Baumung R., Drucker A., Okeyo A.M., Semambo D.K., Byamungu N., et al. (2006) Comparison of production systems and selection criteria of Ankole cattle by breeders in Burundi, Rwanda, Tanzania and Uganda. *Tropical Animal Health and Production* **38**: 571-581.

Xie X., Meng Q., Ren L., Shi F., Zhou B. (2012) Effect of cattle breed on finishing performance, carcass characteristics and economic benefits under typical beef production system in China. *Italian Journal of Animal Science* **11**.

Xie Z.L., Zhang J., Zhang D.M., Li J.F., Lin Y.H. (2016) Effect of a high-concentrate diet on milk components and mammary health in Holstein dairy cows. *Genetics and Molecular Research* **16**.

Xue B., Wang L.Z., Yan T. (2014) Methane emission inventories for enteric fermentation and manure management of yak, buffalo and dairy and beef cattle in China from 1988 to 2009. *Agriculture Ecosystems & Environment* **195**: 202-210.

Yadava R.K. (2009) *Studies on growth pattern for better management of Sahiwal animals. MSc thesis*: National Dairy Research Institute (Deemed university) (I.C.A.R.).

Yalcin B., Stepan V., Cihan D. (2017) Prediction of liveweight of holstein and brown swiss cattle grown in an 12 month intensive beef production system by using real-time body measurements. *Scientific Papers-Animal Science Series: Lucrări Ştiinţifice - Seria Zootehnie*.

Yang B., Zeng X.L.Q., Qin J., Yang C. (2007) Dairy buffalo breeding in countryside of China. *Italian Journal of Animal Science* **6**: 25-29.

Yang B.Z., Liang X.W., Qin J., Yang C.J., Shang J.H. (2013) Brief introduction to the development of Chinese dairy buffalo industry. *Buffalo Bulletin* **32**: 111-120.

Yang L., Yang Q., Yi M., Pang Z.H., Xiong B.H. (2013) Effects of seasonal change and parity on raw milk composition and related indices in Chinese Holstein cows in northern China. *J. Dairy Sci.* **96**: 6863–6869.

Yasothai R. (2014) Importance of Protein on Reproduction in Dairy Cattle. *International Journal of Science, Environment and Technology* **3**: 2081-2083.

Yavuz F., Zulauf C.R. (2004) Introducing a new approach to estimating red meat production in Turkey. *Turkish Journal of Veterinary & Animal Sciences* **28**: 641-648.

Yilmaz O., Akin O., Yener S.M., Ertugrul M., Wilson R.T. (2012) The domestic livestock resources of Turkey: cattle local breeds and types and their conservation status. *Animal Genetic Resources/Ressources génétiques animales/Recursos genéticos animales* **50**: 65-73.

Young H., Osman A.M., Aklilu Y., Dale R., Badri B., Fuddle A.J.A. (2005) Darfur - Livelihoods under Siege. Feinstein International Famine Center, Tufts University, Medford, MA, USA. pp 178.

Yousif I.A., El- Moula A.A.F. (2006) Characterisation of Kenana cattle breed and its production environment. *Animal Genetic Resources Information* **38**: 47-56.

Zadnepryanskiy I., Zakirko V. (2012) Red-and-white breed milk cattle in Belgorod region. *Dairy and Beef Cattle Breeding* **3**: 21-23.

Zeoula L.M., Prado O.P.P., Geron L.J.V., Beleze J.R.F., Aguiar S.C., Maeda E.M. (2014) Digestibilidade total e degradabilidade ruminal in situ de dietas volumosas com inclusão de ionóforo ou probiótico para bubalinos e bovinos: Total digestibility and in situ degradability of bulky diets with the inclusion of ionophores or probiotics for cattle and buffaloes. *Ciências Agrárias, Londrina* **35**: 2063-2076.

Zerabruk M., Vangen O. (2005) *The Abergelle and Irob cattle breeds of North Ethiopia : description and on-farm characterisation*.

Zhai S.W., Liu J.X., Wu Y.M., Ye J.A., Xu Y.N. (2006) Responses of milk urea nitrogen content to dietary crude protein level and degradability in lactating Holstein dairy cows. *Czech J. Anim. Sci.* **51**: 518-522.

Zhou G.H. (1998) Developing a Beef Grading System for China. *Reciprocal Meat Conference Proceedings* **51**.

Zi X.D., Ma L., Zhou G.Q., Chen C.L., Wei G.M. (2003) Fertility of Holstein cows in Chengdu, China. *Asian-Aust. J. Anim. Sci.* **16**: 185-188.

Zicarelli L., Ariota B., Gasparrini B., Neglia G., Di Palo R. (2007) Buffalo Beef Production. *Italian Journal of Animal Science* **6**: 1313-1315.

10B.2 Estimation of Cattle/Buffalo CH_4 conversion factors (Y_m)

(References in Section 10.3 Methane Emissions from Enteric Fermentation)

10B.3 Estimation of Default Emission Factor(s) for Goat Tier 2 parameters

Abecia L., Toral P.G., Martín-García A.I., Martínez G., Tomkins N.W., Molina-Alcaide E., Newbold C.J., et al. (2012) Effect of bromochloromethane on methane emission, rumen fermentation pattern, milk yield, and fatty acid profile in lactating dairy goats. *Journal of Dairy Science* **95**: 2027-2036.

AFRC (1998) *The Nutrition of Goats*, Wallingford: CAB International. pp 118.

Aguilera J.F., Prieto C., Fonolla J. (1990) Protein and energy metabolism of lactating Granadina goats. *British Journal of Nutrition* **63**: 165-175.

Animut G., Puchala R., Goetsch A.L., Patra A.K., Sahlu T., Varel V.H., Wells J. (2008) Methane emission by goats consuming different sources of condensed tannins. *Animal feed science and technology* **144**: 228-241.

Arco-Pérez A., Ramos-Morales E., Yáñez-Ruiz D.R., Abecia L., Martín-García A.I. (2017) Nutritive evaluation and milk quality of including of tomato or olive by-products silages with sunflower oil in the diet of dairy goats. *Animal feed science and technology* **232**: 57-70.

Arif M., Sarwar M., Mehr un N., Hayat Z., Younas M. (2016) Effect of supplementary sodium nitrate and sulphur on methane production and growth rates in sheep and goats fed forage based diet low in true protein. *JAPS, Journal of Animal and Plant Sciences* **26**: 69-78.

Azlan P.M., Jahromi M.F., Ariff M.O., Ebrahimi M., Candyrine S.C.L., Liang J.B. (2018) Aspergillus terreus treated rice straw suppresses methane production and enhances feed digestibility in goats. *Tropical Animal Health and Production* **50**: 565-571.

Barbosa A.L., Voltolini T.V., Menezes D.R., Moraes S.A.d., Nascimento J.C.S., Rodrigues R.T.d.S. (2017) Intake, digestibility, growth performance, and enteric methane emission of Brazilian semiarid non-descript breed goats fed diets with different forage to concentrate ratios. *Tropical Animal Health and Production* 1-7.

Bhatta R., Enishi O., Takusari N., Higuchi K., Nonaka I., Kurihara M. (2008) Diet effects on methane production by goats and a comparison between measurement methodologies. *The Journal of Agricultural Science* **146**: 705-715.

Bhatta R., Enishi O., Yabumoto Y., Nonaka I., Takusari N., Higuchi K., Tajima K., et al. (2013) Methane reduction and energy partitioning in goats fed two concentrations of tannin from Mimosa spp. *The Journal of Agricultural Science* **151**: 119-128.

Castro-Lima A.R., Fernandes M.H.M.d.R., Teixeira I.A.M.d.A., Frighetto R.T.S., Bompadre T.F.V., Biagioli B., Meister N.C., et al. (2016) Effects of feed restriction and forage:concentrate ratio on digestibility, methane emission, and energy utilization by goats. *Revista Brasileira de Zootecnia* **45**: 781-787.

Chethan K.P., Verma A.K., Singh P. (2013) Effect of fumaric acid supplementation on methanogenesis and rumen fermentation in Barbari goats. *The Indian Journal of Animal Sciences* **83**: 63-66.

Criscioni P., Fernández C. (2016) Effect of rice bran as a replacement for oat grain in energy and nitrogen balance, methane emissions, and milk performance of Murciano-Granadina goats. *Journal of Dairy Science* **99**: 280-290.

Fernández C., Martí J.V., Pérez-Baena I., Palomares J.L., Ibáñez C., Segarra J.V. (2018) Effect of lemon leaves on energy and C–N balances, methane emission, and milk performance in Murciano-Granadina dairy goats. *Journal of Animal Science* **96**: 1508-1518.

Gerber P., Vellinga T., Opio C., Steinfeld H. (2011) Productivity gains and greenhouse gas emissions intensity in dairy systems. *Livestock Science* **139**: 100-108.

Haque N., Khan M.Y., Murarilal (1997) Effect of level of Leucaena leucocephala in the diets of Jamunapari goats on carbon nitrogen and energy balances. *Asian-Australasian Journal of Animal Sciences* **10**: 455-459.

Haque N., Murarilal M.Y., Khan M.Y., Biswas J.C., Singh P. (1998) Metabolizable energy requirements for maintenance of pashmina producing Cheghu goats. *Small Ruminant Research* **27**: 41-45.

Haque N., Toppo S., Saraswat M.L., Khan M.Y. (2008) Effect of feeding Leucaena leucocephala leaves and twigs on energy utilization by goats. *Animal feed science and technology* **142**: 330-338.

Ibáñez C., López M.C., Criscioni P., Fernández C. (2015) Effect of replacing dietary corn with beet pulp on energy partitioning, substrate oxidation and methane production in lactating dairy goats. *Animal Production Science* **55**: 56-63.

Ibáñez C., Moya V.J., Arriaga H., López D.M., Merino P., Fernández C. (2015) Replacement of cereal with low starch fibrous by-products on nutrients utilization and methane emissions in dairy goats. *Open Journal of Animal Sciences* **5**: 198-209.

Islam M., Abe H., Hayashi Y., Terada F. (2000) Effects of feeding Italian ryegrass with corn on rumen environment, nutrient digestibility, methane emission, and energy and nitrogen utilization at two intake levels by goats. *Small Ruminant Research* **38**: 165-174.

Islam M., Enishi O., Purnomoadi A., Higuchi K., Takusari N., Terada F. (2001) Energy and protein utilization by goats fed Italian ryegrass silage treated with molasses, urea, cellulase or cellulase + lactic acid bacteria. *Small Ruminant Research* **42**: 49-60.

Jeong W.Y., Yi O.H., Choi H.J., Nam K.T., Kim B.G., Lee S.R. (2012) Effects of dietary vegetable oils on intake, digestibility and methane emission from black goats. *Journal of Animal and Veterinary Advances* **11**: 4689-4692.

Keli A., Ribeiro L.P.S., Gipson T.A., Puchala R., Tesfai K., Tsukahara Y., Sahlu T., et al. (2017) Effects of pasture access regime on performance, grazing behavior, and energy utilization by Alpine goats in early and mid-lactation. *Small Ruminant Research* **154**: 58-69.

Kumar S., Dutta N., Pattanaik A.K., Ojha B.K., Chaturvedi V.B. (2017) Effect of Feed Restriction on Energy Metabolism and Methane Emission in Goats. *Journal of Animal Research* **7**: 369.

Lassey K. (2012) *Methane Emissions and nitrogen Excretion Rates for New Zealand Goats. MAF Technical Paper No: 2012/13*, Wellington, New Zealand: Ministry of Agriculture and Forestry.

Li D.H., Beob Gyun K., Sang Rak L. (2010) A respiration-metabolism chamber system for measuring gas emission and nutrient digestibility in small ruminant animals. *Revista Colombiana de Ciencias Pecuarias* **23**: 444-450.

Li Z., Liu N., Cao Y., Jin C., Li F., Cai C., Yao J. (2018) Effects of fumaric acid supplementation on methane production and rumen fermentation in goats fed diets varying in forage and concentrate particle size. *Journal of Animal Science and Biotechnology* **9**: 21.

López M.C., Estellés F., Moya V.J., Fernández C. (2014) Use of dry citrus pulp or soybean hulls as a replacement for corn grain in energy and nitrogen partitioning, methane emissions, and milk performance in lactating Murciano-Granadina goats. *Journal of Dairy Science* **97**: 7821-7832.

López M.C., Fernández C. (2013) Energy partitioning and substrate oxidation by Murciano-Granadina goats during mid lactation fed soy hulls and corn gluten feed blend as a replacement for corn grain. *Journal of Dairy Science* **96**: 4542-4552.

López M.C., Ibáñez C., García-Diego F.J., Moya V.J., Estellés F., Cervera C., Fernández C. (2012) *Determination of methane production from lactating goats fed diets with different starch levels. Ninth International Livestock Environment Symposium Sponsored by ASABE Valencia Conference Centre Valencia, Spain July 8 - 12, 2012*: American Society of Agricultural and Biological Engineers. pp. 3.

López M.C., Ródenas L., Piquer O., Cerisuelo A., Cervera C., Fernández C. (2011) Determinación de producción de metano en caprinos alimentados con dietas con distintos cereales. *Archivos de Zootecnia* **60**: 943-951.

López M.C., Ródenas L., Piquer O., Martínez E., Cerisuelo A., Cervera C., Fernández C. (2010) Determination of the proportion of the ingested gross energy lost as exhaled methane by dairy goats consuming contrasting concentrate ingredients in mixed rations. *Canadian Journal of Animal Science* **90**: 585-590.

López M.C., Ródenas L., Piquer O., Martínez E., Cerisuelo A., Pascual J.J., Fernández C. (2010) Effect of Different Physical form Alfalfa on Methane Production in Murciano-Granadina Dairy Goats. *Journal of Applied Animal Research* **38**: 93-96.

Lu Q., Jiao J., Tang S., He Z., Zhou C., Han X., Wang M., et al. (2015) Effects of dietary cellulase and xylanase addition on digestion, rumen fermentation and methane emission in growing goats. *Archives of Animal Nutrition* **69**: 251-266.

Lu Q., Wu J., Wang M., Zhou C., Han X., Odongo E.N., Tan Z., et al. (2016) Effects of dietary addition of cellulase and a Saccharomyces cerevisiae fermentation product on nutrient digestibility, rumen fermentation and enteric methane emissions in growing goats. *Archives of Animal Nutrition* **70**: 224-238.

Martínez-Fernández G., Abecia L., Martín-García A.I., Ramos-Morales E., Hervás G., Molina-Alcaide E., Yáñez-Ruiz D.R. (2013) In vitro–in vivo study on the effects of plant compounds on rumen fermentation, microbial abundances and methane emissions in goats. *animal* **7**: 1925-1934.

Martínez-Fernández G., Abecia L., Ramos-Morales E., Martin-García A.I., Molina-Alcaide E., Yáñez-Ruiz D.R. (2014) Effects of propyl propane thiosulfinate on nutrient utilization, ruminal fermentation, microbial population and methane emissions in goats. *Animal feed science and technology* **191**: 16-25.

Miri V.H., Tyagi A.K., Ebrahimi S.H., Mohini M. (2013) Effect of cumin (Cuminum cyminum) seed extract on milk fatty acid profile and methane emission in lactating goat. *Small Ruminant Research* **113**: 66-72.

Mitsumori M., Shinkai T., Takenaka A., Enishi O., Higuchi K., Kobayashi Y., Nonaka I., et al. (2012) Responses in digestion, rumen fermentation and microbial populations to inhibition of methane formation by a halogenated methane analogue. *British Journal of Nutrition* **108**: 482-491.

Na Y., Hwang S., Choi Y., Park G., Lee S. (2018) Nutrient Digestibility and Greenhouse Gas Emission in Castrated Goats (*Capra hircus*) Fed Various Roughage Sources. *Journal of The Korean Society of Grassland and Forage Science* **38**: 39-43.

Na Y., Li D.H., Choi Y., Kim K.H., Lee S.R. (2018) Effects of feeding level on nutrient digestibility and enteric methane production in growing goats (*Capra hircus hircus*) and Sika deer (*Cervus nippon hortulorum*). *Asian-Australasian Journal of Animal Sciences* **31**:1238-1243.

Na Y., Li D.H., Lee S.R. (2017) Effects of dietary forage-to-concentrate ratio on nutrient digestibility and enteric methane production in growing goats (*Capra hircus hircus*) and Sika deer (*Cervus nippon hortulorum*). *Asian-Australasian Journal of Animal Sciences* **30**: 967-972.

Nielsen M.O., Kiani A., Tejada E., Chwalibog A., Alstrup L. (2014) Energy metabolism and methane production in llamas, sheep and goats fed high- and low-quality grass-based diets. *Archives of Animal Nutrition* **68**: 171-185.

Patra A.K., Lalhriatpuii M. (2016) Development of statistical models for prediction of enteric methane emission from goats using nutrient composition and intake variables. *Agriculture, Ecosystems & Environment* **215**: 89-99.

Prieto C., Aguilera J.F., Lara L., FonollÁ J. (1990) Protein and energy requirements for maintenance of indigenous Granadina goats. *British Journal of Nutrition* **63**: 155-163.

Puchala R., Animut G., Patra A.K., Detweiler G.D., Wells J.E., Varel V.H., Sahlu T., et al. (2012) Effects of different fresh-cut forages and their hays on feed intake, digestibility, heat production, and ruminal methane emission by Boer × Spanish goats. *Journal of Animal Science* **90**: 2754-2762.

Puchala R., Animut G., Patra A.K., Detweiler G.D., Wells J.E., Varel V.H., Sahlu T., et al. (2012) Methane emissions by goats consuming Sericea lespedeza at different feeding frequencies. *Animal feed science and technology* **175**: 76-84.

Puchala R., LeShure S., Gipson T.A., Tesfai K., Flythe M.D., Goetsch A.L. (2018) Effects of different levels of lespedeza and supplementation with monensin, coconut oil, or soybean oil on ruminal methane emission by mature Boer goat wethers after different lengths of feeding. *Journal of Applied Animal Research* **46**: 1127-1136.

Puchala R., Min B.R., Goetsch A.L., Sahlu T. (2005) The effect of a condensed tannin-containing forage on methane emission by goats. *Journal of Animal Science* **83**: 182-186.

Rapetti L., Bava L., Tamburini A., Crovetto G.M. (2005) Feeding behaviour, digestibility, energy balance and productive performance of lactating goats fed forage-based and forage-free diets. *Italian Journal of Animal Science* **4**: 71-83.

Rapetti L., Crovetto G.M., Galassi G., Sandrucci A., Succi G., Tamburini A., Battelli G. (2002) Effect of maize, rumen-protected fat and whey permeate on energy utilisation and milk fat composition in lactating goats. *Italian Journal of Animal Science* **1**: 43-53.

Romero-Huelva M., Molina-Alcaide E. (2014) Nutrient utilization, ruminal fermentation, microbial nitrogen flow, microbial abundances, and methane emissions in goats fed diets including tomato and cucumber waste fruits. *Journal of Animal Science* **91**: 914-923.

Romero-Huelva M., Ramírez-Fenosa M.A., Planelles-González R., García-Casado P., Molina-Alcaide E. (2017) Can by-products replace conventional ingredients in concentrate of dairy goat diet? *Journal of Dairy Science* **100**: 4500-4512.

Romero-Huelva M., Ramos-Morales E., Molina-Alcaide E. (2012) Nutrient utilization, ruminal fermentation, microbial abundances, and milk yield and composition in dairy goats fed diets including tomato and cucumber waste fruits. *Journal of Dairy Science* **95**: 6015-6026.

Shibata M., Terada F., Iwasaki K., Kurihara M., Nishida T. (1992) Methane Production in Heifers, Sheep and Goats Consuming Diets of Various Hay-Concentrate Ratios. *Nihon Chikusan Gakkaiho* **63**: 1221-1227.

Tovar-Luna I., Goetsch A.L., Puchala R., Sahlu T., Carstens G.E., Freetly H.C., Johnson Z.B. (2007) Effects of diet quality on energy expenditure by 20-month-old Alpine, Angora, Boer, and Spanish wethers. *Small Ruminant Research* **72**: 18-24.

Tovar-Luna I., Goetsch A.L., Puchala R., Sahlu T., Carstens G.E., Freetly H.C., Johnson Z.B. (2007) Effects of moderate feed restriction on energy expenditure by 2-year-old crossbred Boer goats. *Small Ruminant Research* **72**: 25-32.

Tovar-Luna I., Goetsch A.L., Puchala R., Sahlu T., Carstens G.E., Freetly H.C., Johnson Z.B. (2007) Efficiency of energy use for pregnancy by meat goat does with different litter size. *Small Ruminant Research* **71**: 83-91.

Tovar-Luna I., Puchala R., Sahlu T., Freetly H.C., Goetsch A.L. (2010) Effects of stage of lactation and dietary concentrate level on energy utilization by Alpine dairy goats. *Journal of Dairy Science* **93**: 4818-4828.

Tovar-Luna I., Puchala R., Sahlu T., Freetly H.C., Goetsch A.L. (2010) Effects of stage of lactation and level of feed intake on energy utilization by Alpine dairy goats. *J Dairy Sci* **93**: 4829-4837.

Tovar-Luna I., Puchala R., Sahlu T., Freetly H.C., Goetsch A.L. (2011) Effects of level of feeding on energy utilization by Angora goats. *Journal of Animal Science* **89**: 142-149.

Tovar-Luna I., Puchala R., Sahlu T., Goetsch A.L. (2017) Effects of gender and age on energy use by young Boer goats. *Livestock Science* **199**: 86-94.

Vermorel M., Jouany J.P., Eugène M., Sauvant D., Noblet J., Dourmad J.-Y. (2008) Evaluation quantitative des émissions de méthane entérique par les animaux d'élevage en 2007 en France. *Productions animales* **21**: 403-418.

Wang L., Xue B. (2015) Effects of Cellulase Supplementation on Nutrient Digestibility, Energy Utilization and Methane Emission by Boer Crossbred Goats. *Asian-Australasian Journal of Animal Sciences* **29**: 204-210.

Wang L.Z., Zhou M.L., Wang J.W., Wu D., Yan T. (2016) The Effect of Dietary Replacement of Ordinary Rice with Red Yeast Rice on Nutrient Utilization, Enteric Methane Emission and Rumen Archaeal Diversity in Goats. *PLOS ONE* **11**.

Wang P., Xue Y., Ma G., Luo J. (2016) Effects of corn silage levels on methane emissions and blood metabolite concentrations of drying-off Xinong Saanen dairy goats. *Journal of Animal Science* **94**: 835-835.

Yang C.J., Mao S.Y., Long L.M., Zhu W.Y. (2012) Effect of disodium fumarate on microbial abundance, ruminal fermentation and methane emission in goats under different forage : concentrate ratios. *animal* **6**: 1788-1794.

10B.4 Feed intake estimates using a simplified Tier 2 method

Appuhamy J.A., France J., Kebreab E. (2016) Models for predicting enteric methane emissions from dairy cows in North America, Europe, and Australia and New Zealand. *Glob Chang Biol* **22**: 3039-3056.

Appuhamy J.A.D.R.N., Moraes L.E., Wagner-Riddle C., Casper D.P., Kebreab E. (2018) Predicting manure volatile solid output of lactating dairy cows. *J. Dairy. Sci.* **101**: 820-829.

Arnerdal S. (2005) *Predictions for voluntary dry matter intake in dairy cows. Thesis*: Department of Animal Nutrition and Management, Swedish University of Agricultural Sciences.

Charmley E., Williams S.R.O., Moate P.J., Hegarty R.S., Herd R.M., Oddy V.H., Reyenga P., et al. (2016) A universal equation to predict methane production of forage-fed cattle in Australia. *Animal Production Science* **56**: 169-180.

Fox D.G., Sniffen C.J., O'connor J.D., Russell J.B., Vansoest P.J. (1992) A Net Carbohydrate and Protein System for Evaluating Cattle Diets. III. Cattle Requirements and Diet Adequacy. *Journal of Animal Science* **70**: 3578-3596.

Intergovernmental Panel on Climate Change (IPCC) (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories, Prepared by the National Greenhouse Gas Inventories Programme*, eds. HS Eggleston, L Buendia, K Miwa, T Ngara, K Tanabe. Japan: IGES.

Lindgren E., Murphy M., Andersson T. (2001) *Värdering av foder*, Uppsala: Lantmännen Foderutveckling AB, Nötfor. Almqvist & Wiksell.

NRC (2001) *Nutrient Requirements of Dairy Cattle: Seventh Revised Edition, 2001*, ed. BoAaNR National Research Council, Committee on Animal Nutrition, Subcommittee on Dairy Cattle Nutrition. Washington, DC: The National Academies Press. pp. 408.

10B.5 Basis for Changes to MCF Calculations for Liquid/Slurry

Balde H., VanderZaag A.C., Burtt S., Evans L., Wagner-Riddle C., Desjardins R.L., MacDonald J.D. (2016) Measured versus modelled methane emissions from separated liquid dairy manure show large model underestimates. *Agriculture Ecosystems & Environment* **230**: 261-270.

Balde H., VanderZaag A.C., Burtt S.D., Gordon R.J., Desjardins R.L. (2016) Does Fall Removal of the Dairy Manure Sludge in a Storage Tank Reduce Subsequent Methane Emissions? *Journal of Environmental Quality* **45**: 2038-2043.

Elsgaard L., Olsen A.B., Petersen S.O. (2016) Temperature response of methane production in liquid manures and co-digestates. *Science of the Total Environment* **539**: 78-84.

Intergovernmental Panel on Climate Change (IPCC) (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories, Prepared by the National Greenhouse Gas Inventories Programme*, eds. HS Eggleston, L Buendia, K Miwa, T Ngara, K Tanabe. Japan: IGES.

Le Riche E.L., VanderZaag A.C., Wood J.D., Wagner-Riddle C., Dunfield K., Ngwabie N.M., McCabe J., et al. (2016) Greenhouse Gas Emissions from Stored Dairy Slurry from Multiple Farms. *Journal of Environmental Quality* **45**: 1822-1828.

Leytem A.B., Bjorneberg D.L., Koehn A.C., Moraes L.E., Kebreab E., Dungan R.S. (2017) Methane emissions from dairy lagoons in the western United States. *Journal of Dairy Science* **100**: 6785-6803.

Mangino J., Bartram D., Brazy A. (2001) *Development of a Methane Conversion Factor to Estimate Emissions from Animal Waste Lagoons. USEPA Technical Report*, Washington, D. C.: Environmental Protection Agency. pp. 14.

Masse D.I., Masse L., Claveau S., Benchaar C., Thomas O. (2008) Methane Emissions from Manure Storages. *Transactions of the Asabe* **51**: 1775-1781.

Owen W., Stuckey D., Healy Jr J., Young L., McCarty P. (1979) Bioassay for monitoring biochemical methane potential and anaerobic toxicity. *Water research* **13**: 485-492.

Petersen S.O., Olsen A.B., Elsgaard L., Triolo J.M., Sommer S.G. (2016) Estimation of Methane Emissions from Slurry Pits below Pig and Cattle Confinements. *PLOS ONE* **11**.

Pham C.H., Triolo J.M., Cu T.T.T., Pedersen L., Sommer S.G. (2013) Validation and Recommendation of Methods to Measure Biogas Production Potential of Animal Manure. *Asian-Australasian Journal of Animal Sciences* **26**: 864-873.

Rennie T.J., Balde H., Gordon R.J., Smith W.N., VanderZaag A.C. (2017) A 3-D model to predict the temperature of liquid manure within storage tanks. *Biosystems Engineering* **163**: 50-65.

Rennie T.J., Gordon R.J., Smith W.N., VanderZaag A.C. (2018) Liquid manure storage temperature is affected by storage design and management practices—A modelling assessment. *Agriculture, Ecosystems and Environment* **260**: 47-57.

Safley L.M., Westerman P.W. (1990) Psychrophilic Anaerobic Digestion of Animal Manure: Proposed Design Methodology. *Biological Wastes* **34**: 133-148.

VanderZaag A.C., Baldé H., Crolla A., Gordon R.J., Ngwabie N.M., Wagner-Riddle C., Desjardins R., et al. (2018) Potential methane emission reductions for two manure treatment technologies. *Environmental technology* **39**: 851-858.

VanderZaag A.C., Gordon R.J., Jamieson R.C., Burton D.L., Stratton G.W. (2010) Permeable Synthetic Covers for Controlling Emissions from Liquid Dairy Manure. *Applied Engineering in Agriculture* **26**: 287-297.

Wightman J.L., Woodbury P.B. (2016) New York Dairy Manure Management Greenhouse Gas Emissions and Mitigation Costs (1992-2022). *Journal of Environmental Quality* **45**: 266-275.

Zeeman G., Gerbens S. (2000) *CH_4 emissions from animal manure. IPCC Background Papers—IPCC Expert Meetings on Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories*.

10B.6 Revision of MCFs from dung deposited onto pasture, range and paddocks (Table 10.17)

Andueza D., Picard F., Dozias D., Aufrère J. (2017) Fecal Near-Infrared Reflectance Spectroscopy Prediction of the Feed Value of Temperate Forages for Ruminants and Some Parameters of the Chemical Composition of Feces: Efficiency of Four Calibration Strategies. *Applied Spectroscopy* **71**: 2164-2176.

Cai Y., Chang S.X., Cheng Y. (2017) Greenhouse gas emissions from excreta patches of grazing animals and their mitigation strategies. *Earth-Science Reviews* **171**: 44-57.

Carran R.A., Dewar D., Theobold P.W. (2003) Methane and nitrous oxide emission from sheep dung. Client Report, March 2003. In: p. 14. Ministry of Agriculture and Fisheries.

Fries G.F., Marrow G.S., Snow P.A. (1982) Soil Ingestion by Dairy Cattle. *Journal of Dairy Science* **65**: 611-618.

Karn J.F. (1991) Chemical composition of forage and feces as affected by microwave oven drying. *Journal of Range Management* **44**: 512-515.

Kelly K.B., Ward G.N., Hollier J.W. (2016) Greenhouse gas emissions from dung, urine and dairy pond sludge applied to pasture. 2. Methane emissions. *Animal Production Science* **58**: 1094-1099.

Saggar S., Clark H., Hedley C., Tate K., Carran A., Cosgrove G. (2003) Methane emissions from animal dung and waste management systems, and its contribution to the national methane budget. Landcare Research Contract Report: LC0301/02. Prepared for the Ministry of Agriculture and Forestry : New Zealand. 39.

Sherlock D.R.R., de Klein D.C.A.M., Li D.Z. (2003a) Determination of the N_2O and CH_4 emission factors from animal excreta, following a summer application in 3 regions of New Zealand. A final report of an NzOnet study, March 2003. Prepared for: Ministry of Agriculture & Forestry. In: p. 27. Lincoln University; AgResearch; Landcare Research.

Sherlock D.R.R., de Klein D.C.A.M., Li D.Z. (2003b) Determination of the N_2O and CH_4 emission factors from animal excreta, following a spring application in 3 regions of New Zealand. A final report of an NzOnet study, November 2003. Prepared for: Ministry of Agriculture & Forestry. In: p. 28. Lincoln University; AgResearch; Landcare Research.

Waghorn G., Gregory N.G., Todd S.E., Wesselink R. (1999) Dags in sheep; a look at faeces and reasons for dag formation. *Proceedings of the New Zealand Grassland Association* **61**: 43-49.

10B.7 Estimation of default emission factors for MCF CH_4 values, EF for direct N_2O emissions, NH_3, NO_3 leaching and N_2 emissions from solid storage and composting systems

Aguerre M.J., Wattiaux M.A., Powell J.M. (2012) Emissions of ammonia, nitrous oxide, methane, and carbon dioxide during storage of dairy cow manure as affected by dietary forage-to-concentrate ratio and crust formation. *J. Dairy Sci.* **95**: 7409-7416.

Amon B., Amon T., Boxberger J., Alt C. (2001) Emissions of NH_3, N_2O and CH_4 from dairy cows housed in a farmyard manure tying stall (housing, manure storage, manure spreading). *Nutrient Cycling in Agroecosystems* **60**: 103-113.

Amon B., Kryvoruchko V., Amon T., Zechmeister-Boltenstern S. (2006) Methane, nitrous oxide and ammonia emissions during storage and after application of dairy cattle slurry and influence of slurry treatment. *Agriculture, Ecosystems & Environment* **112**: 153-162.

Amon B., Kryvoruchko V., Fröhlich M., Amon T., Pöllinger A., Mösenbacher I., Hausleitner A. (2007) Ammonia and greenhouse gas emissions from a straw flow system for fattening pigs: Housing and manure storage. *Livestock Science* **112**: 199-207.

Bierman S., Erickson G.E., Klopfenstein T.J., Stock R.A., Shain D.H. (1999) Evaluation of nitrogen and organic matter balance in the feedlot as affected by level and source of dietary fiber. *Journal of Animal Science* **77**: 1645-1653.

Clemens J., Trimborn M., Weiland P., Amon B. (2006) Mitigation of greenhouse gas emissions by anaerobic digestion of cattle slurry. *Agriculture, Ecosystems & Environment* **112**: 171-177.

Eghball B., Power J.F. (1994) Beef-Cattle Feedlot Manure Management. *Journal of Soil and Water Conservation* **49**: 113-122.

Erickson G., Klopfenstein T. (2010) Nutritional and management methods to decrease nitrogen losses from beef feedlots. *Journal of Animal Science* **88**: E172-180.

Guarino A., Fabbri C., Brambilla M., Valli L., Navarotto P. (2006) Evaluation of simplified covering systems to reduce gaseous emissions from livestock manure storage. *Transactions of the Asabe* **49**: 737-747.

Hou Y., Velthof G.L., Oenema O. (2015) Mitigation of ammonia, nitrous oxide and methane emissions from manure management chains: a meta-analysis and integrated assessment. *Glob Chang Biol* **21**: 1293-1312.

Intergovernmental Panel on Climate Change (IPCC) (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories, Prepared by the National Greenhouse Gas Inventories Programme*, eds. HS Eggleston, L Buendia, K Miwa, T Ngara, K Tanabe. Japan: IGES.

Kizil U., Lindley J.A., Padmanabhan G. (2006) Verification of Nutrient Transport Modelling of a Bison Feedlot. *Biosystems Engineering* **94**: 453-460.

Lekasi J., Tanner J., Kimani S., Harris P. (2001) *Managing manure to sustain smallholder livelihoods in the East African Highlands for high potential production systems of the Natural Resources Systems Programme Renewable Natural Resources Knowledge Strategy, Department for International Development*: HDRA publications.

Matulaitis R., Juskiené V., Juska R. (2015) The effect of floating covers on gas emissions from liquid pig manure. *Chilean Journal of Agricultural Research* **75**: 232-238.

Misselbrook T., Hunt J., Perazzolo F., Provolo G. (2016) Greenhouse gas and ammonia emissions from slurry storage: impacts of temperature and potential mitigation through covering (pig slurry) or acidification (cattle slurry). *Journal of Environmental Quality* **45**: 1520-1530.

Moral R., Bustamante M.A., Chadwick D.R., Camp V., Misselbrook T.H. (2012) N and C transformations in stored cattle farmyard manure, including direct estimates of N 2 emission. *Resources, Conservation and Recycling* **63**: 35-42.

Nielsen D.A., Schramm A., Nielsen L.P., Revsbech N.P. (2013) Seasonal methane oxidation potential in manure crusts. *Applied and environmental microbiology* **79**: 407-410.

Pardo G., Moral R., Aguilera E., del Prado A. (2015) Gaseous emissions from management of solid waste: a systematic review. *Global change biology* **21**: 1313-1327.

Rufino M.C., Tittonell P., van Wijk M.T., Castellanos-Navarrete A., Delve R.J., de Ridder N., Giller K.E. (2007) Manure as a key resource within smallholder farming systems: Analysing farm-scale nutrient cycling efficiencies with the NUANCES framework. *Livestock Science* **112**: 273-287.

Uusi-Kämppä J. (2002) nitrogen and phosphorus losses from a feedlot for suckler cows. *Agricultural and Food Science in Finland* **11**: 355-369.

Vadas P.A., Powell J.M. (2013) Monitoring nutrient loss in runoff from dairy cattle lots. *Agriculture, Ecosystems and Environment* **181**: 127-133.

VanderZaag A.C., Gordon R.J., Glass V.M., Jamieson R.C. (2008) Floating covers to reduce gas emissions from liquid manure storages: a review. *Applied Engineering in Agriculture* **24**: 657.

VanderZaag A.C., Gordon R.J., Jamieson R.C., Burton D.L., Stratton G.W. (2009) Gas emissions from straw covered liquid dairy manure during summer storage and autumn agitation. *Transactions of the Asabe* **52**: 599.

Williams J.R., Harman W.L., Magre M., Kizil U., Lindley J.A., Padmanabhan G., Wang E. (2006) APEX feedlot water quality simulation. *Transactions of the Asabe* **49**: 61-73.

GREENHOUSE GAS PROTOCOL

FAQ

1. What are scope 3 emissions?

The GHG Protocol Corporate Standard classifies a company's GHG emissions into three 'scopes'. Scope 1 emissions are direct emissions from owned or controlled sources. Scope 2 emissions are indirect emissions from the generation of purchased energy. Scope 3 emissions are all indirect emissions (not included in scope 2) that occur in the value chain of the reporting company, including both upstream and downstream emissions.

2. What are product life cycle emissions?

Product life cycle emissions are all the emissions associated with the production and use of a specific product, from cradle to grave, including emissions from raw materials, manufacture, transport, storage, sale, use and disposal.

3. What is the main difference between the two standards?

The GHG Protocol Corporate Value Chain (Scope 3) Standard and GHG Protocol Product Standard both take a value chain or life cycle approach to GHG accounting. The Corporate Value Chain (Scope 3) Standard accounts for emissions at the corporate level, while the Product Standard accounts for emissions at the individual product level. The Corporate Value Chain (Scope 3) Standard helps companies identify GHG reduction opportunities, track performance, and engage suppliers at a corporate level, while the Product Standard helps a company meet the same objectives at a product level. Together with the GHG Protocol Corporate Standard, the three standards provide a comprehensive approach to value chain GHG measurement and management.

4. Why are value chain emissions important?

Most of the largest companies in the world now account and report on the emissions from their direct operations (scopes 1 and 2). The new standards close the GHG gap: businesses can now act on the full range of corporate value chain and product emissions as well.

Emissions along the value chain often represent a company's biggest greenhouse gas impacts, which means companies have been missing out on significant opportunities for improvement. For example, road tester Kraft Foods found that value chain emissions comprise more than 90 percent of the company's total emissions. Developing a full GHG emissions inventory – incorporating corporate-level scope 1, scope 2, and scope 3 emissions – enables companies to understand their full value chain emissions and to focus their efforts on the greatest GHG reduction opportunities.

5. Why should businesses care?

Businesses have found that developing corporate value chain (scope 3) and product GHG inventories delivers a positive return on investment. The new standards help companies to:

- Identify and understand risks and opportunities associated with value chain emissions;
- Identify GHG reduction opportunities, set reduction targets and track performance;
- Engage suppliers and other value chain partners in GHG management and sustainability;
- Enhance stakeholder information and corporate reputation through public reporting.

Through these activities, companies can reduce emissions and costs to meet strategic business objectives.

6. Why do the standards only account for GHG emissions and not other environmental impacts? Can the standards be used for other impacts (e.g. water)?

The GHG Protocol standards address GHG emissions. GHG emissions are a great starting point for businesses because of the data availability, their correlation with energy use, and often their correlation with other environmental impacts. The general accounting methodology of both standards can be adapted by businesses to account for other impacts.

7. Should the standards be used to compare products or companies?

In the future, industries will be able to build off the Product Standard to develop industry specific product rules to give them the ability to compare products. For now, the main benefits are to identify hot spots in a product life cycle and efficiently concentrate resources.

The Product Standard provides some guidance on how companies with a goal for comparison can use and/or develop product rules in conjunction with the standard. Product rules offer more specification for a given product category than the general standard can provide.

The Corporate Value Chain (Scope 3) Standard is designed to enable comparisons of a company's GHG emissions over time. It is not designed to support comparisons between companies based on their scope 3 emissions. Differences in reported emissions may be a result of differences in inventory methodology, company size or structure. Additional measures are necessary to enable valid comparisons across companies, such as consistency in methodology, consistency in data used to calculate the inventory, and reporting of intensity ratios or performance metrics. Additional consistency can be provided through GHG reporting programs or sector-specific guidance.

8. How will the standards help drive global emissions reductions?

Businesses can't manage what they can't measure. Because climate change is a complex and global problem, decisions about how to reduce emissions need to be based on facts rather than assumptions.

The new standards provide an essential foundation for strategic thinking about reducing emissions. They allow businesses to identify the biggest "hot spots" in their value chains – the activities that generate the most emissions. This insight allows businesses to focus on achieving the most meaningful reductions, not only from within their operations, but across global value chains. If the standards are successful, product and value chain GHG measurement will become standard business practice and companies all around the globe will have the information they need to effectively reduce emissions.

9. Are the new standards compulsary?

Use of the new standards is voluntary. In the future, governments and programs may decide to use the

standards or some version of the standards when creating mandatory programs or regulations.

10. Why is having one consistent global standard important?

Climate change is a global problem and businesses operate in a global environment. Value chains – and the risks and opportunities associated with GHG emissions – span national borders. Businesses operating in a global economy need a single, consistent, harmonized approach. Since the new standards take a value chain approach to emissions measurement and management that crosses national borders, the need for a global standard is even more important.

11. How were the standards developed?

The standards development process is a defining feature of the GHG Protocol. The GHG Protocol follows a broad and inclusive multi-stakeholder process to develop greenhouse gas accounting and reporting standards with participation from businesses, government agencies, NGOs, and academic institutions from around the world.

In 2008, WRI and WBCSD launched a three-year process to develop the new standards. A 25-member Steering Committee of experts provided strategic direction throughout the process. The first drafts of the standards were developed in 2009 by Technical Working Groups consisting of over 207 members (representing diverse industries, government agencies, academic institutions, and non-profit organizations worldwide). In 2010, 60 companies from a variety of industry sectors road-tested the standards and provided feedback on their practicality and usability. Members of a Stakeholder Advisory Group (consisting of more than 2,300 participants) provided feedback on each draft of the standards.

12. Which companies road-tested the standards?

The following companies road-tested one or both of the standards:

- 3M
- Abengoa
- Acer
- Airbus
- AkzoNobel
- Alcoa
- Amcor Ltd.
- Anvil Knitwear
- Autodesk, Inc.
- Baosteel Group Corporation
- BASF
- Belkin International, Inc.
- Bloomberg LP
- BT plc
- Coca-Cola Erfrischungsgetränke AG
- Danisco
- Deutsche Post DHL
- Deutsche Telekom AG
- Diversey
- DuPont
- Ecolab, Inc.
- Edelweiss
- Ford Motor Company
- GE Global Research
- GNP Company
- Herman Miller, Inc.
- IBM Corporation
- IKEA
- Italcementi Group
- Kraft Foods
- Kunshan Tai Ying Paint
- Lenovo
- Levi Strauss & Co.
- Mitsubishi Chemical Holdings Corporation
- National Grid
- New Belgium Brewing
- Ocean Spray Cranberries, Inc.
- PE INTERNATIONAL
- PepsiCo
- Pfizer Inc.
- Pinchin Environmental Ltd.
- PricewaterhouseCoopers Hong Kong
- Procter & Gamble
- Public Service Enterprise Group. Inc.
- Quanta Shanghai Manufacturing City, Tech-Front (Shanghai) Computer Co. Ltd.
- Rogers Communications
- RSA Insurance Group
- SAP
- S.C. Johnson & Son, Inc.
- Shanghai Zidan Food Packaging and Printing Co., Ltd.
- Shell

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- Siemens AG
- Suzano Pulp & Paper
- Swire Beverages (Coca-Cola Bottling Partner)
- TAL Apparel
- United States General Services Administration
- Veolia Water
- Verso Paper Corp.
- Webcor Builders
- WorldAutoSteel

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Scope 3 GHG Inventory Guidance

For U.S. Dairy Cooperatives and Processors



2024
December

BUILT ON GHG PROTOCOL

This U.S. dairy-specific guidance document has been reviewed by the GHG Protocol and is in conformance with the requirements set forth in the Corporate Value Chain (Scope 3) Accounting and Reporting Standard.

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NOTE: This document contains numerous hyperlinked tools and resources. It is, therefore, best viewed and used in PDF rather than print format.

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Scope 3 GHG Inventory Guidance

List of Terms

- **GHG** – *Greenhouse Gas; any gas that contributes to the greenhouse effect and climate change by absorbing infrared radiation. There are seven greenhouse gases accounted for by the GHG Protocol: carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), sulfur hexafluoride (SF_6), nitrogen trifluoride (NF_3), hydrofluorocarbons (HFCs), and perfluorocarbons (PFCs).*
- **SBT** – *Science Based Target; greenhouse gas reduction target adopted by companies to achieve the level of decarbonization necessary to keep global temperatures from rising above 2 degrees Celsius compared to preindustrial temperatures. In October 2019, the ambition requirements for SBTs increased to "well below 2 degrees."*
- **CDP** – *Formerly the Carbon Disclosure Project; a global platform that collects and publicly displays environmental performance data from companies, cities, states and regions to inform investor and shareholder decision-making.*
- **Reporting Processor** – *The dairy cooperative, manufacturing company, or processing company utilizing this guidance tool in preparation to publicly disclose its greenhouse gas emissions inventory.*
- **CNG** – *Compressed natural gas; methane stored at high pressure.*
- **LNG** – *Liquefied natural gas; a cooled mixture of methane and ethane.*
- **LPG** – *Liquefied petroleum gas; flammable hydrocarbon gases including propane and butane.*
- **CO_2e** – *Carbon dioxide equivalent; a standardized unit used to normalize and report emissions of greenhouse gases.*
- **GWP** – *Global Warming Potential; a relative measure of the potential of a specific GHG to absorb infrared radiation and influence climate change. GWP values are used to calculate the carbon dioxide equivalent of a GHG, with CO_2 being the benchmark (GWP = 1) and other GHGs having values many times greater than CO_2 (e.g., GWP of methane = 28).*
- **Emission Factor** – *The emission rate of a greenhouse gas for a given source.*
- **Activity Data** – *Data related to the magnitude of emissions from various anthropogenic activities.*
- **Scope 1 Emissions** – *Direct emissions from owned or controlled sources.*
- **Scope 2 Emissions** – *Indirect emissions from the generation of purchased energy.*
- **Scope 3 Emissions** – *All indirect emissions (not included in Scope 2) that occur in the value chain of the reporting company, including both upstream and downstream emissions.*
- **GHG Protocol** – *A standards organization developed by the World Resources Institute (WRI) that establishes comprehensive global standardized frameworks to measure and manage greenhouse gas (GHG) emissions from private and public sector operations, value chains and mitigation actions.*
- **Environmentally Extended Input-Output Databases** – *Based on national economic and environmental statistics. These databases have advantages over process databases in that they cover the complete economy, eliminating the need for cut-offs in life cycle assessment.*

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Scope 3 GHG Inventory Guidance

Introduction to this Tool

Within the last few years, global realization of the necessity to implement climate change mitigation strategies has become paramount. As a result, organizations such as the Science Based Targets Initiative have mobilized in an effort to engage companies to set climate goals on par with those of the 2015 Paris Climate Agreement—keeping global temperatures from rising more than two degrees Celsius. Furthermore, the Science Based Targets Initiative introduced more ambitious climate targets in October 2019, targeting global temperature stabilization to 1.5 degrees.

Many large dairy purchasing companies have already set or have pledged to set a Science Based Target (hereafter "SBT"). For these companies to meet their SBTs, they require a comprehensive account of their supply chain GHG emissions each year to track progress over time. Therefore, large consumer-facing companies such as these increasingly expect their suppliers to collect and externally disclose their GHG emissions data.

Scope 3 Emissions in U.S. Dairy

Similar to many other industries, the majority of GHG emissions in U.S. dairy arise from supply chain activities upstream of the dairy processors or cooperatives. More specifically, over half of the industry's GHG emissions are generated on the dairy farm as a result of feed production, manure management, and enteric processes. From both dairy retailers' and processors' perspectives, upstream on-farm emissions, along with other processes such as transportation, are considered Scope 3 indirect emissions. As a result, this guidance places particular importance on upstream Scope 3 GHG accounting, although guidance on both upstream and downstream Scope 3 GHG emissions is included to be as comprehensive as possible and account for all 15 Scope 3 GHG categories identified by the GHG Protocol. (Figure 1.0 below)

Although guidance on all 15 Scope 3 categories is included in this resource, the categories determined to emit the most GHGs in the U.S. dairy supply chain comprise the main component of this document. The categories that are considered insignificant and/or non-integral to composing a dairy processors Scope 3 GHG inventory are appended at the end of the document. These categories are deemed insignificant because the basis for determining their associated emissions is not significant in the U.S. dairy value chain. For the purposes of this guidance, insignificant Scope 3 categories in U.S. dairy either do not contain a large quantity of emissions and/or are not feasible to account for due to lack of relevant data, resources and/or time.

However, a caveat to this rule is that the relative importance of individual Scope 3 categories may vary depending on the composition of the reporting processor's supply chain. If possible, reporting processors should attempt to account for emissions from all Scope 3 categories. Furthermore, the reporting processor should not exclude any Scope 3 category that is expected to contribute significantly to their total Scope 3 emissions. However, if resources and time are limited, this guidance recommends taking inventory of emissions from the Scope 3 categories in the main component of this document first, followed by emissions from the categories in the Appendix section. Table 1.0, page 3, differentiates between significant and insignificant Scope 3 categories in the U.S. dairy value chain.



(Figure 1.0) Differentiating between upstream and downstream in the U.S. dairy value chain from dairy processing perspective

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In addition, reporting processors may refer to the "Setting the Scope 3 Boundary" section of this guidance, located on page 7.

Defining Scope 3 Indirect Emissions

The Greenhouse Gas Protocol defines Scope 3 emissions as "all indirect emissions (not included in Scope 2) that occur in the value chain of the reporting company, including both upstream and downstream emissions."[1] Since on-farm emissions are both dairy buyers' and dairy processors' Scope 3 emissions and they comprise such a large proportion of U.S. dairy's total GHG inventory, and it is imperative that said emissions are accurately accounted for and quantified.

Additionally, the GHG Protocol is launching the Land Sector and Removals Guidance to explain how companies should account for and report emissions and removals from land management and land use change, building on the Scope 3 Standard. The Innovation Center plans to release dairy-specific guidance based on the Land Sector and Removals Guidance as an addendum to this document in 2025.

Purpose

This guidance document is intended to assist U.S. dairy cooperatives and processing companies to accurately account for and calculate their Scope 3 GHG emissions. It is intended to coincide with the Innovation Center for U.S. Dairy's Scope 1 & 2 GHG Inventory Guidance. Therefore, cooperatives and

Differentiating Between Significant/Feasible and Insignificant/Unfeasible Scope 3 Categories in U.S. Dairy	
Significant Scope 3 Categories	Insignificant Scope 3 Categories
Purchased Goods and Services	Business Travel
Capital Goods (unless processor does not purchase operational equipment in reporting year)	Employee Commuting
Fuel and Energy Related Activities	Processing of Sold Products
Upstream Transportation and Distribution	Use of Sold Products
Waste Generated in Operations	End of Life Treatment of Sold Products
Upstream Leased Assets (unless processor does not have large portfolio of leased assets as a lessee)	Investments
Downstream Transportation and Distribution	Franchises
Downstream Leased Assets (unless processor does not have large portfolio of leased assets as a lessor)	

(Table 1.0) Differentiating between significant and insignificant Scope 3 categories in U.S. dairy based on emissions quantities and feasibility of accounting

U.S. Dairy Industry Supply Chain GHG Emissions Categorization – Processing Point of View	
Supply Chain Stage	GHG Emissions Scope
Feed Production	Scope 3 (Possible Scopes 1, 2 for cooperatives)
Milk Production	Scope 3 (Possible Scopes 1, 2 for cooperatives)
Milk Transport	Scope 3 (Scopes 1, 2 if processor or cooperative owns/controls fleet)
Processing	Scopes 1, 2
Packaging	Scopes 1, 2
Distribution	Scope 3 (Scopes 1, 2 if processor or cooperative owns/controls fleet)
Retail	Scope 3
Consumer	Scope 3

(Table 1.1) Differentiating between Scope 1, 2 and 3 emissions from U.S. dairy cooperatives and processors' perspectives

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processors that utilize this guidance document should ensure they implement the same organizational boundary for Scope 1, 2 and 3. The Greenhouse Gas Protocol does not permit reporting companies to vary their organizational boundary for each Scope. For more guidance on setting organizational boundaries, refer to the Inventory Management Plan chapter of The Innovation Center's Scope 1 & 2 GHG Inventory Guidance.

For the purposes of credibility and consistency, this document is primarily based on the Greenhouse Gas Protocol's Corporate Value Chain (Scope 3) Accounting and Reporting Standard, as well as the Greenhouse Gas Protocol's Technical Guidance for Calculating Scope 3 Emissions.

This guidance document coincides with the FARM (Farmers Ensuring Responsible Management) Environmental Stewardship program (below). Managed by the National Milk Producers Federation, FARM obtains relevant on-farm data to quantify Scope 3 GHG emissions from Purchased Goods and Services, U.S. dairy's largest Scope 3 emissions category.

FARM Environmental Stewardship (FARM ES) is a farm-level environmental assessment and customer assurance program that provides a comprehensive estimate of GHG emissions on dairy farms. Powered by the Ruminant Farm Systems (RuFaS) model, the program provides tools and resources for farmers to measure and improve their footprint, and data can be aggregated by dairy cooperatives and processors for reporting emissions to dairy buyers.

Additional resources are referenced throughout the document that provide useful information and data relevant to certain necessary calculations.

Although this guidance document is designed to equip reporting processors with the tools and resources necessary to compose their own Scope 3 inventory, Scope 3 GHG accounting is an onerous task. If the reporting entity has sufficient financial resources, it is recommended that a consultant be hired for the first year of conducting a Scope 3 inventory. This ensures professional and expert GHG accounting and sets a baseline standard for the company to model going forward.

If possible, the consultant should compose a consolidated list of resources used in the Scope 3 accounting exercise, so that the reporting processor may utilize them in future reporting years. The consultant's expertise, in combination with this accounting guidance resource, should combine to serve reporting processors with a strong foundation of Scope 3 GHG support.

The FARM (Farmers Assuring Responsible Management) Environmental Stewardship Program

Farmers are the original environmental stewards. The Farmers Assuring Responsible Management (FARM) Environmental Stewardship (ES) program helps tell that story for dairy farmers.

Launched in 2017, FARM ES is a farm-level environmental assessment and customer assurance program. The core FARM ES evaluation provides a comprehensive estimate of greenhouse gas emissions on dairy farms powered by the Ruminant Farm Systems (RuFaS) model. The program provides tools and resources for farmers to measure and improve their footprint. Data can be aggregated by dairy cooperatives and processors for reporting emissions to dairy buyers.

The Conservation Practice Questionnaire (CPQ) is an optional add-on to the FARM Environmental Stewardship evaluation that addresses field and dairy-level conservation activities to capture a more holistic sustainability story.

The program website offers a variety of tools and resources that explain the program, support continuous improvement efforts and give information on the model methodology.

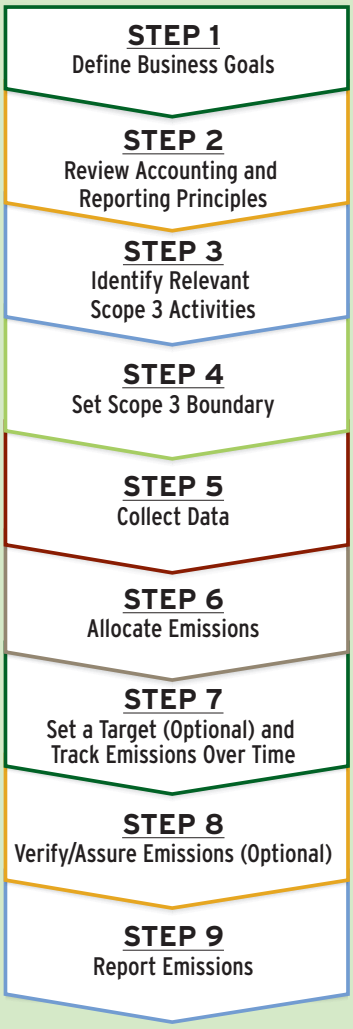
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Steps to Create a Scope 3 Inventory

This section provides background information on the overall process of developing a Scope 3 GHG inventory. It includes the chronological steps processors should use to sufficiently account for their Scope 3 emissions.

Developing an accurate and representative Scope 3 inventory can be an arduous task. It contains significantly more categories than Scopes 1 and 2; therefore, it is recommended that the reporting dairy processor or cooperative thoroughly reviews and understands the steps involved in accounting and reporting a Scope 3 inventory.

A chronological list of the steps involved in creating a sufficient Scope 3 inventory is presented in Figure 2.0. More detailed descriptions of what each step entails are included below. Several of the steps have specific requirements that must be met according to the GHG Protocol Corporate Value Chain (Scope 3) Standard.



(Figure 2.0) A chronological roadmap of the steps reporting processors should take when conducting a Scope 3 GHG inventory

Defining Business Goals

Before reporting processors begin measuring their Scope 3 emissions, it is important to identify which business goal(s) to pursue by taking an inventory. By clearly understanding and defining business goals at the start of the Scope 3 accounting and reporting process, reporting processors can better allocate limited resources for developing the most effective operational boundary possible. This saves time and money. For more information on operational boundaries, consult the Inventory Management Plan chapter of the Scope 1 and 2 GHG Inventory Guidance.

Furthermore, identifying which business goals to achieve can potentially offer economic incentives for dairy stakeholders throughout the supply chain. Not only is measuring and managing GHG emissions the right thing to do, it often makes financial sense.

A more detailed breakdown of common business goals (from the GHG Protocol Corporate Value Chain Accounting and Reporting Standard) that reporting companies identify and pursue by taking a Scope 3 GHG inventory is depicted in Table 2.0 on page 6.

All of these business goals outlined by the GHG Protocol are germane to reporting processors in U.S. dairy. However, it is up to the reporting processor to identify which business goals it intends to pursue. Often, large dairy purchasing companies may expect reporting processors to collect and disclose their GHG inventories, which is categorized under the "Enhance stakeholder information and corporate reputation through public reporting" goal (page 6, Table 2.0). While this should be a priority, reporting processors can incentivize Scope 3 GHG accounting and measurement by pursuing business goals that may help identify cost-saving opportunities or operational hotspots for GHG emissions.

This guidance therefore recommends that reporting processors pursue business goals that accommodate customer requests and goals that are mutually beneficial. All four goals listed (page 6) are relevant to U.S. dairy. Marketplace expectations, however, should be prioritized in scenarios where reporting processors lack adequate time or dedicated resources to developing a Scope 3 inventory.

Reviewing Accounting and Reporting Principles

Much like the GHG Protocol Corporate Standard, on which the Scope 1 & 2 GHG Inventory Guidance is based, the GHG Protocol Corporate Value Chain Accounting and Reporting Standard requires that reporting processors' Scope 3 inventories "represent a faithful, true, and fair account" of their emissions.[2] Reporting processors should ensure that they abide by all five principles outlined below: (page 6, Table 2.1)

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GHG Protocol Corporate Value Chain Business Goal Table	
Business Goal	Details
Identify and understand risks and opportunities associated with value chain emissions	• Identify GHG-related risks in the value chain • Identify new market opportunities • Inform investment and procurement decisions
Identify GHG reduction opportunities, set reduction targets, and track performance	• Identify GHG "hot spots" and prioritize reduction efforts across the value chain • Set Scope 3 GHG reduction targets • Quantify and report GHG performance over time
Engage value chain partners in GHG management	• Partner with suppliers, customers, and other companies in the value chain to achieve GHG reductions • Expand GHG accountability, transparency, and management in the supply chain • Enable greater transparency on companies' efforts to engage suppliers • Reduce energy use, costs, and risks in the supply chain and avoid future costs related to energy and emissions • Reduce costs through improved supply chain efficiency and reduction of material, resource and energy use
Enhance stakeholder information and corporate reputation through public reporting	• Improve corporate reputation and accountability through public disclosure • Meet needs of stakeholders (e.g., investors, customers, civil society, governments), enhance stakeholder reputation, and improve stakeholder relationships through public disclosure of GHG emissions, progress toward GHG targets, and demonstration of environmental stewardship • Participate in government- and NGO-led GHG reporting and management programs to disclose GHG-related information

(Table 2.0) Common business goals identified & pursued by reporting companies when conducting a Scope 3 inventory

GHG Inventory Accounting and Reporting Principles	
Principle	Description
Relevance	GHG inventory reflects company's GHG emissions, and allows external and internal entities to use data for making decisions
Completeness	All GHG emissions sources within the inventory boundary are accounted for and reported; if exclusions are made, a detailed disclosure is included in their place
Consistency	Methodologies are the same across different scopes and categories of emissions to ensure robust performance tracking over time
Transparency	All assumptions and references to associated calculation methodologies/data sources are clearly and openly disclosed
Accuracy	Ensure GHG calculations are correct and reduce uncertainty as much as possible*

(Table 2.1) Accounting and reporting principles that reporting processors should abide by when composing a comprehensive GHG inventory

NOTE: * More information on accounting for uncertainty in Scope 3 quantification can be found in Appendix B of the GHG Protocol Corporate Value Chain Accounting and Reporting Standard. In addition, the World Resources Institute provides an Uncertainty Calculation Excel Tool with an accompanying Uncertainty Guidance Document.

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Scope 3 GHG Inventory Guidance

Identifying Relevant Scope 3 Activities

Given the limited resources that most organizations have to manage their Scope 3 GHG emissions, it is imperative that the relevancy of sources be determined. Identification of the relevant Scope 3 categories is a critical step that can be dependent on several factors including:

- The size of the Scope 3 category (its contribution to the reporting processor's total GHG emissions)
- The importance of the Scope 3 category to key stakeholder groups (is the information being requested)
- The ability of the reporting processor to reduce the Scope 3 emissions from certain categories

Depending on the reporting processor's consolidation approach, certain categories of Scope 3 emissions may be accounted for in its Scope 1 and/or 2 inventories. Furthermore, the reporting processor may voluntarily exclude certain Scope 3 categories from its inventory so long as a justified and transparent explanation is included in its place.

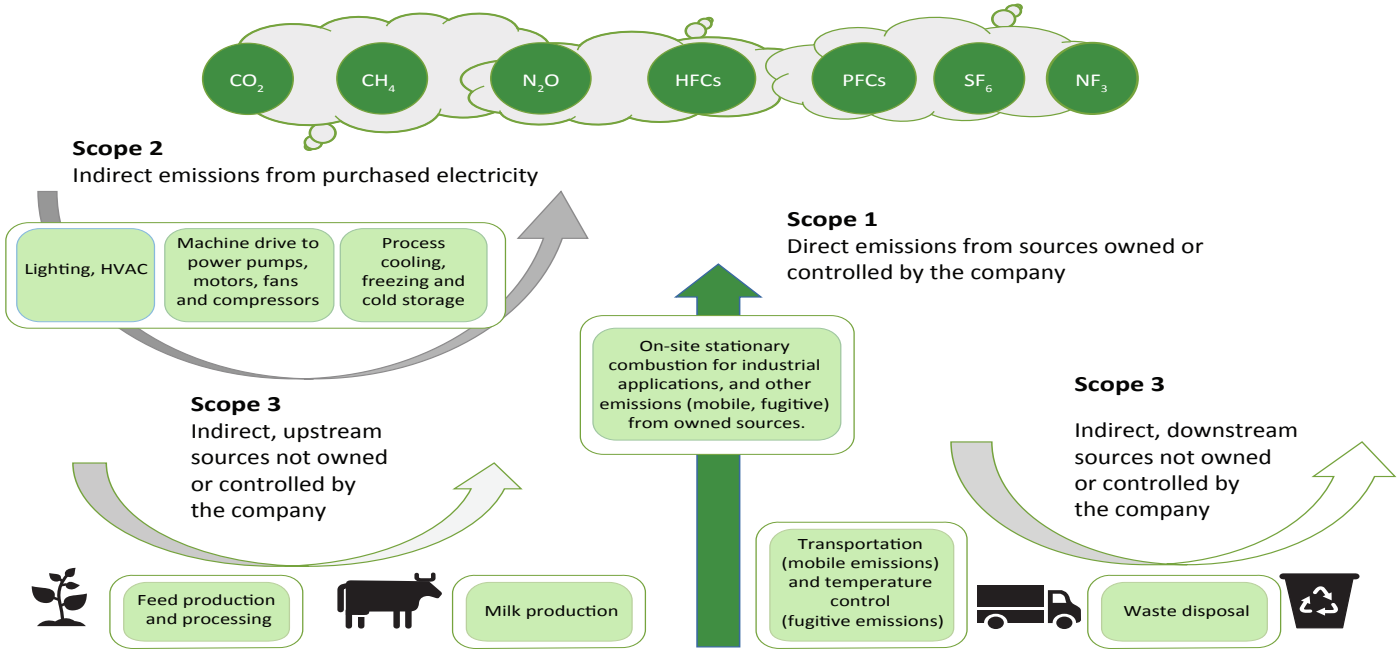
Each Scope 3 category has a minimum required boundary that all reporting processors must adhere to. These minimum boundaries are available in chapter five of the Corporate Value Chain Accounting and Reporting Standard.

Setting the Scope 3 Boundary

Reporting processors should include all Scope 3 GHG emissions from each category to the extent feasible. Oftentimes, reporting processors may not be able to procure necessary data from various emission sources in their supply chain. As stated, reporting processors may include a transparent and justified explanation as a substitute. However, if certain Scope 3 categories in the dairy supply chain are significant sources of emissions, such as Purchased Goods and Services, reporting processors should report emissions data in this category. The GHG Protocol Corporate Value Chain Accounting and Reporting Standard Table 6.1 outlines the criteria that reporting entities should use to determine if each Scope 3 category is significant.

Several Scope 3 categories may not apply to the reporting processor. For example, smaller processors may not own franchises or have investments. In this case, it is permissible to either report zero emissions for these categories or simply state that the category is not applicable.

To ensure reporting processors account for all GHG emission sources, they should map their value chain in order to identify all relevant categories of their Scope 3 inventory. The map should include a list of dairy farmers and the milk volumes purchased from each farm.



(Figure 2.1) Common Scope 1, 2 and 3 emission sources in the dairy processing industry

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This value chain map can be achieved by contacting suppliers and obtaining relevant on-farm data relative to GHG emissions categories. The FARM Environmental Stewardship Program (discussed in more detail in Scope 3: Purchased Goods and Services, (page 11) is particularly useful for obtaining this data. In addition, the reporting processor should procure a list of the types and quantities of the different dairy products it sells.

For the Scope 3 categories that do apply to reporting processors, abiding by this guidance will ensure that the minimum boundary of GHG emissions are accounted for. However, reporting processors may consult Table 5.4 of the GHG Protocol Corporate Value Chain Accounting and Reporting Standard for more details.

To account for changing supply chain partners over time, reporting processors should select a fixed starting date to encompass all Scope 3 emissions over the reporting year. For example, one option is to sync the reporting of Scope 3 accounting at the start of the processor's fiscal year. This is a processor decision. Regardless of the fixed starting date, the Scope 3 boundary should account for the company's emissions over one full year (i.e., January 1 through December 31).

When utilizing this guidance resource, reporting processors should select their start date and account for emissions from that date until the same date the following year. Reporting processors may find it easiest to set their fixed starting date for the reporting year at the outset of the accounting exercise.

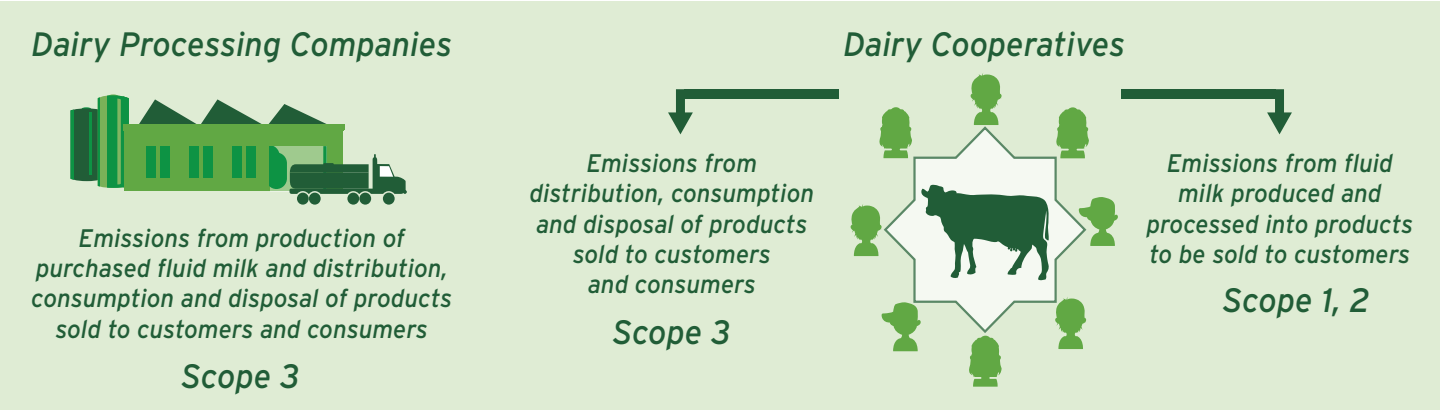
Collecting Data

Scope 1 and Scope 2 data are often much easier to collect as opposed to Scope 3. This is due to the greater amount of external engagement reporting processors must do in order to procure the information necessary to complete a Scope 3 inventory. As a result, the GHG Protocol Corporate Value Chain Standard recommends prioritizing data collection efforts that are likely to contribute most significantly to the reporting processor's Scope 3 GHG emissions.

In the dairy industry, the largest proportion of GHG emissions arise from on-farm activities such as enteric emissions, feed production and manure management. From the reporting processor's perspective, these emissions would be categorized in the Scope 3: Purchased Goods and Services section since these on-farm practices are directly related to producing raw milk that ultimately ends up at processing plants. Many dairy cooperatives process significant portions of the fluid milk they produce; therefore, this is a crucial differentiation to note when composing a Scope 3 inventory. Figure 2.2 clearly depicts which scopes of GHG emissions apply to different dairy processing business scenarios.

As for the other categories, relative proportions of Scope 3 GHG emissions are subjective to each individual reporting processor. For example, some reporting processors, which manufacture a wide variety of dairy products, have more processing facilities than others and, as a result, have a larger quantity of capital goods, waste, and/or distribution networks. To determine their Scope 3 priorities, they may conduct a Scope 3 screening to estimate which categories contribute most significantly to their overall inventory.

The GHG Protocol outlines other methods of prioritizing data collection. This guidance, however, strongly recommends conducting a Scope 3 screening and prioritization based on the magnitude of requests from larger consumer-facing companies seeking granular data from processors' activities.



(Figure 2.2) Differentiating GHG emissions between dairy processing companies and dairy cooperatives

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In its calculations, Scope 3 uses the same emission factor approach as Scopes 1 and 2. The emission factors, however, are different and could come from an Environmentally-Extended Input Output (EEIO) life cycle database to account for all phases of the emissions' lifetime. (See page 1, List of Terms)

When possible, reporting processors should collect primary data, which is sourced from specific activities throughout their own value chain. However, this may not be possible as certain companies upstream and/or downstream in the value chain may not be able to supply the reporting processor with primary data. In this case, reporting processors may use secondary data, which is less specific, but gives an industry-average estimation of the GHG emissions from specific activities based on magnitude. Refer to the GHG Protocol Corporate Value Chain Accounting and Reporting Standard (Table 7.3) for additional guidance and explanation on primary and secondary data.

Allocating Emissions

In many instances, reporting processors may receive a certain proportion of suppliers' fluid milk, as farms may sell their milk to numerous customers. Additionally, reporting processors often distribute their dairy products to different customers and retailers.

This dynamic receiving and distributing setup in the dairy processing industry makes allocation necessary. Allocation is the process of partitioning the emissions from various categories based on the quantity or amount of goods or products purchased/sold. According to the GHG Protocol Corporate Value Chain Standard, there are two scenarios where allocation is necessary. (See Table 2.2)

The GHG Protocol strongly urges reporting entities to avoid allocation whenever possible. This is because allocating emissions adds uncertainty to calculations. Allocation is avoided by collecting granular data. The best approaches to collect granular data are:

- Obtain GHG data from value chain companies on dairy products purchased or sold specifically
- Sub-meter energy use and other activity data where possible
- Use engineering models to estimate emissions from each produced dairy product

For reporting processors that must allocate emissions for certain Scope 3 categories, additional guidance and examples are provided in Chapter 8 of the Corporate Value Chain Accounting and Reporting Standard. Specifically, reporting processors may find Table 8.2 particularly useful to determine if allocation is necessary, as this graphic depicts examples of the data necessary. (Table 8.2 shows examples of data need and the allocation method to use.)

Setting a Target and Tracking Emissions Over Time

Reporting processors may choose to set a Scope 3 reduction target and track emissions reductions over time. In the U.S. dairy industry, large consumer-facing dairy purchasing companies, most likely, will be interested in setting targets and tracking emissions over time. This is due to the fact that these companies are larger than the majority of dairy processing companies and therefore, have a much larger Scope 3 GHG footprint. Also, while the majority of dairy processing companies are privately owned, many dairy buyers are publicly traded and face increased shareholder requirements for public, non-financial disclosure of topics such as GHG emissions.

Allocation Scenarios in Dairy Processing

Allocation Scenario	Example
One facility/activity/vehicle/production line/business unit produces multiple outputs	The same dairy processing plant produces milk and cheese
Emissions are only quantified for an entire facility/activity/vehicle/production line/business unit, rather than fractionally	A dairy customer only purchases yogurt from a processing company that manufactures milk, cheese, yogurt and whey OR A processor purchases only a subset of a given supplier's milk

(Table 2.2) Common allocation scenarios and examples in U.S. dairy

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As mentioned in the introduction, the primary purpose of this guidance is to assist dairy processors in accurately measuring their Scope 3 GHG emissions to accommodate the needs and requests of larger dairy purchasers. The Science Based Targets Initiative (SBTi) requires companies to set Scope 3 targets whenever Scope 3 emissions represent greater than 40 percent of total emissions (Scope 1 + Scope 2 + Scope 3 emissions combined). Additionally, SBTi requires businesses with SBTs in land-intensive sectors, such as dairy, to set forest, land and agriculture (FLAG) targets — a near-term and long-term target related to land-based emissions reductions and removals. Large dairy customers, such as supermarkets, are increasingly requesting suppliers to set SBTs as part of the customers' own SBT commitments. Therefore, reporting processors may consult Chapter 9 of the Corporate Value Chain Accounting and Reporting Standard for information regarding GHG reduction target setting and tracking over time.

Verifying/Assuring Emissions

Similar to setting targets and tracking progress, assurance is optional in the Scope 3 inventory process as well. However, when feasible, reporting processors should attempt to verify their Scope 3 inventory. Doing this will increase both the processing company's and other stakeholders confidence that the Scope 3 inventory abides by the GHG Protocol reporting principles of completeness, accuracy, consistency, transparency and relevance.

The two most common forms of assurance are first-party assurance and third-party assurance. First-party assurance involves people from within the reporting processing company who were not directly a part of measuring and quantifying the Scope 3 inventory. Third-party assurance involves people from an external organization who were not a part of composing the Scope 3 inventory, nor who are affiliated with the reporting entity.

If the reporting processor decides to conduct an assurance process of its Scope 3 inventory, this guidance recommends utilizing a third-party verifier. This ensures more independence from the reporting company, mitigating any bias or conflict of interest that may arise from a first-party audit. Chapter 10 of the GHG Protocol Corporate Value Chain Accounting and Reporting Standard contains guidance on how to properly conduct the assurance process.

Reporting Emissions

This guidance strongly recommends that reporting processors publicly disclose their comprehensive GHG inventory through the CDP (formerly Carbon Disclosure Project) Climate Change Questionnaire.

The CDP is a globally-recognized nonprofit organization that collects and externally displays environmental performance data from companies, cities, states and regions so that investors and purchasers may make informed decisions and identify sustainability strategies. The CDP has three questionnaires — Forestry, Water and Climate Change — that various reporting organizations may utilize to disclose their environmental metrics. The Climate Change Questionnaire collects information related to GHG emissions specifically and represents a credible and renowned platform by which dairy processors may effectively report their Scope 1, 2 and 3 GHG inventory.

The Climate Change Questionnaire includes an array of both qualitative and quantitative questions. The quantitative questions request GHG metrics that are specific to the reporting entity. Many of the qualitative questions, however, request information that pertains to the U.S. dairy industry as a whole. As a result, reporting processors may consult the CDP Climate Change Questionnaire Response Guidance to guide their CDP Climate Change responses and/or to familiarize themselves with the types of responses that are sufficiently detailed for the CDP questionnaire.

As for the quantitative CDP Climate Change questions, the GHG inventory information collected and calculated in the U.S. dairy processing Scope 1, 2 and 3 accounting and reporting guidance literature is sufficient. This guidance literature abides by the GHG Protocol Corporate Standard and/or Corporate Value Chain Standard, identified by the CDP as a robust and acceptable protocol by which to account for and calculate GHG emissions.

Chapter 11 of the GHG Protocol Corporate Value Chain Accounting and Reporting Standard includes more detailed information on the required and optional GHG information a reporting processor must and may include in its GHG inventory disclosure.

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Scope 3: Purchased Goods and Services

Chapter at a Glance

- Defining Purchased Goods and Services
- Identifying Sources
- Collecting Activity Data
- Data Collection Guidance

This section provides guidance on how to identify and account for Scope 3 indirect GHG emissions from dairy processors' purchased goods and services upstream in the value chain.

1

Defining Purchased Goods and Services: The Purchased Goods and Services Scope 3 category captures "cradle-to-gate" GHG emissions from all products purchased by the reporting processor in the reporting year. In other words, any and all GHG emissions created from producing products and/or services up to when they leave the farm are accounted for under the Purchased Goods and Services category. This excludes any emissions from sources owned or controlled by the processor (for example farm operations owned by the cooperative organization).[2] Therefore, Scope 3: Purchased Goods and Services captures the GHG emissions associated with the on-farm production of raw milk that the reporting processor purchases (a purchased good). GHG emissions from the Purchased Goods and Services category account for roughly three quarters of the industry's total emissions; therefore, accurate and detailed accounting and reporting procedures for this category are paramount.

Dairy processors may also purchase an array of other goods and/or services necessary to further process fluid milk into products like cheese and yogurt. Although it is beyond the scope of this guidance document, the Scope 3 GHG emissions from Purchased Goods and Services for products other than fluid milk also must be calculated in order to produce a complete summary of GHG emissions from this category.

2

Identifying Sources: Raw milk generally comprises the largest portion of goods purchased from dairy suppliers, and the on-farm processes necessary to produce raw milk are the largest contributor of dairy supply chain GHG emissions. A more detailed breakdown of the dairy production processes and the main GHG emissions associated with each process are included below:

GHG Emissions Associated with On-Farm Milk Production Processes

Process	GHG Emissions Generated
Nitrogen fertilizer production	CO_2
Manure and chemical crop fertilizer application	N_2O
Manure/urine deposition on pasture crops	N_2O
Energy consumption in field operations, drying and processing of feed crops and fodder	CO_2
Crop processing into by-products and concentrates	CO_2
Feed transport from production site to feeding site	CO_2
Enteric fermentation from ruminant cows	CH_4
Direct and indirect emissions from manure storage	CH_4 and N_2O

(Table 3.0) Processes involved in producing raw milk upstream from the processing phase of the dairy value chain and their associated GHG emissions

continued on next page

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Scope 3: Purchased Goods and Services

2

As mentioned above, the U.S. dairy industry's largest source of GHG emissions comes from the farm. More specifically, a comprehensive life cycle assessment for fluid milk[7] conducted by the Innovation Center for U.S. Dairy found that GHG emissions in the U.S. dairy industry are divided into proportions identified in Table 3.1.

U.S. Dairy Industry Fluid Milk GHG Emissions Allocation	
Fluid Milk Production Process	Approximate GHG Emissions
Enteric Emissions	26%
Manure Management	25%
Feed Production	20%
Refrigeration and Packaging	9%
Distribution, Retail and Consumer	20%

(Table 3.1) Approximate source allocation of U.S. dairy GHG emissions according to comprehensive fluid milk LCA

Enteric emissions, manure management and feed production alone comprise over 70 percent of the entire industry's GHG emissions. From a reporting processor's perspective, these areas are considered Scope 3: Purchased Goods and Services. Accurately accounting for and quantifying emissions from this category is an extremely important component of a reporting processor's Scope 3 inventory. An updated U.S. dairy cradle-to-processing gate life cycle assessment (202 baseline) is currently being conducted, and updated GHG emissions allocations will be published in 2025.

NOTE: GHG emissions from conversion of land for crop growing (land use change) should also be reported. However, these emissions should be reported in a special "Biogenic Carbon" category that is not included in Scope 1, 2, or 3, but rather as a separate category (see GHG Protocol's Land Sector and Removals Guidance).

3

Collecting Activity Data: In order to account for and quantify Scope 3: Purchased Goods and Services, this guidance recommends using the Supplier-Specific method, which entails collecting farm level data from each milk supplier. This method is designed to collect more granular data from value chain emissions because it captures specific information associated with each purchased good or service.

4

Data Collection Guidance: This guidance recommends utilizing the FARM Environmental Stewardship program, managed by the National Milk Producers Federation. This on-farm evaluation collects data on milk production, herd size, energy, crop and feed production and manure management through a limited set of questions. The tool allows dairy cooperatives and processors to obtain accurate and specific data necessary to generate a scientifically robust estimate of Scope 3 GHG emissions from the production of raw milk, while reducing the burden on farmers. Collecting and then aggregating accurate farm-level data associated with all of the processes involved in producing raw milk will reflect a comprehensive Scope 3: Purchased Goods and Services inventory associated with dairy processors' purchased raw milk.

If the reporting cooperative or processor is a large company that sources from many different farms, the FARM Environmental Stewardship module has a sampling protocol that is based on the "stratified random sampling" concept. It takes a number of factors into account to generate an on-farm GHG footprint that is applicable and representative of the entire reporting processor's supplier footprint. This eliminates the need for larger reporting processors to obtain supplier-specific data from all of its farms, which may pose a significant logistical and financial burden.

NOTE: Data collection guidance for Purchased Goods and Services is based on the FARM Environmental Stewardship module. FARM ES calculations are based on a whole-farm model that simulates dairy farm production and environmental impact. For details on the model's methodologies and scope, visit the FARM website.

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Scope 3: Capital Goods

Chapter at a Glance

- Defining Capital Goods
- Identifying Sources
- Collecting Activity Data
- Data Collection Guidance
- Calculation Approach

This section provides guidance on how to account for and calculate Scope 3 indirect GHG emissions from the production of capital goods procured by the reporting processor in the reporting time frame.

1

Defining Capital Goods: The Greenhouse Gas Protocol defines capital goods as "final products that have an extended life and are used by the company to manufacture a product, provide a service, or sell, store, and deliver merchandise."[1] This category captures emissions associated with the production and manufacturing of capital goods used in the reporting processor's direct operations. The only Scope 3: Capital Goods emissions that need be accounted for are from newly purchased and/or acquired capital goods in the reporting year. Capital goods previously owned before the reporting year should not be included in this section.

2

Identifying Sources: Common capital goods that dairy processors use to produce retail-ready milk and other dairy products are listed below. The arrow represents the chronology associated with dairy processing from raw milk receiving through producing retail-ready milk.

Common Capital Goods in U.S. Dairy Processing	
Processing Stage	Capital Good
Raw Milk Inflow	Holding Tanks
	Filters
	Separators
	Standardizers
Pasteurization	Boilers
	Combustion Turbines
	Process Heaters
	Cooling Equipment
Homogenization	Homogenizers
Finishing and Packaging	Automated Fillers
	Cold Storage Tanks
	Forklifts and Other Off-Road Equipment
Other	Air Conditioning Equipment

Chronological Process

(Table 4.0) Common capital goods in U.S. dairy processing to be accounted for in Scope 3: Capital Goods

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Scope 3: Capital Goods

3

Collecting Activity Data: Dairy processing is rather infrastructure-heavy throughout the processing phase, demanding an array of machines and equipment to transform the raw milk brought in from the farm into consumer-ready products. Therefore, emissions from capital goods may be a significant source of Scope 3 emissions in the value chain. In order to collect robust product-level data on each capital good, the GHG Protocol recommends using the Supplier-Specific method. However, it may be often difficult for reporting processors to consult each and every capital good supplier for GHG inventory data specific to each piece of equipment. Therefore, this guidance recommends using the Hybrid method, which is a balance between acquiring capital good supplier-specific activity data when available and using industry average data to fill in gaps. For each capital good, the reporting processor should try to obtain as much of the following information as possible:

Supplier-Specific Methodology for Capital Goods Activity Data	
Capital Good Supplier Activity Data Category	Activity Data to Collect
Fuel and Electricity Information	Capital good suppliers allocated Scope 1 and 2 data (see Chapter 8 of the GHG Protocol Scope 3 Standard and the Innovation Center's Scope 1 and 2 GHG Inventory Guidance for additional guidance)
Raw Material Information	Mass/volume of material inputs, mass/volume of fuel inputs, distance from origin of raw material inputs to capital good manufacturer
Waste Information	Capital good suppliers waste output quantities in capital good manufacturing

(Table 4.1) Activity data to be collected on capital goods using the Supplier-Specific method. This methodology should be used first to obtain all relevant information available from the reporting processor's capital goods suppliers. Then, secondary data may be used to fill in remaining gaps.

4

Data Collection Guidance: Similar to Scope 3: Purchased Goods and Services, reporting processors may consult several internal resources as a means of procuring primary activity data from their capital goods suppliers. These resources include:

- Internal data systems
- Publicly available GHG reports detailing emissions from sourcing and manufacturing capital goods
- User manuals

Capital goods, which may not have readily available supplier-specific data, may have to use secondary emission factors to fill the gaps where primary activity data is not included. It is important to note that if the reporting processor uses secondary emission factors, it must disaggregate and then overwrite them with supplier-specific data. For example, if the reporting processor collects supplier-specific data only on Scope 1, Scope 2 and waste, all other emissions associated with said capital goods must be estimated using secondary data. Specific equations necessary for factoring in disaggregation of secondary emission factors are included in the Calculation Approach section.

Relevant emission factors can be found in the following sources:

- GHG Protocol website
- Supplier-developed emission factors (if the capital good supplier conducted an LCA study on its products)
- Life cycle databases
- Industry associations
- Government or multilateral agencies

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Scope 3: Capital Goods

5

Calculation Approach: Reporting processors may use the equation (below) as a baseline calculation to quantify GHG emissions from capital goods. The equation assumes that the reporting processor's capital good supplier(s) only have supplier-specific data on Scope 1, Scope 2 and waste emissions, and all other GHG emissions data associated with the production of said capital good must be accounted for using secondary data.

Equation for All Capital Goods Purchased

Σ Allocated Scope 1 and Scope 2 Emissions of Capital Good Supplier (kg CO_2e)

PLUS (+)

Σ Mass of Waste Generated from Capital Good Production (kg) **X** Waste Activity Emission Factor (kg CO_2e/kg)

PLUS (+)

Σ Quantity of Capital Good (kg, units, $) **X** Capital Good Emission Factor (Excluding Scope 1, Scope 2 and Waste Emissions Generated by Producer) (kg CO_2e/kg or unit or $)

If the reporting processor is able to procure 100 percent of the supplier-specific data, leaving no need for gaps to be filled in with secondary data, the following equation should be used.

Equation for All Capital Goods Purchased

Σ Allocated Scope 1 and Scope 2 Emissions of Capital Good Supplier (kg CO_2e)

PLUS (+)

Σ Mass or Quantity of Material Inputs for Capital Good Production (kg) **X** Cradle-to-Gate Emission Factor for Material (kg CO_2e)

PLUS (+)

Σ Transport Distance of Material Inputs to Capital Good Supplier (km) **X** Mass or Volume of Material Input (tons or TEUs) **X** Cradle-to-Gate Emission Factor for Capital Good Delivery Vehicle Type (kg CO_2e/ton or TEU/km)

PLUS (+)

Σ Mass of Waste Generated from Capital Good Production (kg) **X** Waste Activity Emission Factor (kg CO_2e/kg)

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Scope 3: Fuel and Energy Related Activities

Chapter at a Glance

- Defining Fuel and Energy
- Identifying Sources
- Collecting Activity Data
- Data Collection Guidance
- Calculation Approach

This section provides guidance on how to account for and calculate Scope 3 indirect GHG emissions from the production of fuel and energy that the reporting processor purchases.

1

Defining Fuel and Energy Related Activities: This category accounts for emissions from purchased fuels and electricity much like Scope 1 and 2. However, the key difference is that the reporting processor's Scope 3 GHG emissions from purchased fuel and electricity comprise those emissions arising from the extraction, production and transportation of the fuel and electricity that it purchases, not the consumption. For example, if a reporting processor consumes 100 kWh of fuel, and 200 kWh of electricity in the reporting year, then its Scope 3: Fuel and Energy Related Activities inventory would be the GHG emissions associated with extracting, producing and distributing that quantity of fuel and electricity over a given distance to the reporting processor (end consumer). Therefore, it is important for the reporting processor to use emission factors that exclude GHG emissions from combustion in their calculations.

2

Identifying Sources: Table 5.0 (below) gives a more detailed depiction of the upstream fuel and electricity production activities relevant to reporting processors:

Scope 3 Fuel and Energy Related Emissions Sources

Emission Source	Description	Example
Purchased Fuels	Extraction, production and transportation of fuels	Coal mining, gasoline refining, biofuel production, natural gas distribution
Purchased Energy	Extraction, production and transportation of fuels used to produce electricity, steam, heating, and cooling	Coal mining, fuel refining, natural gas extraction
Transmission & Distribution Losses	Fuel and/or electricity that escapes either in generation at the plant, or in transmission to the reporting processor	Electricity loss through the transmission line due to resistance

(Table 5.0) Upstream fuel and energy production processes that represent Scope 3 sources to dairy processors

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Scope 3: Fuel and Energy Related Activities

3

Collecting Activity Data: Quantifying a wholly representative Scope 3: Fuel and Energy Related Activities inventory requires several equations, each demanding different activity data and different emission factors. The appropriate activity data that corresponds to each emission source is included in Table 5.1 (below).

Relevant Activity Data and Emission Factors for Scope 3: Fuel and Energy Related Activities

Emission Source	Activity Data Needed	Emission Factor Needed
Purchased Fuels	Type and amount of all fuels directly consumed	Fuel provider-specific – for extraction, production and transportation per unit of fuel consumed at processing facility, by fuel type and region
Purchased Energy	Quantities of electricity, steam, heating and cooling purchased (sub-divided by supplier, or grid region)	Utility-specific – for extraction, production and transportation of fuels consumed by processing facility per MWh of electricity/ steam/heat/cooling generated Available in eGRID2016 Datafile (XLSX) EPA eGRID sub-region emission factor database
Transmission & Distribution Losses	Electricity, steam, heating and cooling per unit of consumption; divided by grid region	Utility-specific – transmission & distribution loss rate, specific to grid where processing facility's energy is generated and consumed Available in EPA eGRID sub-region emission factor database

(Table 5.1) Activity data and emission factors to be collected to compose a full account of Scope 3: Fuel and Energy Related Activities inventory

4

Data Collection Guidance: For Purchased Fuels: Reporting processors may reference a number of resources to obtain this activity data, such as:

- Reporting processor's own Scope 1 inventory
- Fuel suppliers

Emission factor resources (if necessary):

- Life cycle databases, available on the GHG Protocol website
- EPA eGRID database

For Purchased Electricity: This category requires that the reporting processor disaggregate the total quantity of electricity, steam, heat or cooling purchased by either supplier, or grid region. Resources for this data are as follows:

- Reporting processor's own Scope 2 inventory
- Government agency energy management departments
- Energy suppliers/generators

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Scope 3: Fuel and Energy Related Activities

4

Emission factor resources:

- Supplier-developed emission factors
- Life cycle databases, available on the GHG Protocol website
- EPA eGRID database

For Transmission & Distribution (T&D) Losses: This category requires that the reporting processor apply the percentage of transmission and distribution losses to the total quantity of electricity, steam, heat, or cooling purchased. Resources for this data are as follows:

- Reporting processor's own Scope 2 inventory
- Resources for transmission and distribution loss percentages
- EPA eGRID database

5

Calculation Approach: This guidance recommends using the Supplier-Specific method for all three emission sources within this category. This method involves collecting fuel, electricity and T&D loss rates data specifically from the reporting processor's suppliers. The corresponding equations for each emission source are included below.

Once the reporting processor has accounted for GHG emissions from all three sources in this category, the individual source totals may be aggregated to quantify the complete Scope 3: Fuel and Energy Related Activities inventory.

Equation for For Purchased Fuels

Σ (Fuel Consumed (kWh, m^3, etc.) **X** Upstream Fuel Emission Factor (kg CO_2e/kWh, m^3, etc..))
Where: Upstream Fuel Emission Factor **=** Life Cycle Emission Factor **-** Combustion Emission Factor

Equation For Purchased Electricity

Σ (Electricity Consumed (kWh) **X** Upstream Electricity Emission Factor (kg CO_2e/kWh))

PLUS (+)

(Steam Consumed (kWh) **X** Upstream Steam Emission Factor (kg CO_2e/kWh))

PLUS (+)

(Heat Consumed (kWh) **X** Upstream Heat Emission Factor (kg CO_2e/kWh))

PLUS (+)

(Cooling Consumed (kWh) **X** Upstream Cooling Emission Factor (kg CO_2e/kWh))
Where: Upstream Emission Elec./Steam/Heat/Cooling Emission Factor **=** Life Cycle Emission Factor **-** Combustion Emission Factor **-** Transmission & Distribution Losses

NOTE: The ∑ in this equation represents summing across either electricity suppliers or regions.

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Scope 3: Fuel and Energy Related Activities

5

Equation for Transmission and Distribution

Σ (Electricity Consumed (kWh) **X** Elec. Life Cycle Emission Factor (kg CO_2e/kWh) **X** T&D Loss Rate (%))

PLUS (+)

(Steam Consumed (kWh) **X** Steam Life Cycle Emission Factor (kg CO_2e/kWh) **X** T&D Loss Rate (%))

PLUS (+)

(Heat Consumed (kWh) **X** Heat Life Cycle Emission Factor (kg CO_2e/kWh) **X** T&D Loss Rate (%))

PLUS (+)

(Cooling Consumed (kWh) **X** Cooling Life Cycle Emission Factor (kg CO_2e/kWh) **X** T&D Loss Rate (%))

NOTE: The Σ in this equation represents summing across either electricity suppliers or regions.

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Scope 3: Upstream Transportation and Distribution

Chapter at a Glance

- Defining Transportation and Distribution
- Identifying Sources
- Collecting Activity Data
- Data Collection Guidance
- Calculation Approach

*This section provides guidance on how to account for and calculate Scope 3 indirect GHG emissions from transportation and distribution of products purchased by the reporting processor from its Tier 1 suppliers.**

TIP: *Tier 1 suppliers refer to the farms where the reporting processor has a purchase order for goods and services.

1

Defining Upstream Transportation and Distribution: Upstream transportation and distribution refers to the transportation and distribution services that the reporting processor purchases over the reporting period. Any transportation and distribution service not purchased by the reporting processor is classified as downstream transportation and distribution. Therefore, if the reporting processor hires an external company owning its own fleet of delivery trucks to distribute the processor's products, the GHG emissions from those trucks would constitute the reporting processor's Scope 3: Upstream Transportation and Distribution emissions. However, if the reporting processor does not purchase the transportation and distribution service, the resultant GHG emissions would be accounted for in Scope 3: Downstream Transportation and Distribution.

Furthermore, if the reporting processor's Tier 1 supplier purchases from a supplier as well (the reporting processor's Tier 2 supplier), emissions from the transportation and distribution between the Tier 1 and 2 suppliers are accounted for in Scope 3: Purchased Goods and Services.

2

Identifying Sources: Much like the Scope 1: Mobile Combustion Emissions guidance, accounting for Scope 3: Upstream Transportation and Distribution emissions sources involves identifying the mobile emission sources in the reporting processor's value chain that are owned and/or operated by other companies.

Common Mobile Emission Sources in U.S. Dairy Transportation and Distribution

Common Scope 3 Mobile Combustion Sources		Common Fuels Used
On-Road Vehicles	Combination trucks and fluid milk trucks	Diesel fuel, gasoline, biodiesel
Non-Road Vehicles (Mobile Machinery)	Forklifts and non-road equipment	Diesel fuel, gasoline, propane
	Construction equipment	Diesel fuel

(Table 6.0) Common Scope 3 mobile emission sources and accompanying fuels used in the dairy value chain

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Scope 3: Upstream Transportation and Distribution

3

Collecting Activity Data: Again, like Scope 1: Mobile Combustion Emissions, key activity data is needed to calculate Scope 3: Upstream Transportation and Distribution emissions. Fuel use data or distance-traveled data can both be used for calculating Scope 3: Upstream Transportation and Distribution GHG emissions. If the distance-traveled approach is used, some additional information on the vehicle characteristics is required.

Activity Data for Mobile Emission Calculations	
Data Type	Common Fuels Used
Vehicle Characteristics	Type and model year
Distance Traveled	Miles, kilometers
Fuel Type	Gasoline, diesel, fuel oil, CNG, LNG, LPG
Fuel Amount	Gallon, liter, barrel, cubic foot, cubic meter

(Table 6.1) Activity data to be collected for each mobile combustion emissions source not owned or operated by the reporting processor

4

Data Collection Guidance: Sources for activity data necessary to calculate Scope 3: Upstream Transportation and Distribution data include:

- Aggregated fuel receipts from suppliers
- Purchase records from suppliers
- Internal transport management systems[3]

5

Calculation Approach: Use the GHG Protocol Mobile Combustion GHG Emissions Calculation Tool as in the Scope 1: Mobile Combustion Emissions guidance. Ensure that "Scope 3" is selected under the "Scope" column in the "Activity Data" tab. This tool developed by the GHG Protocol, has the appropriate emissions factors built in. It automatically calculates Scope 3 emissions from transportation and distribution so long as the appropriate activity data is included.

If the reporting processor chooses to use an alternate method of calculating Scope 3: Upstream Transportation and Distribution emissions, data sources for appropriate emission factors include[5]:

- Transportation carriers
- Government agencies (i.e., EPA, IPCC)
- The Climate Registry
- GHG Protocol website
- Industry associations

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Scope 3: Waste Generated in Operations

Chapter at a Glance

- Defining Operations
- Identifying Sources
- Collecting Activity Data
- Data Collection Guidance
- Calculation Approach

This section provides guidance on how to account for and calculate Scope 3 indirect GHG emissions from disposal and treatment of waste generated by the reporting processor.

1

Defining Waste Generation in Operations: This Scope 3 category specifically captures emissions generated from the handling and disposal of waste generated in the reporting processor's owned and/or operated facilities. It is important to note that CO_2 emissions from biomass materials are reported outside of the scopes in a separate memo item. Since much of dairy processing waste is generated from biomass materials, reporting processors should account for CO_2 emissions from waste in an appended memo. However, CH_4 (methane) and N_2O (nitrous oxide) emissions are still accounted for in the scopes for this category. Furthermore, this category accounts for all future emissions deriving from the reporting processor's waste in the reporting year.

U.S. dairy processing generally yields little solid waste, making this a rather insignificant Scope 3 source for reporting processors. However, the American dairy processing industry does generate significant quantities of wastewater that produce GHG emissions when treated and/or disposed of.[4] Undoubtedly, reporting processors will produce varying quantities of wastewater depending on the number of processing facilities and the type of dairy products produced.

2

Identifying Sources: Table 7.0 identifies key procedures in the dairy processing industry that produce waste. Depending on the dairy products produced by the reporting processor, these waste sources may or may not apply. Reporting processors should consult the table based on products produced.

Source: UNFAO

Typical U.S. Dairy Processes that Produce Waste

Dairy Process	Waste Source	Waste Type
Milk Receiving	Storage tank washing, pipeline washing and sanitizing	Wastewater
Whole Milk Processing	Cleaning operations between product changes	Wastewater
Cheese/Whey/Curd Processing	Whey production, wash water, curd particles	Wastewater
Butter/Ghee Processing	Butter washing	Wastewater
Milk Powder Processing	Cleaning, fine dust emission from drying	Wastewater
Condensed Milk/Cream/Khoa Processing	Coagulated milk, fine cheese curd particles	Wastewater
Wastewater Purification	Resulting sludge after purification	Solid Waste

(Table 7.0) Waste-producing processes typical of the U.S. dairy industry's processing activities

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Scope 3: Waste Generated in Operations

3

Collecting Activity Data: This guidance recommends using the Waste-Type-Specific method to account for and calculate GHG emissions from the reporting processor's third-party handled waste. This entails differentiating between waste types and the disposal method for each waste type. Reporting processors should collect the following:

- Waste produced per quantity of product (i.e., m^3 of wastewater per gallon of fat and protein corrected milk)
- Different waste types associated with dairy processing
- Waste treatment applied to each waste type (i.e., landfill, wastewater treatment, recycling)

4

Data Collection Guidance: Third-party waste handlers often charge companies based on method of waste disposal, so this is a relatively easy way for reporting processors to identify waste disposal methods that apply. Waste management bills often contain this specific information. Furthermore, appropriate emission factors necessary for calculating operation-derived waste can be found in a variety of databases, including:

- IPCC Guidelines
- Life cycle databases
- Industry associations

If a third-party waste handler does not charge based on waste disposal method, this guidance recommends using the Average-Data method. It involves using average emission factors for each disposal method (i.e., landfill) and multiplying these emission factors by quantities of each waste type.

5

Calculation Approach: Reporting processors may use the calculation equation below to account for Scope 3: Waste Generated in Operations.

Once the reporting processor applies this equation for each waste type, simply aggregating the CO_2e for each waste type will yield the total GHG emissions from waste management. Alternatively, reporting processors may utilize the U.S. EPA's Waste emission factors in the Emission Factors Hub to quantify emission in this category.

Equation for Waste Generated in Operations
Σ (Waste Produced (tons or m^3) **X** Specific Emission Factor for Waste Type (kg CO_2e/ton or m^3))

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Scope 3: Upstream Leased Assets

Chapter at a Glance

- Defining Leased Assets
- Identifying Sources
- Collecting Activity Data
- Data Collection Guidance
- Calculation Approach

This section provides guidance on how to account for and calculate Scope 3 indirect GHG emissions from sources the reporting processor leases upstream in its supply chain.

1

Defining Upstream Leased Assets: If the reporting processor does not own all of its processing facilities and/or equipment, but rather leases them, the associated GHG emissions from these assets may be accounted for in this category depending on the GHG inventory consolidation approach utilized.

If the reporting processor has adopted the Operational Control approach, GHG emissions from operation of leased facilities/equipment are considered under Scope 1 and Scope 2, despite not being owned by the reporting entity. However, if another consolidation approach has been implemented, the Scope 3 emissions in this category include the Scope 1 and 2 emissions of the reporting processor's lessor(s).

2

Identifying Sources: GHG emission sources from leased assets can be calculated as detailed in the methodology for Scope 1 and 2 inventories. By aggregating Scope 1 and 2 emissions from all leased assets (buildings, equipment etc.), the reporting processor can clearly define its Scope 3: Upstream Lease Assets inventory.

GHG Emission Sources from Leased Assets		
Leased Asset	Emissions	Scope
Processing Facilities/Office Space	Fuel consumed, refrigerant leaked, process emissions	Scope 1
	Electricity consumed, steam consumed, heat consumed, cooling consumed	Scope 2
Equipment/Machines	Fuel consumed	Scope 1
	Electricity consumed	Scope 2

(Table 8.0) GHG emission sources from leased assets

3

Collecting Activity Data: This guidance recommends using the Asset-Specific method, outlined by the GHG Protocol Corporate Value Chain Standard. This method involves obtaining data specific to each and every asset that the reporting processor leases. For each leased asset, the reporting processor should collect activity data outlined in Table 8.0. If the reporting processor is unable to obtain the fuel and energy data associated with each leased asset, other methods of accounting for Scope 3: Upstream Leased Assets emissions can be found in the GHG Protocol Technical Guidance for Calculating Scope 3 Emissions.

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Scope 3: Upstream Leased Assets

4

Data Collection Guidance: Much like Scope 1 and 2 accounting, the necessary activity data for this category can be collected via many different methods:

- Utility bills
- Purchase records
- Meter readings
- Internal IT systems

Appropriate emission factors are available from an array of different sources as well, such as:

- The EPA GHG Emissions Factors Hub
- Life cycle databases
- Other government agencies such as the IPCC, and Climate Registry
- Industry associations
- Company-developed factors if applicable

5

Calculation Approach: The following equation represents the appropriate methodology for calculating Scope 3: Upstream Leased Assets using the Asset-Specific method:

Calculating Scope 3: Upstream Leased Assets using the Asset-Specific Method

Scope 1 Emissions from Upstream Leased Assets

(Fuel Consumed **X** Fuel Emission Factor (kg CO_2e/fuel unit)) **+** (Refrigerant Leakage (kg) **X** Refrigerant Emission Factor (kg CO_2e/kg))

PLUS (+)

Scope 2 Emissions from Upstream Leased Assets

(Electricity, Steam, Heating, Cooling Consumed (kWh)) **X** (Electricity, Steam, Heating, Cooling Emission Factor (kg CO_2e/kWh))

EQUALS (=)

Scope 3 Emissions from Upstream Leased Assets

Scope 3: Upstream Leased Assets Inventory **=** Σ Scope 3 Emissions from All Upstream Leased Assets

Reporting processors may use the GHG Emissions from Purchased Electricity, GHG Emissions from Stationary Combustion, and Refrigeration and Air-Conditioning Equipment Excel tools as resources to assist in quantifying emissions in this category. They all have built-in GHG Protocol emission factors in order to streamline GHG emissions from fuel, electricity, steam, heat, cooling and refrigeration.

If the reporting processor only leases a section or portion of the facility, and the facility lacks sub-metering infrastructure, then energy consumption may be allocated using an estimation based on the share of space the reporting processor leases (based on floor space). This may be calculated using the following equation:

Equation for Section or Portion Leases

(Reporting Processor's Used Space (m^2) **/** (Building's Total Area (m^2) **X** Building Occupancy Rate) **X** Total Building Energy Use (kWh)

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Scope 3: Downstream Transportation and Distribution

Chapter at a Glance

- Defining Transportation and Distribution
- Identifying Sources
- Collecting Activity Data
- Data Collection Guidance
- Calculation Approach

This section provides guidance on how to account for and calculate Scope 3 indirect GHG emissions from transportation and distribution of sold products not owned or operated by the reporting facility.

1

Defining Downstream Transportation and Distribution: Downstream Transportation and Distribution refers to the transportation and distribution services that the reporting processor does not purchase over the reporting period. Any transportation and distribution service purchased by the reporting processor is classified as Upstream Transportation and Distribution. Therefore, if the reporting processor receives or sells a product from/to another company that pays for all transportation and distribution needs, the GHG emissions from said transportation and distribution would constitute the reporting processor's Scope 3: Downstream Transportation and Distribution emissions.

Furthermore, emissions resulting from storage of the milk downstream from the reporting processor are accounted for in this category. For example, GHG emissions arising from leaking refrigerants, as well as fuel and/or electricity used to refrigerate the sold milk in the distribution trucks, are included in this category.

Differentiating Between Upstream and Downstream Transportation and Distribution in U.S. Dairy

Scenario	Entity	
	Reporting Processor	Retailer
If reporting processor does not pay for transportation of dairy products to retailer	Scope 3: Downstream Transportation and Distribution	Scope 3: Upstream Transportation and Distribution
If reporting processor does pay for transportation of dairy products to retailer	Scope 3: Upstream Transportation and Distribution	Scope 1 & 2 Or Scope 3: Downstream Transportation and Distribution

(Table 9.0) Differentiation of transportation and distribution of dairy throughout the U.S. dairy value chain

2

Identifying Sources: Much like the Scope 1: Mobile Combustion Emissions guidance, accounting for Scope 3: Downstream Transportation and Distribution emissions sources involves identifying the mobile emission sources in the reporting processor's value chain that are owned and/or operated by other companies.

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Scope 3: Downstream Transportation and Distribution

2

Downstream Transportation and Distribution Emission Sources		
Downstream Activity	Infrastructure	Emission Source
On-Road Vehicles	Combination trucks and fluid milk trucks	Diesel fuel, gasoline, biodiesel
	In-truck refrigeration	Leaking refrigerants
Warehouses and Distribution Centers	Refrigeration	Purchased electricity, leaking refrigerants
Retail Facilities	Refrigeration	Purchased electricity, leaking refrigerants

(Table 9.1) Activity data to be collected for each mobile combustion emissions source not owned or operated by the reporting processor

3

Collecting Activity Data: Again, like Scope 1: Mobile Combustion Emissions, key activity data is needed to calculate Scope 3: Downstream Transportation and Distribution emissions. Use the Distance-Based method to quantify downstream transportation emissions, which requires the following activity data:

Activity Data for Mobile Emission Calculations	
Data Type	Information Needed
Vehicle Characteristics	Type and model year
Distance Traveled	Miles, kilometers
Fuel Type	Gasoline, diesel, fuel oil, CNG, LNG, LPG
Fuel Amount	Gallon, liter, barrel, cubic foot, cubic meter

(Table 9.2) Activity data to be collected for each mobile combustion emissions source not owned or operated by the reporting processor

Activity Data for Refrigerant Leakage	
Data Type	Information Needed
Type of Equipment	In-truck refrigeration, warehouse refrigeration, retail refrigeration
Refrigerant Used	HFC type, PFC type
Annual Leakage Rate	Percent
Total Refrigerant Charge	Pounds

(Table 9.3) Activity data to be collected for each refrigeration source not owned or operated by the reporting processor

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Scope 3: Downstream Transportation and Distribution

4

Data Collection Guidance: Sources for activity data necessary to calculate Scope 3: Downstream Transportation and Distribution data include:

- Aggregated fuel receipts from customers
- Purchase records from customers
- Internal transport management systems[3]
- Retailer equipment records
- Third-party transportation fleet records
- Life cycle databases

5

Calculation Approach: Use the GHG Protocol Mobile Combustion GHG Emissions Calculation Tool as in the Scope 1: Mobile Emissions guidance. However, this time ensure that "Scope 3" is selected under the "Scope" column in the "Activity Data" tab. This tool, developed by the GHG Protocol, has the appropriate emission factors built in. It automatically calculates Scope 3 emissions from transportation and distribution so long as the appropriate activity data is input.

To calculate emissions from refrigeration throughout the downstream value chain, reporting processors may utilize the GHG Protocol Refrigeration and Air-Conditioning Equipment calculation tool. It has built-in emissions factors for calculating refrigerant emissions and offers a variety of methods with instructions.

If the reporting processor chooses to use an alternate method of calculating Scope 3 upstream transportation and distribution emissions, data sources for appropriate emission factors include[5]:

- Transportation carriers
- Government agencies (i.e., EPA, IPCC)
- The Climate Registry
- GHG Protocol website
- Industry associations

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Scope 3: Downstream Leased Assets

Chapter at a Glance

- Defining Leased Assets
- Identifying Sources
- Collecting Activity Data
- Data Collection Guidance
- Calculation Approach

This section provides guidance on how to account for and calculate Scope 3 indirect GHG emissions from owned assets that the reporting company leases to other parties.

1

Defining Downstream Leased Assets: This category accounts for emissions from leased assets that the reporting processor owns and rents to other companies. Although uncommon in the dairy processing industry, there may be occasions where a cooperative or large processing company leases one or several of its facilities and/or equipment to other companies. Contrary to Scope 3: Upstream Leased Assets, the reporting processor is the lessor in this category, which captures GHG emissions from any and all facilities, or equipment that are generated by the lessee.

Similar to Scope 3: Upstream Leased Assets, GHG emissions from owned, but not operated assets may be considered under Scope 1 or Scope 2 for the lessor, depending on the reporting processor's consolidation approach. Furthermore, this category of GHG emissions mirrors Scope 3: Upstream Leased Assets in that the leasing company's Scope 1 and 2 GHG emissions associated with the asset(s) are equivalent to the Scope 3: Downstream Leased Assets for the reporting processor.

2

Identifying Sources: By aggregating leasing companies' Scope 1 and 2 emissions from all reporting processor-owned assets (buildings, equipment etc.), the reporting processor can clearly define its Scope 3: Upstream Lease Assets inventory.

GHG Emission Sources from Leased Assets		
Leased Asset	Emissions	Scope
Processing Facilities/Office Space	Fuel consumed, refrigerant leaked, process emissions	Scope 1
	Electricity consumed, steam consumed, heat consumed, cooling consumed	Scope 2
Equipment/Machines	Fuel consumed	Scope 1
	Electricity consumed	Scope 2

(Table 10.0) GHG emission sources from leased assets

3

Collecting Activity Data: This guidance recommends using the Asset-Specific method, outlined by the GHG Protocol Corporate Value Chain Standard. This method involves obtaining data that is specific to each and every asset that the reporting processor is the lessor to. For each asset, the reporting processor should collect activity data outlined in Table 10.0. If the reporting processor is unable to obtain the fuel and energy data associated with each asset, other methods of accounting for Scope 3: Downstream Leased Assets emissions can be found in the GHG Protocol Technical Guidance for Calculating Scope 3 Emissions.

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Scope 3: Downstream Leased Assets

4

Data Collection Guidance: Much like Scope 1 and 2 accounting, the necessary activity data for this category can be collected via many different methods:

- Utility bills
- Purchase records
- Meter readings
- Internal IT systems

Appropriate emission factors are available from an array of different sources as well, such as:

- The EPA GHG Emissions Factors Hub
- Life cycle databases
- Other government agencies such as the IPCC, and Climate Registry
- Industry associations
- Company-developed factors if applicable

5

Calculation Approach: The following equation represents the appropriate methodology for calculating Scope 3: Downstream Leased Assets using the Asset-Specific method. It is the same methodology for Scope 3: Upstream Leased Assets:

Calculating Scope 3: Downstream Leased Assets using the Asset-Specific Method

Scope 1 Emissions from Upstream Leased Asset

(Fuel Consumed **X** Fuel Emission Factor (kg CO_2e/fuel unit)) **+** (Refrigerant Leakage (kg) **X** Refrigerant Emission Factor (kg CO_2e/kg))

PLUS (+)

Scope 2 Emissions from Upstream Leased Asset

(Electricity, Steam, Heating, Cooling Consumed (kWh)) **X** (Electricity, Steam, Heating, Cooling Emission Factor (kg CO_2e/kWh))

EQUALS (=)

Scope 3 Emissions from Upstream Leased Asset

Scope 3: Upstream Leased Assets Inventory **=** Σ Scope 3 Emissions from All Upstream Leased Assets

Reporting processors may use the GHG Emissions from Purchased Electricity, GHG Emissions from Stationary Combustion and Refrigeration and Air-Conditioning Equipment Excel tools as resources to assist in quantifying emissions in this category. They have built-in GHG Protocol emission factors to streamline GHG emissions from fuel, electricity, steam, heat, cooling and refrigeration.

If the leasing company only leases a section or portion of the facility, and the facility lacks sub-metering infrastructure, then energy consumption may be allocated using an estimation based on the share of space the company leases (based on floor space). This may be calculated using the following equation:

Equation for Section or Portion Leases

Leasing Company's Used Space (m^2) **/** (Building's Total Area (m^2) **X** Building Occupancy Rate) **X** Total Building Energy Use (kWh)

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Appendix: This category is not a priority in the U.S. dairy value chain, but is recommended for a comprehensive Scope 3 inventory.

Scope 3: Business Travel

Chapter at a Glance

- Defining Business Travel
- Identifying Sources
- Collecting Activity Data
- Data Collection Guidance
- Calculation Approach

This section provides guidance on how to account for and calculate Scope 3 indirect GHG emissions from business-related travel.

While this section is not a priority in U.S. dairy GHG accounting, reporting processors should include it to compose the most comprehensive Scope 3 inventory (account for prioritized sections first).

1

Defining Business Travel: Business-related travel emissions are considered Scope 3 indirect emissions if the method of transportation used by the traveling employee is not owned and/or operated by the reporting processor. If the vehicle used by the traveling employee is owned by the reporting processor, emissions from said vehicle would be accounted for under Scope 1 (if powered by fuel) or Scope 2 (if powered by electricity). Emissions from leased vehicles operated by the reporting processor are considered Scope 3, but are accounted for in Scope 3: Upstream Leased Assets. Emissions from employee commuting are accounted for in Scope 3: Employee Commuting.

Differentiating Mobile Emission Sources and Scopes		
Emitting Transportation Activity	Category	Scope
Operation of owned/controlled vehicles	Fuel/electricity consumption	Scope 1, Scope 2
Business travel in unowned/non-processor operated vehicles	Business travel	Scope 3
Transportation to and from work in unowned/non-processor operated vehicles	Employee commuting	Scope 3
Transportation in leased vehicles operated by reporting processor	Upstream leased assets	Scope 3

(Table 11.0) Differentiation of transportation-related emission sources

2

Identifying Sources: Identifying sources of emissions from business travel simply involves keeping track of any and all business trips via air, rail, bus, automobile (i.e., rental cars), or other travel methods. Reporting processors may also include emissions from hotel stays in this category. Although optional, including this information may give a more accurate and robust account of Scope 3 emissions from business travel. Hotel emissions are quantified using emission factors specific to hotel type (i.e., kg CO_2 per hotel night).

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Scope 3: Business Travel

3

Collecting Activity Data: The GHG Protocol Scope 3 Calculation Guidance recommends using the Distance-Based method for calculating business travel-related emissions for reporting entities not significantly impacted by business travel as a contributor to overall Scope 3 inventory. This method requires keeping track of the distance traveled and transportation method used for all business trips in the reporting year. If activity data is not available for calculating emissions using the Distance-Based method, reporting processors may employ the Spend-Based method, which involves a different set of emission factors called secondary (EEIO) emission factors. By determining the total amount spent on business travel in the reporting year, the reporting processor may calculate emissions using these secondary emission factors. However, the GHG Protocol recommends using the Distance-Based method when possible.

Activity Data for Business Travel Emissions Calculations	
Data Type	Information Needed
Mode of Transport	Road, Rail, Water, Aircraft
Vehicle Characteristics	Type and Class
Distance Traveled	Miles, Kilometers
Passengers	Number of passengers traveling

(Table 11.1) Relevant activity data to collect for Scope 3: Business Travel accounting

4

Data Collection Guidance: Sources of activity data necessary to calculate Scope 3: Business Travel emissions include:

- Distance tracking reports through a travel agency or other travel providers
- Distance tracking through internal expense and reimbursement systems
- Annual employee surveys
- Emissions data obtained through travel providers

5

Calculation Approach: Use the GHG Protocol's Mobile Combustion GHG Emissions Calculation Tool, which has built-in emission factors for various transportation methods, and will automatically calculate CO_2, CH_4 and N_2O emissions data from the reporting processor's input activity data. It is important to select "Scope 3" under the "Scope" column in the "Activity Data" tab. If a reporting processor wishes to utilize a calculation resource other than the GHG Protocol's Mobile Combustion GHG Emissions Calculation Tool, the U.S. EPA Climate Leaders GHG Inventory Protocol, "Optional Emissions from Commuting, Business Travel and Product Transport"[5] may be consulted.

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Appendix: This category is not a priority in the U.S. dairy value chain, but is recommended for a comprehensive Scope 3 inventory.

Scope 3: Employee Commuting

Chapter at a Glance

- Employee Commuting
- Identifying Sources
- Collecting Activity Data
- Data Collection Guidance
- Calculation Approach

This section provides guidance on how to account for and calculate Scope 3 indirect GHG emissions from employee commuting.

While this section is not a priority in U.S. dairy GHG accounting, reporting processors should include it to compose the most comprehensive Scope 3 inventory (account for prioritized sections first).

1

Defining Employee Commuting: This Scope 3 category captures all GHG emissions generated from the reporting processor's employee base traveling to and from work at the processing and/or manufacturing facilities and corporate offices.

Differentiating Mobile Emission Sources and Scopes		
Emitting Transportation Activity	Category	Scope
Operation of owned/controlled vehicles	Fuel/electricity consumption	Scope 1, Scope 2
Business travel in unowned/non-processor operated vehicles	Business travel	Scope 3
Transportation to and from work in unowned/non-processor operated vehicles	Employee commuting	Scope 3
Transportation in leased vehicles operated by reporting processor	Upstream leased assets	Scope 3

(Table 12.0) Differentiation of transportation-related emission sources

2

Identify Sources: Depending on region, access to public transportation and processing facility location, employees may utilize a diverse array of transportation methods to commute to and from work. Therefore, employee commuting emissions may arise from sources such as automobile, bus, rail, air and subway. Reporting processors may also include emissions arising from employees working remotely in this category, although this is optional.

3

Collecting Activity Data: Commuting employees may contribute significantly to the Scope 3 inventory depending on company size. The GHG Protocol Scope 3 Corporate Value Chain Standard recommends using the Fuel-Based method, which requires collecting data on the amount of fuel consumed through employee commuting. Data on the types and quantities/cost of various fuels consumed for all employees at all processing facilities may be difficult to collect. If so, the reporting processor may utilize the Distance-Based method, as in Scope 3: Business Travel, to accurately quantify emissions from employee commuting.

For Fuel-Based activity data and calculation methodology, use the Scope 3: Upstream Transportation and Distribution. The reporting processor may refer to this category if using the Fuel-Based approach. If the Distance-Based method is used, apply the methodology for Scope 3: Business Travel.

continued on next page

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Scope 3: Employee Commuting

3

Activity Data for Employee Commuting Emissions Calculations	
Data Type	Information Needed
Mode of Transport	Road, Rail, Water, Aircraft
Vehicle Characteristics	Type and Class
Distance Traveled	Miles, Kilometers
Passengers	Number of passengers traveling via each method

(Table 12.1) Relevant activity data to collect for Scope 3: Employee Commuting accounting

4

Data Collection Guidance: The reporting processor may distribute a survey or questionnaire to collect data on commuting habits. The survey should include the questions in Table 12.2 (below).

Employee Commuting Survey Questions	
Survey Question	Applicable Metrics
How far do employees travel to and from work? (OR calculate distance from employee residence to processing facility)	Miles per day
How many days do employees commute per week?	Days per week
How many weeks do employees work per year?	Weeks per year
How many days per week do employees use different transportation methods?	Days per week for each transportation method
If there is a car-pooling initiative among the company – • What's the proportion of employees carpooling? • What is the average carpooling occupancy per vehicle?	Percentage of employees who carpool and/or average persons per vehicle
If applicable – what is the energy used from employees who work remotely?	kWh

(Table 12.2) Survey questions that are useful for collecting Scope 3: Employee Commuting data

5

Calculation Approach: Use the GHG Protocol's Mobile Combustion GHG Emissions Calculation Tool, which has built-in emission factors for various transportation methods. It will automatically calculate CO_2, CH_4 and N_2O emissions data from the reporting processor's input activity data. This tool may be used to calculate Scope 3 emissions from employee commuting using both the Fuel-Based method and the Distance-Based method. It is important that the reporting processor ensures "Scope 3" is selected under the "Scope" column in the "Activity Data" tab.

Once the reporting processor has obtained emissions for every employee at each processing facility, the reporting processor may simply aggregate commuting emissions from all company-owned or operated facilities to determine its total Scope 3: Employee Commuting footprint.

If a reporting processor wishes to utilize a calculation resource other than the GHG Protocol's Mobile Combustion GHG Emissions Calculation Tool, the U.S. EPA Climate Leaders GHG Inventory Protocol, "Optional Emissions from Commuting, Business Travel and Product Transport"[5] may be consulted.

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Appendix: This category is not a priority in the U.S. dairy value chain, but is recommended for a comprehensive Scope 3 inventory.

Scope 3: Processing of Sold Products

Chapter at a Glance

- Defining Sold Products
- Identifying Sources
- Collecting Activity Data
- Data Collection Guidance

This section provides guidance on how to account for and calculate Scope 3 indirect GHG emissions from processing of sold intermediate products by other processors further down the supply chain.

While this section is not a priority in U.S. dairy GHG accounting, reporting processors should include it to compose the most comprehensive Scope 3 inventory (account for prioritized sections first).

1

Defining Processing of Sold Products: Certain reporting processors may distribute their milk to other processors to be used for products such as ice cream, cheese, yogurt, etc. These products are considered intermediate products in dairy. The GHG Protocol defines intermediate products as those that "require further processing, transformation, or inclusion in another product before use, and therefore result in emissions from processing subsequent to sale by the reporting company and before use by the end consumer."[2] The reporting processor's Scope 3: Processing of Sold Products emissions are equivalent to other processors' Scope 1 and 2 emissions down their supply chain.

2

Identifying Sources: Intermediate dairy processing mainly creates GHG emissions from fuel and electricity used at processing facilities, as well as from waste generated from said processing. However, collecting primary data on emissions from these sources can often be difficult and unrealistic, especially if the reporting processor distributes to a large quantity of intermediate processors. Therefore, reporting processors should use the Average-Data method to estimate emissions from sold intermediate product-derived GHG emissions.

3

Collecting Activity Data: Using the Average-Data method entails collecting information on the downstream intermediate processing activities in the reporting processor's supply chain in order to select and apply the relevant industry-average emission factors.

Average Data Method – Processing of Sold Products	
Activity Data Categories	Information Needed
Intermediate processing activities	Coagulation, acidification, cutting, washing, draining, freezing, packaging, homogenizing, etc.
Allocation information	Mass, economic value

(Table 13.0) Activity data necessary to utilize the Average-Data method for quantifying Scope 3: Processing of Sold Products in the downstream supply chain

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Scope 3: Processing of Sold Products

4

Data Collection Guidance: Reporting processors may refer to purchasing records, internal data systems, and industry-average data from associations or databases to accurately identify the mass of dairy products sold to its intermediate suppliers.

Once the reporting processor has collected relevant information on the processes involved in further processing for every sold product, it should seek the appropriate emission factors that coincide with each process. Reporting processors may consult a variety of resources that publish robust emission factors relevant to intermediate product processing activities. Some of these resources include:

- U.S.-specific GHG emission analysis for fluid milk processing plants[4]
- Life cycle databases
- The GHG Protocol website
- Companies or manufacturers
- Industry associations
- Environmental organizations such as the EPA, IPCC, or the Climate Registry

From here, quantifying emissions from Scope 3: Processing of Sold Products is calculated by the equation below:

Intermediate Process Emissions
Mass of sold milk to intermediate processor **X** Emission factor for processing activity (kg CO_2e/kg FPCM)

The reporting processor should execute this calculation for every shipment of milk that endures a different intermediate process, making sure to apply the correct emission factor for each intermediate process and factoring in the correct mass of milk that undergoes said processes. Once done, the reporting processor may aggregate emissions from all intermediate processes germane to its downstream supply chain to arrive at its total Scope 3: Processing of Sold Products footprint.

Scope 3: Processing of Sold Products Emissions
((Intermediate Process 1 Emissions) (kg CO_2e **+** (Intermediate Process 2 Emissions) (kg CO_2e) **+** .....)

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Appendix: This category is not a priority in the U.S. dairy value chain, but is recommended for a comprehensive Scope 3 inventory.

Scope 3: Use of Sold Products

Chapter at a Glance

- Defining Sold Products
- Identifying Sources
- Collecting Activity Data
- Data Collection Guidance
- Calculation Approach

This section provides guidance on how to account for and calculate Scope 3 indirect GHG emissions from the use and consumption phase of sold milk and other dairy products by end consumers.

While this section is not a priority in U.S. dairy GHG accounting, reporting processors should include it to compose the most comprehensive Scope 3 inventory (account for prioritized sections first).

1

Defining Use of Sold Products: For U.S. dairy, the use of sold products is relatively easy to define, as fluid milk does not directly produce GHG emissions in its use phase. The GHG Protocol's Corporate Value Chain Standard requires that direct-use phase emissions are accounted for in this category, while indirect-use phase emissions are optional to report.

2

Identifying Sources: For fluid milk specifically, indirect-use phase emissions come from refrigerating the milk in the consumers' homes or businesses between point-of-purchase and complete consumption. Additionally, other dairy products such as cheese may produce indirect-use phase emissions if they are cooked, which demands fuel and/or electricity.

Measuring indirect-use phase emissions is often difficult. For this category, follow and adopt the methodology in Table 14.0.

GHG Emission Sources from Dairy Use Phase

Use Phase Activity	Emissions Source
Refrigeration	Electricity Consumption
	Refrigerant Leakage
Cooking	Fuel Consumption
	Electricity Consumption

(Table 14.0) Common emissions sources from the use of dairy products by the end consumer

3

Collecting Activity Data: The reporting processor should first create and/or obtain a typical use-phase profile based on the average lifetime that the dairy product is in the "use" phase and implement relevant emission factors.

Use Phase Activity Data Collection Guideline

Indirect Emissions Activity Data Category	Activity Data
Use Scenarios	Cooking (Roasting, Boiling, Microwaving, Frying)
Fuel Consumed	LNG, LPG, CNG, Propane (in therms, cubic feet, cubic meters)
Electricity Consumed	kWh
Refrigerant Leakage	HFCs, PFCs (in kg CO_2e)

(Table 14.1) Activity data to be collected to calculate indirect-use phase emissions from consumption of dairy

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Scope 3: Use of Sold Products

4

Data Collection Guidance: Developing a typical use-phase profile involves identifying the use phase scenarios (shown in table 14.1) for each product the reporting processor sells, and creating a weighted average based on each use scenario, length of use and quantity sold. Reporting processors may consult a variety of resources to obtain this information, such as:

- Industry recognized benchmark testing specifications
- Product category rules
- Previous emissions studies
- Consumer studies

5

Calculation Approach: Reporting processors can quantify their Scope 3: Use of Sold Products footprint using the calculation on page 39.

The calculation represents how to account for and quantify use phase emissions from dairy. For fluid milk, the only necessary equations to be included in the calculations are the Refrigerant Leakage and Refrigerator equations. If the reporting processor sells dairy products that are often cooked, such as cheese, all the equations may need to be utilized in order to quantify an accurate and fully-encompassing account of Scope 3: Use of Sold Products inventory. Calculate emissions from each equation for each product sold, then aggregate all emissions from each equation to arrive at a total Scope 3: Use of Sold Products account.

Reporting processors may consult a variety of resources that publish robust emission factors relevant to stationary combustion and refrigerating activities. Some of these resources include:

- Life cycle databases
- The GHG Protocol
- Companies or manufacturers
- Industry associations
- Environmental organizations such as the EPA, IPCC, or the Climate Registry

For the reporting processor's convenience, the GHG Protocol Stationary Combustion Excel Tool with relevant emission factors for various fuels and electricity is linked. Furthermore, the GHG Protocol Refrigerant Emissions Calculation Excel Tool is linked.

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Scope 3: Use of Sold Products

5

Calculating Scope 3: Use of Sold Products Footprint

Gas Stove Baking Equation

Σ (Total Lifetime Expected Uses of Product (i.e., meals cooked) **X** % of Total Lifetime Uses Using Gas Stove for Baking **X** Quantity Sold (lbs, kg) **X** Fuel Consumed per Use in this Scenario (therms, cubic meters, cubic feet) **X** Emission Factor for Fuel (kg CO_2e/fuel unit)

PLUS (+)

Gas Stove Burner Equation

Σ (Total Lifetime Expected Uses of Product (i.e., meals cooked) **X** % of Total Lifetime Uses Using Gas Burner **X** Quantity Sold (lbs, kg) **X** Fuel Consumed per Use in this Scenario (therms, cubic meters, cubic feet) **X** Emission Factor for Fuel (kg CO_2e/fuel unit)

PLUS (+)

Electric Stove Equation

Σ (Total Lifetime Expected Uses of Product (i.e., meals cooked) **X** % of Total Lifetime Uses Using Electric Oven/Burners **X** Quantity Sold (lbs, kg) **X** Electricity Consumed per Use in this Scenario (kWh) **X** Emission Factor for Electricity (kg CO_2e/kWh)

PLUS (+)

Microwave Equation

Σ (Total Lifetime Expected Uses of Product (i.e., meals cooked) **X** % of Total Lifetime Uses Using Microwave **X** Quantity Sold (lbs, kg) **X** Electricity Consumed per Use in this Scenario (kWh) **X** Emission Factor for Electricity (kg CO_2e/kWh)

PLUS (+)

Refrigerant Leakage Equation

Σ (Total Lifetime Expected Uses of Product (i.e., meals cooked) **X** % of Total Lifetime in Refrigerator **X** Quantity Sold (lbs, kg, gallons) **X** Refrigerant Leakage per Use in this Scenario (kg) **X** Emission Factor for Refrigerant (kg CO_2e/kg)

PLUS (+)

Refrigerator Equation

Σ (Total Lifetime Expected Uses of Product (i.e., meals cooked) **X** % of Total Lifetime Uses in Leaking Refrigerator **X** Quantity Sold (lbs, kg, gallons) **X** Electricity Consumed per Use in this Scenario (kWh) **X** Emission Factor for Electricity (kg CO_2e/kWh)

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Appendix: This category is not a priority in the U.S. dairy value chain, but is recommended for a comprehensive Scope 3 inventory.

Scope 3: End-of-Life Treatment of Sold Products

Chapter at a Glance

- Defining End-of-Life
- Identifying Sources
- Collecting Activity Data
- Data Collection Guidance
- Calculation Approach

This section provides guidance on how to account for and calculate Scope 3 indirect GHG emissions from the end-of-life waste disposal and treatment of sold dairy products by the reporting processor.

While this section is not a priority in U.S. dairy GHG accounting, reporting processors should include it to compose the most comprehensive Scope 3 inventory (account for prioritized sections first).

1

Defining End-of-Life Treatment of Sold Products: This category captures GHG emissions associated with waste, much like Scope 3: Waste Generated in Operations. However, the key difference in this category is that it accounts for GHG emissions deriving from end-of-life waste disposal and treatment of dairy products sold by the reporting processor (in the reporting period). Like Scope 3: Waste Generated in Operations, this category accounts for emissions from biomass materials, and therefore CO_2 emissions must be accounted for outside any of the three scopes in a separate memo item. Methane and nitrous oxide emissions, however, are still accounted for within the scopes for this category. Rather than using the sheer volume of waste produced during dairy processing to quantify emissions, reporting processors should use the mass of product sold (including packaging).

Obtaining accurate and quality data on the proportions and distribution of waste management activities associated with sold products is often difficult for reporting processors. This category requires the reporting processor to disclose assumptions on its sold product lifetimes, as well as waste treatment methods.

2

Identifying Sources: Almost all dairy products sold on the U.S. market are packaged in recyclable materials. Recycling's emission factor is 0.0 kg CO_2e/kg since all the material re-enters the supply stream. Therefore, reporting processors should try to formulate the most accurate assumptions on what quantities of its sold products and/or packaging material do not actually get recycled but rather go to landfill, or incineration. In addition, dairy products are consumable, so waste from dairy processors in this category is likely to be much lower than the actual mass of products and packaging sold. As a result, reporting processors should consult industry average data on the proportion of sold products that get wasted (not consumed, and/or recycled).

Source: Journal of Food and Dairy Technology

Common Packaging Methods in U.S. Dairy

Packaging Material	Dairy Products	Recyclable?
Plastic Based	Fluid milk, butter, cheese, ghee, whipped cream	Most
Glass Based	Fluid milk, ghee	Yes
Paper Based	Fluid milk, ice cream	Yes
Metal Based	Cheese spread, milk powder, ghee, whipped cream	Yes
Flexible Film Based	Cheese	In specific markets

(Table 15.0) Common U.S. dairy packaging materials and their recyclability[6]

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Scope 3: End-of-Life Treatment of Sold Products

3

Collecting Activity Data: As mentioned above, reporting processors should use the mass of product sold in the reporting year to quantify emissions in this category. Furthermore, reporting processors should collect information on the distribution of their sold products in different waste management methods.

Activity Data Needed for Calculating Scope 3: End-of-Life Treatment of Sold Products	
Activity Data	Examples
Mass of sold dairy products (including packaging of individual consumable products, and packaging used to transport individual products)	Plastic milk cartons, cardboard boxes, glass jugs, paperboard milk cartons, metal cans, cellophane wrapping
Proportion of sold materials in different waste streams	% recycled, % landfilled, % incinerated

(Table 15.1) Relevant activity data necessary for Scope 3: End-of-Life Treatment of Sold Products accounting

4

Data Collection Guidance: Although collecting accurate data on dairy waste streams after products are sold may be difficult, many resources exist to assist with this procedure. Several are included below:

- Specific government directives on waste treatment (for the U.S.: Facts and Figures about Materials, Waste and Recycling)[6]
- Industry associations that have conducted research into consumer disposal habits (if applicable)
- Average data on waste treatment from reporting processor's point-of-sale through end-of-life treatment

5

Calculation Approach: Much like Scope 3: Waste Generated in Operations, this category employs the Waste-Type-Specific method to calculate GHG emissions from the reporting processor's sold products and packaging. The appropriate equation is included below for reference. Reporting processors should ensure that they use an accurate and robust emission factor for each waste treatment method applicable to their supply chain. Resources such as the EPA's Documentation for Greenhouse Gas Emission and Energy Factors Used in the Waste Reduction Model include emission factor data for this category's emission calculations.

Scope 3: End-of-Life Treatment of Sold Products Footprint

Mass of Sold Products and Packaging (kg) **X** % Recycled Waste **X** Recycling Emission Factor (kg CO_2e/kg)

PLUS (+)

Mass of Sold Products and Packaging (kg) **X** % Landfilled Waste **X** Landfill Emission Factor (kg CO_2e/kg)

PLUS (+)

Mass of Sold Products and Packaging (kg) **X** % of Incinerated Waste **X** Incineration Emission Factor (kg CO_2e/kg)

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Appendix: This category is not a priority in the U.S. dairy value chain, but is recommended for a comprehensive Scope 3 inventory.

Scope 3: Franchises

Chapter at a Glance

- Defining Franchises
- Identifying Sources
- Collecting Activity Data
- Data Collection Guidance
- Calculation Approach

This section provides guidance on how to account for and calculate Scope 3 indirect GHG emissions from the operation of franchises down the reporting processor's value chain.

While this section is not a priority in U.S. dairy GHG accounting, reporting processors should include it to compose the most comprehensive Scope 3 inventory (account for prioritized sections first).

1

Defining Franchises: Franchises, although a very common business model, are not often implemented in the U.S. dairy processing industry. However, on the off-chance that a reporting processor owns a franchise network, this category accounts for the GHG emissions generated from the operation of said franchise(s). The GHG Protocol Corporate Value Chain Accounting and Reporting Standard defines franchises as businesses "operating under a license to sell or distribute another company's goods or services within a certain location."[1] The Scope 1 and Scope 2 GHG emissions from these franchise locations that sell or distribute a reporting processor's dairy products are equivalent to the Scope 3 emissions accounted for in this category.

2

Identifying Sources: As briefly described above, Scope 3 GHG emission sources in this category arise from the operation of franchises downstream from the reporting processor. Collecting and accounting for Scope 1 and 2 GHG emissions at each and every franchise location will translate into a comprehensive Scope 3: Franchises inventory.

3

Collecting Activity Data: This guidance recommends using the Franchise-Specific method for collecting activity data, which requires the reporting processor to collect Scope 1 and 2 data specific to each and every franchise operating under its label. If franchisees have conducted a Scope 1 and 2 inventory, then simply applying the inventory to this category accomplishes this data collection strategy. However, if no such inventory exists, reporting processors should aim to collect activity data similar to the Scope 1 and 2 data collected in the Scope 3: Upstream/Downstream Leased Assets categories.

If the reporting processor is unable to obtain the fuel and energy data associated with each franchise, other methods of accounting for Scope 3: Franchises emissions can be found in the GHG Protocol Technical Guidance for Calculating Scope 3 Emissions.

Table 16.0 (below) includes applicable activity data.

GHG Emission Sources from Franchises	
Emission Source	Scope
Fuel consumed, refrigerant leaked, process emissions	Scope 1
Electricity consumed, steam consumed, heat consumed, cooling consumed	Scope 2

(Table 16.0) Scope 1 and 2 GHG emission sources from franchises

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Scope 3: Franchises

4

Data Collection Guidance: Much like Scope 1 and 2 accounting, the necessary activity data for this category can be collected via many different methods:

- Utility bills
- Purchase records
- Meter readings
- Internal IT systems

Appropriate emission factors are available from an array of different sources as well, such as:

- The EPA GHG Emissions Factors Hub
- Life cycle databases
- Other government agencies such as the IPCC, and Climate Registry
- Industry associations
- Company-developed factors if applicable

5

Calculation Approach: The following equation represents the appropriate methodology for calculating Scope 3: Franchises using the Franchise-Specific method and is the same methodology for Scope 3: Upstream/ Downstream Leased Assets:

Calculating Scope 3: Franchises Using the Franchise-Specific Method

Scope 1 Emissions from Franchise

(Fuel Consumed **X** Fuel Emission Factor (kg CO_2e/fuel unit)) **+** (Refrigerant Leakage (kg) **X** Refrigerant Emission Factor (kg CO_2e/kg))

PLUS (+)

Scope 2 Emissions from Franchise

(Electricity, Steam, Heating, Cooling Consumed (kWh)) **X** (Electricity, Steam, Heating, Cooling Emission Factor (kg CO_2e/kWh))

EQUALS (=)

Scope 3 Emissions from Franchise

Scope 3: Franchises Inventory **=** Σ Scope 3 Emissions from All Franchises

Reporting processors may use the GHG Emissions from Purchased Electricity, GHG Emissions from Stationary Combustion, and Refrigeration and Air-Conditioning Equipment Excel tools as resources to assist in quantifying emissions in this category. They have built-in GHG Protocol emission factors to streamline GHG emissions from fuel, electricity, steam, heat, cooling and refrigeration.

If the franchise company only operates in a section or portion of the facility, and the facility lacks sub-metering infrastructure, then energy consumption may be allocated using an estimation based on the share of space the company leases (based on floor space). This may be calculated using the following equation:

Equation for Section or Portion Operation

Franchise-Used Space (m^2) **/** (Building's Total Area (m^2) **X** Building Occupancy Rate) **X** Total Building Energy Use (kWh)

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Appendix: This category is not a priority in the U.S. dairy value chain, but is recommended for a comprehensive Scope 3 inventory.

Scope 3: Investments

Chapter at a Glance

- Defining Investments
- Identifying Sources
- Collecting Activity Data
- Data Collection Guidance
- Calculation Approach

This section provides guidance on how to account for and calculate Scope 3 indirect GHG emissions from the reporting processor's investments in the reporting period.

While this section is not a priority in U.S. dairy GHG accounting, reporting processors should include it to compose the most comprehensive Scope 3 inventory (account for prioritized sections first).

1

Defining Investments: This category mainly applies to financial institutions and profit-driven investment companies. However, Scope 3: Investments may apply to a dairy processor/cooperative if it has joint financial control of another company, and/or directly influences subsidiaries and associate companies. Again, depending on the reporting processor's organizational boundary, GHG emissions may be accounted for in Scope 1 or 2. More specifically, if the reporting processor uses the equity share approach in its IMP, the GHG emissions from investments would then be equivalent to the share of investment it has in the investee under Scope 1 and 2. However, if using a control approach, emissions are categorized in Scope 3, as the reporting processor does not operate the investment company.

In this regard, the Scope 1 and 2 emissions from each and every investee operation are equivalent to the reporting processor's Scope 3: Investment emissions.

2

Identifying Sources: As briefly described above, Scope 3 GHG emission sources in this category arise from investee operations downstream from the reporting processor. Collecting and accounting for Scope 1 and 2 GHG emissions at each and every investee operation will translate into a comprehensive Scope 3: Investments inventory.

3

Collecting Activity Data: This guidance recommends using the Investment-Specific method for collecting activity data, which requires the reporting processor to collect Scope 1 and 2 data specific to each and every investee operation/company. If investee companies have conducted a Scope 1 and 2 inventory, then simply applying the inventory to this category accomplishes the data collection strategy. However, if no such inventory exists, reporting processors should apply the Average-Data method to fill in the gaps. This involves applying revenue data from the investee company, and combining it with Environmental Extended Input-Output data (from applicable life cycle databases, such as those listed on the GHG Protocol website) to estimate Scope 1 and 2 emissions.

For both methods, reporting processors should account for their proportion of emissions from the investee company based on their share of investment. For example, if a reporting processor has a 30 percent share of equity in a company, then the correct allocation of emissions from this investee company would equal its Scope 1 and 2 emissions multiplied by 0.30. Table 17.0 (page 45) includes applicable activity data.

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continued on next page

Scope 3: Investments

3

GHG Emission Sources from Investments	
Emission Source	Scope
Fuel consumed, refrigerant leaked, process emissions	Scope 1
Electricity consumed, steam consumed, heat consumed, cooling consumed	Scope 2

(Table 17.0) Scope 1 and 2 GHG emission sources from Investments

4

Data Collection Guidance: In addition to the appropriate EEIO data for estimating average emissions, reporting processors should consult their financial records, and/or GHG inventory reports of investee companies for the Investment-Specific method, if they exist.

If the reporting processor is able to obtain relevant GHG inventories from investee companies, no emission factors should be necessary, as the investee companies have already calculated their Scope 1 and Scope 2 inventories.

However, if the Average-Data method is employed, the reporting processor should disaggregate the EEIO emission factor, similar to Scope 3: Capital Goods. This allows for the reporting processor to account for only Scope 1 and 2 GHG emissions from the investee company, as opposed to all three scopes. This disaggregation process can often be arduous and, potentially, impossible. If so, the reporting processor may use the full EEIO factor as long as this information is transparently disclosed.

5

Calculation Approach: If utilizing the Investment-Specific method, the reporting processor's Scope 3: Investments inventory from this approach is simply the aggregate of all the investee company's Scope 1 and 2 inventories multiplied by its equity share in each company.

Investment-Specific Method

Scope 3: Investments Inventory = Σ (Scope 1 and 2 Inventories of Investee Company X % Equity Share)

If utilizing the Average-Data method, the reporting processor's Scope 3: Investments inventory from this approach is the investee company's revenue multiplied by the corresponding emission factor for its sector. The quantity is then multiplied by the equity share in the investee company. Sum across all investee companies that employ this method to find the aggregated Scope 3: Investments inventory via the Average-Data method.

Average-Data Method

Scope 3: Investments Inventory = Σ ((Investee Company Revenue ($) X Investee Sector Emission Factor (kg CO_2e/$ Rev.)) X Equity Share (%))

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Works Cited

1. Corporate Value Chain (Scope 3) Accounting and Reporting Standard. (n.d.). Retrieved August/September, 2018, from https://ghgprotocol.org/sites/default/files/standards/Corporate-Value-Chain-Accounting-Reporing-Standard_041613_2.pdf
2. Greenhouse Gas Emissions from the Dairy Sector - A Life Cycle Assessment (Rep.). (n.d.). Food and Agriculture Organization of the United Nations, Animal Production and Health Division. https://www.fao.org/4/k7930e/k7930e00.pdf
3. "Management of Waste From Animal Product Processing." FAO Corporate Document Repository, Food and Agriculture Organization.
4. Nutter, Darin W, et al. "Greenhouse Gas Emission Analysis for USA Fluid Milk Processing Plants: Processing, Packaging, and Distribution." International Dairy Journal, vol. 31, no. 1, Apr. 2013, doi: https://doi.org/10.1016/j.idairyj.2012.09.011
5. "EPA Center for Corporate Climate Leadership." EPA, Environmental Protection Agency, 25 Aug. 2017, www.epa.gov/climateleadership
6. "Facts and Figures about Materials, Waste and Recycling." EPA, Environmental Protection Agency, 1 Aug. 2018, www.epa.gov/facts-and-figures-about-materials-waste-and-recycling
7. Thoma et al., "Greenhouse Gas Emissions of Fluid Milk in the U.S." University of Arkansas, 2010, http://bit.ly/2a9Md64

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Additional Resources

- WWF Climate Savers
- Climate Registry
- Pew Business Environmental Leadership Council
- Carbon Trust
- NASA's Goddard Institute for Space Studies
- Carbon Budget
- 2018 Carbon Budget Report
- U.S. EIA Energy Atlas
- The Impact of Corporate Sustainability on Organizational Process and Performance: The Harvard Business Journal, Robert G. Eccles, Ioannis Ioannou & George Serafeim

Resources for Setting Science Based Targets

- Introduction to Science Based Targets
- Call to Action: Detailed Guidelines for Setting Science Based Targets
- Science Based Targets and CDP Scoring
- Best Practices for Setting and Achieving Science Based Targets: Presentation at the Climate Leaders Conference, March 2017.
- Science Based Targets: Target setting pitfalls and lessons learned (pdf)
- Science Based Targets: Target setting pitfalls and lessons learned (webinar)
- Science Based Targets: Forest, Land and Agriculture (FLAG) Sector Guidance

Resources for Reducing GHG Emissions

Once a GHG emissions inventory has been developed and a reduction target has been adopted, a company should identify the main sources of GHGs and evaluate the cost-effectiveness of emission reduction measures. Below are resources, tools and webinars to assist companies in reducing GHG emissions.

Energy Efficiency

- EPA, Energy Star. 2011. Energy Efficiency Improvement and Cost Saving Opportunities for the Dairy Processing Industry: A manual created by Energy Star to assist dairy processors in identifying energy efficiency improvements as an important way to reduce costs and to increase predictable earnings
- EPA, Energy Star Portfolio Manager. An online tool that can be used to measure and track energy and water consumption, as well as greenhouse gas emissions associated with commercial buildings
- HVAC (heating, ventilation and air conditioning), Climate Corps Handbook Chapter 9. Overview of how to survey current HVAC system, analyze results of an energy audit for HVAC system and perform a financial analysis on recommendations of energy auditors
- Carbon Trust: Heating, ventilation and air conditioning (HVAC) energy efficiency guide. A guide to improve energy efficiency of heating, ventilation and air conditioning, hot water and boilers
- Lighting in commercial buildings, Climate Corps Handbook, Chapter 10. Describes how to identify lighting opportunities for energy savings in commercial buildings and how to develop estimates of energy usage and calculate the estimated savings potential
- Demand Response and Smart Grid, Climate Corps Handbook, Chapter 16. Overview of demand response (DR) and possible energy savings and revenue opportunities

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Additional Resources

- Demand and Response Research Center. Publications and information on demand response and smart grid infrastructure to best inform end users how to temporarily reduce energy usage in response to either price or system reliability triggers
- Carbon Trust Energy Management Self-Assessment Tool. An Excel workbook and guidance document that assesses an organization's energy management
- Carbon Value Analysis Tool. The Carbon Value Analysis Tool (CVAT) was created by the World Resource Institute to assist project managers with factoring the price of carbon when evaluating reduction projects
- Carbon Trust, Buildings Energy Efficiency. Guide to improving building fabric and insulation and installing appropriate controls to save money and cut carbon emissions
- Carbon Trust, Refrigeration: Improve energy efficiency of your chillers and refrigeration systems with our energy-saving guidance
- EPA Center for Corporate Climate Leadership. A list of free GHG inventory-related webinars and events

Renewable Energy

- The Department of Energy's Office of Energy Efficiency and Renewable Energy (EERE). Provides information on industrial energy-consuming systems; boiler and steam system, compressed air, motors, fans, pumps and process heating
- Property Assessed Clean Energy (PACE). Energy efficiency financing opportunities
- Database of State Incentives for Renewables and Efficiency. Overview of state and federal incentives and policies designed to help companies adopt renewable energy programs
- Guide to Purchasing Green Power. A cooperative effort between the EPA, the U.S. Department of Energy, the World Resources Institute and the Center for Resource Solutions that provides current and potential buyers of green power with information about green power purchasing
- Innovations in Voluntary Renewable Energy Procurement. A guide from National Renewable Energy Laboratory's (NREL) that outlines methods for expanding access and lowering costs for communities, governments and businesses

Mobile Emissions

- Reduce Mobile Emissions, Vehicle selection. ACEEE Greener Cars Identify vehicles that are most fuel-efficient and learn about market trends in automotive technology
- EPA Green Vehicle Guide. Overview of vehicles, fuel use and the impact on both the environment and bottom line
- Fuel Economy Guide, The U.S. Environmental Protection Agency (EPA) and U.S. Department of Energy (DOE). A guide to help buyers identify the most fuel-efficient vehicles

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Food and Agriculture Organization of the United Nations



VERSION 1

Global database of GHG emissions related to feed crops

Methodology

LIVESTOCK ENVIRONMENTAL ASSESSMENT AND PERFORMANCE PARTNERSHIP

VERSION 1

Global database of GHG emissions related to feed crops

Methodology

FOOD AND AGRICULTURE ORGANIZATION OF THE UNITED NATIONS and
Rome, 2017

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1. Introduction

1.1 GOAL AND OBJECTIVES

The wider context for this study is to ensure that benchmarking of livestock supply chains is based on internationally recognized and harmonized methodology and datasets. The overall goal of this assessment is to develop a robust life cycle inventory (LCI) and emission intensity database. Specific objectives were to establish a global database of emission intensities for major feed crops disaggregated by production practices and country as well as provide a consolidated database of life cycle inventories to support continued benchmarking of livestock supply chains.

1.2 SCOPE OF THE STUDY

The main focus is on the quantification of greenhouse gas emissions arising from the **cultivation phase** in crop production. The study focuses on 5 main crops: **maize, wheat, barley, cassava and soybean**. The assessment covers the major GHG emissions: CO_2, N_2O and CH_4 and includes all major processes from raw material production through to on-farm cultivation to the field-gate. In addition, the analysis incorporates carbon stock changes associated with land-use change. Results from this analysis are presented in a database which provides information on the life cycle inventory per crop and the emission intensities associated with the cultivation of the crop. Users are able to query the database to access aggregate information on emission intensities per crop disaggregated by production system and country.

1.3 INTENDED APPLICATION

Emissions attributed to feed production are required to compute any life cycle assessment (LCA) of livestock supply chains. There is however no global dataset on emissions related to feed ingredients available to the practitioners and available data is generally of limited geographical relevance. This database is intended to support benchmarking and evaluation of livestock supply chains.

1.4 OUTLINE OF THE REPORT

This report presents the information on the background to the study, the approach and methodology applied. It also presents and discusses the results from the analysis of GHG emissions. An accompanying document "*A life cycle inventory for wheat, maize, barley, soybean and cassava*" provides more detailed information on the life cycle inventory (LCI).

Section 2 and 3 of this report presents a brief overview of the global feed sector and crop production practices, respectively. Section 4 provides an overview of the approach and methodology applied in the assessment of GHG emissions for the five crops. This information is supplemented by an accompanying document that presents background information on the life cycle inventories of the crops. Section 5 and 6 presents an initial discussion on uncertainty and key challenges and future work that will be undertaken.

2. The Global Feed Sector

The future for farming and agriculture holds many challenges, not least the continued efforts to optimize resource use and reduce greenhouse gas (GHG) emissions. This needs to be set against the urgent and growing need to improve productivity to meet the anticipated requirements to provide more food, feed and fuel, for a growing global population. These challenges are and will increasingly be influenced by the availability and price of resources as well as by policies set to meet carbon emissions targets and other sustainability requirements.

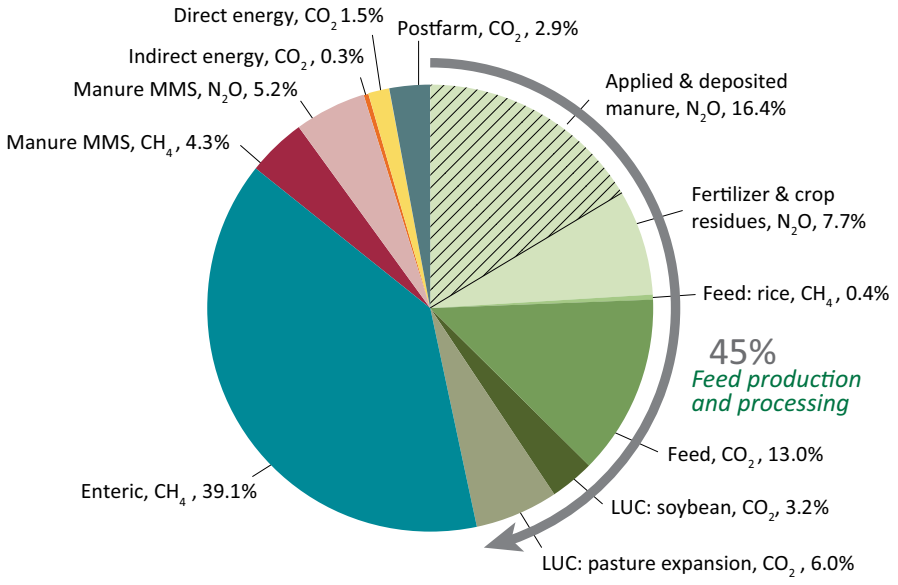
The animal feed industry plays an important role in the global supply of food, enabling production of animal protein throughout the world. Feed is the largest and most important component to ensuring safe, abundant and affordable supply of animal protein. At the same time, producing feed for livestock production is resource demanding: it occupies one-third of the world's ice-free surface and consumes 8% of global human water use, mainly for the irrigation of feed crops (FAO, 2006). The area dedicated to feed-crop production represents 33 percent of total arable land.

Feed production demands high energy inputs and chemicals, land and water resources — all of which are becoming increasingly scarce. Resource scarcity, on-going global warming and frequent and drastic climatic vagaries, increased competition for resources (land, energy, water and nutrients), coupled with increasing resource prices will further pose a greater challenge to the sustainability of food and feed production systems. Similarly, Increase in the use of food crops for animal feeds and for biofuel production could have serious implications for food security.

In 2005, the livestock sector consumed 6.3 billion tons of feed biomass. Feed use differs considerably depending on the region, livestock production systems and species; most feed-grain (69 percent) is fed to pigs and poultry in regions where industrial, intensive systems dominate production (W. Europe, North America, East Asia, and Central and South America). The rest is used for dairy production in mixed systems globally and for feedlot operations, notably in North America, Western Europe and Central and South America. A preliminary assessment identified maize, wheat, barley, soybean and cassava as major crops utilized for animal feed.

Globally, feed production, processing and transport contributed about 3.2 Gt CO_2 eq.; accounting for about 45 percent of the sector's emissions (Figure 1, Gerber *et al.*, 2013). The main source of GHG emissions in most livestock supply chains is feed production (de Vries and de Boer, 2010). Dominant GHGs emitted during feed production include carbon dioxide and nitrous oxide and to a lesser extent, methane (Duxbury, 1994; Herrero *et al.*, 2009).

Figure 1
Contribution of feed production
and processing to GHG emissions from livestock



Source: GLEAM, 2013

Cropping systems belong to complex production systems due to their dependence on environmental conditions that are variable in time (e.g. within a year, from year to year) and in space (e.g. varies by country, region, local site conditions). In addition, the correlation between inputs (such as fertilizers, pesticides, etc.) to outputs (of harvested crop, gaseous field emissions, leachate, etc.) is complex and often non-linear in nature. Because of the high contribution of feed production to GHG emissions and the large variability in production systems, a robust and sound assessment of emissions is important.

3. Crop Management Practices

Maximizing productive output in crop production has been achieved through the use of heavy farm equipment and machinery powered by fossil fuel, intensive tillage, high-yielding crop varieties, irrigation, manufactured inputs, and ever increasing capital intensity. Changing land-use practices, technological advancement and varietal improvement have enabled world grain harvests to double from 1.2 to 2.5 billion tonnes per year between 1970 and 2010 (FAOSTAT, 2015). Average world cereal yields increased from 1602 kg/ha to 3034 kg/ha over the same period (FAOSTAT, 2015) while there has also been a 233% increase in global fertilizer use from 31.8 to 105.9 Mt/yr, and a 73% increase in the irrigated cropland area (FAOSTAT, 2015).

It is now recognized that these enormous gains in agricultural production and productivity are often accompanied by localized negative effects on the natural resource base such as land degradation, salinization of irrigated areas, over-extraction of groundwater, the build-up of pest resistance and the erosion of biodiversity. Agriculture also has negative global environmental impacts through, for example, deforestation, emissions of greenhouse gases and nitrate pollution of water bodies.

Crops are grown under a wide range of production systems. Crop production, encompasses a series of processes ranging from land preparation through planting to the produce/product reaching the farm-gate. Sections below provide brief description of activities in cropping systems.

TILLAGE PRACTICES

Tillage is a fundamental practice in agricultural management. It can be defined as a method of 'working' the soil either physically, chemically, mechanically or biologically to create suitable conditions for seedling germination, establishment and growth (FAO, 2011). Tillage involves preparing soil for planting or seeding by ploughing, cultivating or otherwise turning it. Tillage loosens and aerates the soil, which allows for the deeper penetration of roots. It controls weeds and mixes organic matter, fertilizer and manure with the soil.

Generally, there are two types of tillage systems i.e. **conventional, and conservation tillage system**.

A *conventional tillage practice* refers to use of a mouldboard or animal drawn plough to incorporate residue into the soil by extensive tillage. It is two types i.e. mechanized, and traditional systems. Traditional tillage system is mainly practiced in many developing regions and is carried out by manual labour using native tools e.g., the hoe or cutlass. In mechanized system, mechanical soil manipulation is done by ploughing through one or more harrowing. Conventional tillage embraces not only primary cultivation practices, based on ploughing or soil inversion, but also secondary operations directed at land preparation and sowing or planting. Typically, this involves ploughing (soil inversion), followed by one or two harrowing events to produce a suitable layer for plant establishment, as well as the removal of most of the plant residues derived from the previous crop. Once crops are planted, a cultivator is used, often several times, to keep the weeds down (Abdulla *et al.* 2013).

Thus, in the process the soil was tilled repeatedly at great cost in terms of time and energy.

Conservation tillage systems, in contrast, are primarily based on reducing soil disturbance by restricting any land preparation activities to a shallow depth and eliminating soil inversion, while conserving and managing crop residues (Cunningham *et al.*, 2004). Globally, conservation tillage is practiced on approximately 144 million hectares, predominantly in North and South America (FAO Conservation Tillage database, 2015). Globally, different conservation tillage systems have been developed and they include: non-inversion tillage, eco-tillage, minimum tillage, mulch tillage, reduced tillage, zone tillage or no-tillage. Conservation tillage aims to leave at least 30% of the previous crop residues remaining on the soil surface, whereas conventional tillage leaves less than 15%.

The cultivation of soils through ploughing is the most energy demanding process in the production of arable crops. The diesel fuel used contributes directly to CO_2 emissions along with that used in the manufacture of the machinery. Tillage also has a major influence on soil C emissions and is one of the principal agronomic activities thought to reduce soil organic carbon (SOC) stocks. For this reason, conservation tillage is becoming increasingly attractive to farmers because clearly reduces production cost relative to conventional tillage.

Seeding/sowing in both conventional and conservation tillage, seeding/sowing involves direct seeding into crop residue or directly in the soil**.** Seeding or sowing may be done mechanically or manually.

CROP NUTRITION

This involves the use of mineral or organic substances, natural or manufactured, that are applied to soil or irrigation water to supply plants with nutrients and supply elements that are essential for plant growth. Nitrogen (N), phosphorus (P), and potassium (K) are the primary major nutrients required for plant growth and are the main components of most fertilizers which are consumed in relatively large amounts. The use of fertilizer has been essential for crop production; mineral and organic fertilizers are applied to balance the gap between the nutrients required for optimal crop development and the nutrients supplied by the soil and by available organic sources (Bentrup, 2009). These chemicals are energy intensive to produce, create vast amounts of waste, and contribute to greenhouse gas emissions.

PLANT PROTECTION

Crop protection which includes the use of herbicides, insecticides, fungicides, as well as biotechnology products, helps control weed species, harmful insects and numerous plant diseases that afflict crops. The term pesticide is commonly used to refer to elements used in plant protection and covers a wide range of compounds including insecticides, fungicides, herbicides, rodenticides, molluscicides, nematicides, plant growth regulators and others. In the process of development of agriculture, pesticides have become an important tool as a plant protection agent for boosting food production. Improvements in the control of weedy competitors of crops and crop diseases can significantly increase yields. Pesticides are almost entirely produced from crude petroleum or natural gas products (West and Marland, 2002). Emissions from pesticides are therefore related to the energy input both from the material used as feedstock and the direct

energy inputs. Carbon dioxide emissions from production of pesticides consist of emissions from the manufacture the active ingredient, from the formulation of the active ingredients and those from packaging, transportation, and application of the pesticide formulation.

WEED MANAGEMENT

The occurrence of weeds in agricultural crops leads to substantial yield reductions causing economic losses all over the world. Weed management can be based on a combination of mechanical and chemical practices. Higher weeds generally occur where reduced tillage is practiced. This is because in traditional plough cultivation (conventional tillage) weed seeds are buried and often decay. As a result, conservation tillage systems generally rely more heavily on chemical weed control than conventional tillage systems.

IRRIGATION

Irrigation makes agriculture possible in areas previously unsuitable for intensive crop production. In large areas of the world irrigation significantly increases agricultural production, and many countries have significant fractions of irrigated cropland. About 20% of total arable cropland is under irrigation, producing about 40% of the global harvest (Sauer *et al.*, 2010). Yet, irrigation is a very carbon intensive practice. Sloggett (1979; 1992) estimated that 23% of the on-farm energy use for crop production in the US was for on-farm pumping. The energy required to pump water depends on numerous factors including total dynamic head (based on water lift, pipe friction, and system pressure), the water flow rate and the pumping system efficiency (Whiffen, 1991). The energy use depends on the water table depth or the lift height.

HARVESTING

Harvesting is the process of removal of entire plants or economic parts after crop maturity. The economic product may be grain, seed leaf, root or entire plant. The remaining portion of the stem that is left on the field after harvest is known as stubble. Crops maybe harvested by machine or by hand depending on the level of mechanization and the type of crop. Harvesting emissions are generated by different operations: crop handling by the harvest machine, loading of the harvested crop into trailers or trucks, and transport by trailers or trucks in the field.

4. Methodology

4.1 LIFE CYCLE ASSESSMENT (LCA) METHODOLOGY

Life Cycle Assessment (LCA) is an approach for the integrated assessment of environmental impacts along a life cycle of a product (Guinee *et al.*, 2002). Such an assessment may involve a wide range of environmental impacts such as climate change, eutrophication, acidification, etc.

In this study, the focus is on the assessment of the contribution of major feed crops to climate change. This study uses the LCA methodology described in the LEAP Feed Guidelines: "Environmental performance of animal feeds supply chains".

In this chapter, the methodology used for estimating the total emissions and emission intensities of GHGs resulting from cropping activities is described.

4.2 FUNCTIONAL UNIT

The functional unit in crop cultivation is 1 kg of dry matter (DM) product at harvest. For this study, the functional unit is taken as:

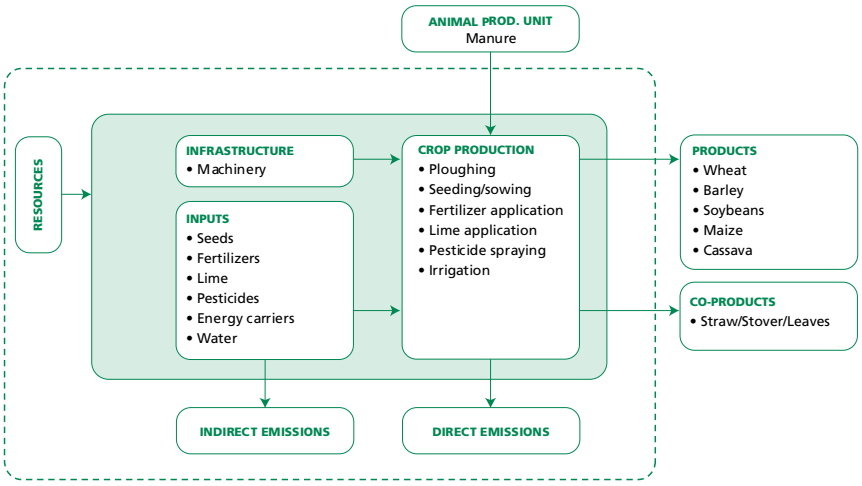
- 1 kg of wheat,
- 1 kg of maize,
- 1 kg of soybean,
- 1 kg of barley,
- 1 kg of cassava.

4.3 SYSTEM BOUNDARY

The system boundary defines the processes and input/output components that have been taken into account in the life cycle study. For this study, the system boundary extends from the extraction of raw materials, through the production and transport of inputs, to field cultivation and harvest of one kg of DM product (Figure 2).

Figure 2

Schematic representation of the system boundary considered in this assessment



Process included within the system boundary

The system defined in this life cycle study includes impacts associated with:

- The extraction, production and transport to the farm of fuel, fertilizers, agrochemicals (pesticides and lime) used in crop cultivation.
- Energy use on the farm for field operations/cultivation activities.
- Indirect/embedded energy in the production and maintenance of machinery and equipment.
- Soil emissions associated with the application of N fertilizers, agricultural lime and manure.
- Emissions from crop residue management.
- Emissions related to land use change.

Process excluded from the system boundary

A number of processes are excluded:

- Production of seed and young plant material due to lack of reliable data.
- The system excludes drying after harvesting due to the lack of reliable data on a global scale.
- Burning of crop residues.
- All processes in the production chain beyond the farm-gate.

Summary of assumptions and considerations

The estimation of GHG emissions from the 5 crops is based on several assumptions or considerations, some of which are suggested by the studies reviewed.

- Emissions associated with irrigation (pumping of water) were calculated only for groundwater. Energy used for on-farm surface water collection and distribution is assumed to be negligible (wang *et al.*, 2014; Daccache *et al.*, 2014; West and Marland, 2002).
- Crops were assumed to grow in monoculture due to insufficient data for determining typical crop rotation practices at a global scale.
- Seeding rates were assumed to be similar across the different tillage intensities (i.e. conventional, reduced and no-till) even though a few studies (Frye, 1984) noted that no-till crops may require up to 20% more seed to produce the same yield using conventional tillage.
- Countries for which the assessment is done for conservation tillage include: USA, Argentina, Paraguay, Brazil, Australia, Canada, Europe 27 and Kazakhstan. These countries represent 90 percent of the global land area under conservation tillage. Other countries with areas under conservation tillage where excluded from the assessment due to lack of sufficient data and the small area under conservation tillage. The rest of the countries were considered to practice conventional tillage only.

4.4 ALLOCATION OF GHG EMISSIONS

Agricultural production usually results in the generation of by-products or co-products, especially if farms have on-site product processing facilities. In addition, certain agricultural activities will contribute to multiple streams of products (and their co/by-products), especially on mixed farms. For instance, fertilizer application will support not only crop growth, but also livestock production, if some of the primary output (the crop) is used as livestock feed.

Allocation is the process of partitioning GHG emissions data from a farm to the different product streams from that farm. Crop production systems are multi-functional and generate multiple products. Typically, several different products and outputs are produced for different purposes and therefore, inputs and emissions need to be allocated between the various products.

This assessment was undertaken with the main objective of improving benchmarking of livestock supply chains by providing data to support such efforts. For this reason, no allocation between outputs is undertaken in this case. This should facilitate LCA practitioners interested in conducting their own assessment to do so in a transparent manner. LCA Practitioners should however refer to the LEAP Guidelines on Feed for rules on allocation between various outputs.

4.5 EMISSIONS FROM THE CULTIVATION OF CROPS

Crop production contributes to the emission of GHGs through disturbance of soil and vegetation carbon pools (e.g., ploughing/tillage and management of crop residues) and the emissions of other GHGs, but also through field or farm operations. (e.g., emissions from energy sources needed for tillage practices or in the application of organic amendments and chemicals).

A number of inputs are used for crop production e.g. fertilizers, pesticides, lime, water and fossil fuel energy. The production, formulation, storage, distribution of these inputs and their application with mechanized equipment lead to combustion of fossil fuel and use of energy from alternate sources, which also emits CO_2 and other greenhouse gases (GHGs) into the atmosphere. Fossil fuel CO_2 emissions on croplands are estimated to be responsible for 0.4-0.6 Gt CO_2 eq. per year in 2010 from agricultural use in machinery, such as tractors, irrigation pumps, etc. (AR5 IPCC, 2014). Emissions from energy use associated with crop production may be grouped into primary and secondary sources. Primary sources of emissions (direct) are either due to on-farm mobile operations (e.g., tillage, sowing, fertilization, harvesting and transport) or stationary operations (e.g., pumping water). Secondary sources of emissions (indirect) comprise of emissions from manufacturing, packaging and storage of synthetic fertilizers and pesticides and the production and maintenance of equipment, etc. The production of N fertilizer alone was estimated to release 410 Tg CO_2 eq. per year, which is equivalent to 0.8% of the global GHG emissions (Bentrup, 2009). Other inputs such as pesticides, phosphate and potassium fertilizers are not considered to produce GHG emissions during their use/application during the crop production phase.

Agricultural soils represent a very large, and growing global source of nitrous oxide. A major direct source of nitrous oxide from agricultural soils is from fertilizer use. Emissions from synthetic fertilizers grew at an average rate of 3.9% per year from 1961 to 2010, with absolute values increasing more than 9-fold, from 0.07 to 0.68 Gt CO_2 eq. per year (Tubiello *et al.*, 2013). Widespread increase in the use of nitrogen based fertilizers has been driven by the need for greater crop yields, and by more intensive farming practices. Similarly, the widespread and often poorly controlled use of animal manure as fertilizer can lead to substantial emissions of nitrous oxide from agricultural soils. Additional nitrous oxide arises from agricultural soils through crop residue management and the process of nitrogen fixation. Indirect agricultural sources of nitrous oxide remain poorly defined in most cases due to the high variability. There are several ways in which such indirect emissions occur.

The most important of these is nitrous oxide emission arising from volatilization, nitrogen leaching and run-off from agricultural soils.

A change in land use causes a change in carbon stocks aboveground and belowground. According to IPCC (2014), land use and changes in land use, principally those associated with deforestation and expansion of agricultural production for food, contribute about 9 – 11 % of total anthropogenic greenhouse gas emission (approximately 4.3 – 5.5 $GtCO_2$ eq. /year). Land-use change (LUC) occurs when land is converted to the production of crop from other uses or states, including non-feedstock agricultural lands, forests, and grasslands. This type of LUC is sometimes called direct LUC.

***Modelling Framework*:**

The emissions were calculated using the Global Livestock Environmental Assessment Model (GLEAM). GLEAM is a modelling framework that simulates the interaction of activities and processes involved in livestock production and the environment. The model is developed to assess livestock's impacts, adaptation and mitigation options at (sub)national, regional and global scale. GLEAM differentiates key stages along livestock supply chains such as feed production, processing and transport; on-farm herd management, animal feeding and manure management; and animal products processing and transport. The model captures the specific impacts of each stage, offering a comprehensive and disaggregated picture of livestock supply chains impacts and valuable information for intervention.

Subsequent sections present the methodology used in the estimation of GHG emissions.

4.6 CARBON DIOXIDE EMISSIONS FROM CROP PRODUCTION

Four sources discussed below relate to production of inputs, while the other 4 to management practices. Each of these is discussed in the subsequent sub-section.

4.6.1 CO_2 emissions from the production of energy for crop production

Use of energy (fossil fuels and electricity) in agriculture results in CO_2 emissions from the combustion, and there are additional emissions associated with production and delivery of fuels to the farm. This section deals with the latter category of emissions. In crop production, three main types of fuels for farm operations are used: diesel oil, natural gas, and electricity. Diesel oil is related to crop production activities and the operation of farm machinery used for various cropping activities. Natural gas and electricity are used more for other farm operations such as such as ground water abstraction, machine maintenance and crop drying. Carbon dioxide emissions attributable to electricity consumption are based on the fuels used in power generation and for each region, an emission factor reflecting the mean generation mix was estimated from the International Energy Agency (IEA) database. Emission factors for electricity generation applied in this assessment are provided in the life cycle inventory document.

4.6.2 CO_2 emissions from the production of synthetic fertilizer and lime

Greenhouse gas emissions associated with fertilizer production vary according to different processing technologies and energy sources (Wood and Cowie, 2004; Cherubini, 2010). This analysis includes emissions from three primary nutrients (N, P and K)

plus agricultural lime ($CaCO_3$). CO_2 emissions during the production of these inputs result from the energy required for production and transport. CO_2 emissions due to fertilizer application are dealt with separately in later calculations of energy use associated with the operation of farm machinery (Section 4.6.6). Nitrous oxide emissions arising from fertilizer application are dealt with separately in Section 3.6 of this report.

To calculate indirect emissions from the production and transportation of fertilizers and agricultural lime, average emission factors were taken from Kool *et al.* (2012) and multiplied by the national average application rate taken from IFA and FAOSTAT databases. Emission factors coefficients applied are provided in the life cycle inventory document.

Emissions were calculated as:

$$\textbf{Application rate} * \textbf{EF}_{\text{synthetic fertilizer}}$$

Where:

Application rate: synthetic fertilizer/ lime application rate per hectare, kg/ha

EF synthetic fertilizer: emission factor for production of synthetic fertilizer, (Kg CO_2 eq. /kg synthetic fertilizer)

Where no specific information on the application of agricultural lime was available, no estimates were made.

4.6.3 CO_2 emissions from production of pesticides

In order to control weeds, pests and diseases, farmers apply chemicals such as herbicides, fungicides, and insecticides to crops. GHG emissions are released during the manufacture of pesticides, which includes the formulation, packaging and transportation. Pesticides are input as the active ingredient application rate (kg a.i. per hectare). Estimation of emissions associated with pesticides is complex; energy consumption in pesticide production will depend on the composition and the manufacturing processes employed. There is also a wide range of energy used in producing different pesticides and significant changes over the years in the pesticide ingredients used.

Equivalent C emissions for pesticides were calculated using the EFs of 25.5 Kg CO_2 eq. /kg a.i. derived from Audley *et al.* (2009). Where data on the amount of active substance of pesticides applied, CO_2 eq. emissions were calculated by multiplying the EFs by the amount of active substance.

Emissions from the production of pesticides are derived as follows:

$$\textbf{Application rate} * \textbf{EF}_{\text{pesticides}}$$

Where:

Application rate: application rate of pesticides, kg a.i./ha

EF pesticides: emission factor for production of pesticides, Kg CO_2 eq. /kg a.i.

4.6.4 CO_2 emissions from the production, amortisation and maintenance of farm machinery and equipment

Greenhouse gas emissions from the use of machinery and equipment for crop production can be categorised into direct and indirect emissions. The direct emissions

are caused by the burning of fossil fuel during field operations and the indirect emissions arise from the manufacture of farm machinery, amortization and maintenance of the machines. This section presents the approach used for the estimation of indirect emissions.

Data on the machinery and equipment, used in each cropping system, degree of mechanization in each country per crop was gathered from literature. This data is presented in Annex 5 of the life cycle inventory document and are based on different data sources. Emissions caused by the manufacture, amortisation and maintenance of machinery were calculated using the approach to assess the indirect energy use from Nemecek and Kagi (2007).

4.6.5 CO_2 emissions from land use change

Soils are an important part of the carbon cycle and changes in soil carbon can influence GHG emissions. GHG emissions can result from soil carbon losses, caused by land use changes (LUC). Emissions from land use change were calculated for direct land use change for the approach 'weighted average' and 'worst-case scenario' based on the approach from PAS 2050-1:2012 as recommended in the LEAP Feed Guidelines. This approach is not crop-specific: the impacts from land use change are allocated to all crops, which increased in area harvested in a specific country, dependent on their respective share of area increase. According to PAS2050, these emissions are distributed over a time period of 20 years (1990-2010).

The approach uses statistical data from FAOSTAT for crop yields, harvested area of crops and area of forest and grassland, from FAO's global forest resource assessment for carbon stocks (in case former land use is unknown) (FAO 2010), and values of soil organic carbon stock and stock change factors (IPCC 2006). Changes in soil organic carbon stock are taken into account with that methodology. The emissions are reported separately as required by the LEAP guidelines. Emission factors are provided in Annex 6 of the LCI document.

4.6.6 CO_2 emissions from on-farm machinery use for field operations

Agricultural machinery can be employed in a number of field activities such as soil management, fertilization, harvesting, irrigation, etc. in this study, direct energy is only calculated for tractors, harvesters and irrigation. Other equipment is usually used in combination with tractors and consequently no direct energy emissions were estimated for these. On-farm emissions associated with the use of fossil fuel use for field operations will vary by cropping practice, scale of production, level of mechanization, type of machinery used and frequency of activity.

An extensive literature review was undertaken to collect information on the type and number of times the field operation is performed, the machinery used and the fuel consumption for each activity. Emission intensity estimates also takes into account the cropping system (conventional versus conservation tillage) as described in Section 2 of this document. The information is presented in Annex 5 of the accompanying document on life cycle inventory.

To estimate direct energy use and emissions from the use of machinery, the following equations based on Nemecek and Kagi (2007) were used:

(1) Diesel-use (a,b) kg/ha = frequency (a) * operation time (a) * MFC (a,b) * density (diesel)

Where:
Frequency (a) = the frequency of the activity a in the growing season
Operation time = the time required to do the activity a on one hectare (hour/ha)
MFC (a,b) = Mean Fuel Consumption, the characteristic fuel consumption for activity a with tractor b (liters/hour)
Density (diesel) = the density of diesel (kg per liter)

(2) Energy-use (mj/ha) = Diesel-use (kg/ha) * MJdiesel (mj/kg)

Where:
MJdiesel = energy density diesel (mj/kg)

(3) Emissions (Kg CO_2/ha) = Energy-use (mj/ha) * CO_2dieselMJ (kg CO_2/MJ diesel)

Where:
CO_2dieselMJ = the direct and indirect GHG emissions per MJ of diesel (in g/MJ)

4.6.7 CO_2 emissions from the abstraction of ground water for irrigation

CO_2 emissions from irrigation were calculated based on the energy required for abstraction (pumping) and water application. Irrigation is a primary consumer of energy on farms particularly when pumping is required, so any changes to the irrigation method used can be expected to change on-farm energy consumption. The direct energy inputs are primarily used to operate farm machinery and pumps, while indirect energy inputs refer to energy that is used to produce equipment and other goods and services that are used on-farm. Where groundwater is used, more energy is required for pumping. The energy required for pumping depends on the crop water requirement, total head, flow rate and system efficiency.

The operational processes involving energy for irrigation are abstraction and application of water. However, many factors within each process influence energy intensity. Energy use varies with the source of water (groundwater, surface water and water stored in reservoirs), the distance and lift over which water is transported before application, and the application method (in the case of pressurized systems). In addition, the intensity of water use in irrigated agriculture is a critical factor determining the amount of water and thereby the energy required for irrigation. Pumping water is the most energy-demanding process (Wang *et al.*, 2012; Lal, 2004).

CO_2 emissions from irrigation were calculated based on the energy needed for abstraction (pumping) and water application. The energy used for abstraction is a function of water source. In this study, the energy required to abstract water from a surface source was assumed to be negligible; only energy (lift) for groundwater abstraction was included. This assumes that water is conveyed to the farm by gravity and not pressurized, but it is recognized that the water source is not always in close proximity to a farm.

Energy for abstraction of water was calculated by apply a basic theoretical physical relationship, which prescribes the energy required to lift 1 m^3 of water (with a density 1000 kg m^3) up 1 m at 100% efficiency is 0.0027 kWh (see equation below), Rothausen and Conway 2011).

The following assumptions and data sources were used in the calculation of emissions from abstraction of ground water:

- Average country lift values were based on the groundwater table depth model (WTD) (Fan and Miguez-Macho, 2013) and the Global Map of Irrigated Areas (GMIA) (2013).
- The efficiency was found to range between 11% -30% for electric pumps and 40% to 67% for electricity pumps.
- Mass of water from groundwater used for irrigation (m3/year) on national base was derived from Siebert *et al.* (2010).

The GHG emissions are equal to the energy consumption multiplied by its emission factor.

$$\textbf{Energy (kWh)} = \frac{\textbf{9.8 m s}^{-2}\ \textbf{x Lift (m) x Mass (kg)}}{\textbf{3.6 x 10}^{6}\ \textbf{x Efficiency (\%)}}$$

Where:
Energy = energy use for calculated for abstraction of water from shallow and deep wells.

The energy source used also determines the quantity of CO_2 emitted for each kWh of energy produced. The estimated CO_2 emissions emitted from a diesel engine to produce 1 kWh of energy are equivalent to 0.32021 kg (Wang *et al.*, 2012).

For electric motors, the energy to CO_2 conversion factor depends on the energy source from which the electricity is produced. For each country, the International Energy Agency (IEA 2015) has calculated the energy to CO_2 conversion factor using the total CO_2 emissions from fossil fuels consumed for electricity generation divided by the outputs of electricity generated from fossil fuels, nuclear, hydro, geothermal, solar, wind, ocean and biofuels. These conversion factors for both diesel and electric engines were used here to estimate the total volume of CO_2 emitted by irrigation pumping.

4.6.8 CO_2 emissions from application of agricultural lime

Agricultural lime is commonly used in the management of croplands and grasslands to decrease soil acidity. Lime is often applied in the form of crushed limestone ($CaCO_3$) or crushed dolomite ($CaMg(CO_3)_2$). Adding carbonates to soils in the form of lime or dolomite leads to CO_2 emissions as the carbonate limes dissolve and release bicarbonate ($2HCO_3$), which evolves into CO_2 and water (H_2O). CO_2 emissions from the dissolution of carbonate rock discussed here do not include emissions from the fossil fuels used to crush, deliver, and spread the crushed rock on agricultural fields. Direct emissions from lime application were calculated according to IPCC (2006) using an emission factor (EF) for limestone of 0.396 kg CO_2/kg limestone.

4.7 NITROUS OXIDE EMISSIONS FROM SOILS

In most soils, an increase in available nitrogen enhances nitrification and denitrification rates, which then increases the production of N_2O, along with indirect emissions from leaching and volatilization. The main sources of N_2O included in the methodology for estimating N_2O emissions from soils include:

- Synthetic nitrogen fertilizers
- Organic nitrogen applied as fertilizers e.g. animal manure
- Nitrogen in crop residues

Many fertilizers contain nitrogen, a part of which is released into the atmosphere as nitrous oxide. In the assessment, nitrous oxide emissions from cultivation of crops were calculated according to the Tier 1 methodology of IPCC (2006). The method includes a direct contribution from N_2O produced from added N in the soil system and an indirect contribution of N_2O produced from N that escapes the cropping system via leaching and volatilization. Tier 1 is the basic method, designed to use readily-available national statistics (also known as activity data) in combination with default EFs and additional parameters that are provided. This approach is straightforward and transparent. The default EFs are derived from very large datasets and hence give an accurate representation of 'average' emissions at the global scale. However, a Tier 1 methodology is less accurate in representing the effects that regional or local variations in management and/or environment within a given source category may have on GHG emissions from soils and on the effects of implementing GHG mitigation methods.

Direct N_2O emission in the IPCC (2006) methodology is calculated from the empirical assumption that 1% of the added nitrogen in soil system is emitted as N_2O. To calculate the amount of added nitrogen, the IPCC methodology includes the amount of fertilizer N applied and a contribution from aboveground and below-ground crop residues:

$$\mathbf{N_2O\ (direct) = (FSN + FON + FCR) \times EFN \times 44/28\ (kg\ N_2O/ha),}$$

Where:
FSN = Amount of synthetic fertilizer applied (kg N/ha)
FON = Amount of annual manure applied (kg N/ha)
FCR = Amount of N crop residues above ground and below-ground (kg N/ha)
EFN = IPCC emission factor for added nitrogen (0.01 kg N_2O-N/kg N)

The quantity of crop residues left after harvesting was calculated based on the crop yield, less any residue removed as the co-product. Estimates for the amount of N in crop residues were calculated according to IPCC equation 11.6 (IPCC, 2006).

Indirect nitrous oxide emissions are calculated from the nitrogen lost by leaching and volatilization. To calculate the contribution of N_2O from the amount of leached N, the IPCC (2006) emission factor of 0.0075 kg N_2O-N/kg N was applied. Nitrogen lost through volatilization of ammonia was assumed to be 10% of the mineral and organic fertilizers applied (IPCC, 2006). To calculate the contribution of N_2O from the amount of volatilized NH_3 the IPCC (2006) emission factor of 0.01 kg N_2O-N/kg NH3-N was applied.

Indirect nitrous oxide emissions (kg N_2O/ha) were calculated as:

$$\mathbf{N_2O\ (indirect) = (FL \times EFL + FA \times EFD) \times 44/28}$$

Where:
FL = Amount of nitrogen lost through leaching (kg N/ha)
EFL = IPCC emission factor for leached nitrogen (0.0075 kg N_2O-N/ha)
FA = Amount of ammonia emitted from fertilizer application
EFD = IPCC emission factor for volatilization and re-deposition (0.01 kg N_2O-N/kg NH_3-N)

5. Challenges and future work

This study was based on the guidance developed under the framework of the LEAP Partnership and is a first attempt to provide a global life cycle inventory dataset that can be used to assess feed supply chains. The study has also highlighted numerous challenges and gaps particularly related to data availability to support benchmarking of livestock supply chains.

A number of issues standout:

- To account for the diversity of agricultural management at the global scale it is crucial to include regional differences in crop varieties and sub-national variability of management practices, e.g. sequential cropping and crop rotations, which are relevant for soil nutrient dynamics, should be included for future model improvements.
- Spatial variability of input use e.g. fertilizer use is important. For example, in this simulation, we apply only one fertilization rate at national level although fertilizer application varies spatially and by crop.
- Better descriptions of current production practices and improving data particularly for developing and emerging regions is key to understanding the impact of the projected demand for livestock products in these regions. A better understanding of input use is an imperative to improving the system.

Short-term developments for future versions of the LEAP database and its content can be classified in the following areas:

- incorporation of data related to changes in soil carbon stocks
- improvements in the estimation of N_2O emissions
- inclusion of information on uncertainty
- improvements in the database system
- improvements in data supply and data query

An extension of the content of the LEAP database and the building up of international collaboration in LCI data collection and supply are key activities for the future.

Long term recommendations for future assessments should be based around two major aspects: improving data quality and increasing the database coverage in terms of crops covered and environmental impacts. An LCA analysis is dependent upon the quality of the data used to construct it. This first assessment has identified areas where improved data quality will allow a more accurate description of GHG emissions. In particular, nitrous oxide emissions that make up a considerable proportion of total on-farm GHG emissions may be more accurately assessed using manufacturing specific emission factors for nitrogen fertilizer and site specific emission factors for nitrogen dependent field emissions. Data quality would be further improved with accurate quantitative data and its allocation amongst operational processes.

The end point for this study was the field gate; a future study should focus on extension of the assessed system boundary. Many feed materials used in the livestock chain are by-products of processes beyond the farm-gate; an expanded assessment would provide an indication on how much this affects the carbon footprint of animal feed products.

One of the strengths of an LCA analysis is the identification of inefficiencies and potential 'hotspots' for optimization. It is envisioned that future LCA work, taking into account the above considerations will allow the discussion of possible efficient production strategies that could be utilized to lower GHG emissions from feed production.

6. References

Abdalla, M., Osborne, B., Lanigan, G., Forristal, D., Williams, M., Smith, P., and M. B. Jones. *(2013). Conservation tillage systems: a review of its consequences for greenhouse gas emissions*

Audsley, E., K. Stacey, K., Parsons, D.J., and Williams A.G. *(2009). Estimation of the greenhouse gas emissions from agricultural pesticide manufacture and use*

Barber, A. Pellow, G. and Barber, M. *(2011). Carbon footprint of New Zealand arable production – Wheat, maize silage, maize grain and Ryegrass seed*

Brentrup, Frank, *(2009).The impact of mineral fertilizers on the carbon footprint of crop production. The Proceedings of the International Plant Nutrition Colloquium XVI*

Cherubini, F., *(2010). GHG balances of bioenergy systems – overview of key steps in the production chain and methodological concerns. Renewable Energy 35, 1565–1573.*

de Vries, M. and de Boer, I.J.M. *(2010). Comparing environmental impacts for livestock products: A review of life cycle assessments. Livestock Science, 128 (2010) 1–11*

Duxbury, J.M. *(1994). The significance of agricultural sources of greenhouse gas emissions. Fertil. Res. 38, 151-163.*

FAO *(2015). FAO Conservation Tillage database.* http://www.fao.org/ag/ca/6c.html

Frye, W. *(1984). Energy requirement in conservation tillage.*

Herrero, M., Thornton, P.K., Gerber, P., and Reid, R.S. *(2009). Livestock, livelihoods and the environment: understanding the trade-offs. Curr. Opin.Environ. Sustain. 1, 111-120.*

IPCC. *(2006). 2006 IPCC Guidelines for National Greenhouse Gas Inventories, Volume 4: Agriculture, Forestry and Other Land Use. Intergovernmental Panel on Climate Change.*

Kool, A., marinussen, M. and Blonk, H. *(2012): LCI data for the calculation tool Feedprint for greenhouse gas emissions of feed production and utilization: GHG emissions of N, P, and K fertilizer production.*

Nemecek, T. and Kagi, T. *(2007). Life cycle inventories of agricultural systems. EcoInvent Report 15.*

Rothausen, S. and Conway, D. *(2011). Greenhouse gas emissions from energy use in the water sector. Nature Clim. Change, 1 210–9*

Sauer, T., P. Havlík, U. A. Schneider, E. Schmid, G. Kindermann, and M. Obersteiner *(2010), Agriculture and resource availability in a changing world: The role of irrigation, Water Resour. Res., 46, W06503, doi:10.1029/2009WR007729.*

Tubiello F.N., M. Salvatore, S. Rossi, A. Ferrara, N. Fitton, and P. Smith *(2013). The FAOSTAT database of greenhouse gas emissions from agriculture. Environmental Research Letters 8, 015009.*

Wang, J., Rothausen, S., Conway, D., Zhang, L., Xiong, W., Holman, I.P., Li, Y. *(2012). China's water–energy nexus: greenhouse-gas emissions from groundwater use for agriculture. Environ. Res. Lett. 7 (2012)*

Wood S. and Cowie A. *(2004). A review of greenhouse gas emission factors for fertiliser production. Paris, France: IEA Bioenergy*

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Our Sustainability Efforts

We are redefining dairy and food production through our unwavering commitment to environmental stewardship

Our Sustainability Vision

Grounded in a full life cycle approach, our sustainability program integrates best-in-class practices that reduce greenhouse gas emissions, conserve water, and close resource loops, setting a new standard for the industry.

We envision a holistic dairy and food manufacturing ecosystem that thrives in harmony with nature, one where every product reflects our respec

Across our dairies, processing facilities, and extended supply chain, we commit to innovating in resource conservation, renewable energy, and regenerative practices.

By partnering closely with suppliers who share our values, we deliver wholesome, natural products while safeguarding our shared environment for generations to come.

Sustainability Policy

Our **Environmental Sustainability Policy** applies across every facet of our operation, from our dairies and processing facilities to distribution and supplier partnerships, reflecting our commitment to responsible **resource management** and **environmental stewardship**.

Anchored by the core principles of **Compliance & Integrity**, **Continuous Improvement**, and **Collaboration & Transparency**, the policy details our three key commitments:

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→ Water Stewardship & Conservation

→ Circular Economy & Waste ,

and outlines robust implementation, monitoring, and review processes to ensure accountability at every level of our business.

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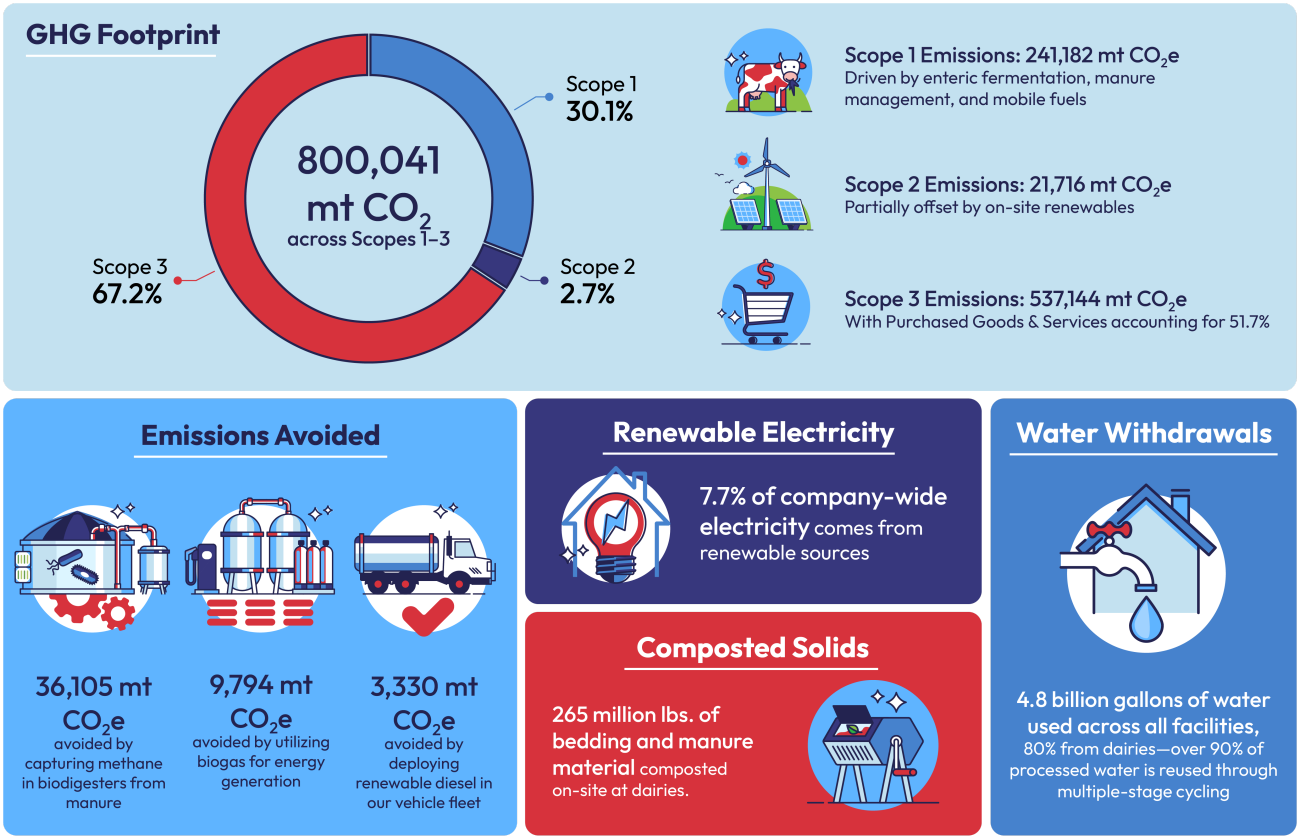
2024 Sustainability Data

Sustainability isn't just a side initiative; it's a core part of how we operate every day. We've invested in renewable electricity, clean fuels, and multi-stage water reuse systems, helping us reduce emissions and conserve vital natural resources across all our facilities.

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ARTICLES

Dairy Sense: Keeping the Dairy Right Sized

Regardless of the dairy's herd size, there is one key theme that applies to everyone, a land base that matches the number of cows and heifers in the herd.

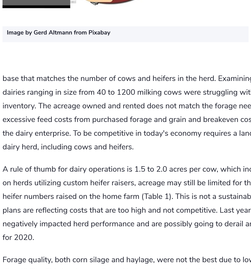


Image by Gerd Altmann from Pixabay

March 2020

Production Perspective

Dairy operations need to be "custom-tailored" to the resources available, as there is no cookie-cutter approach to managing the business. However, regardless of the dairy's herd size, there is one key theme that applies to everyone: a land base that matches the number of cows and heifers in the herd. Examining cash flows from 2019, dairies ranging in size from 40 to 1200 milking cows were struggling with inadequate forage inventory. The acreage owned and rented does not match the forage needs of the herd. The result is excessive feed costs from purchased forage and grain and breakeven costs exceeding $22.00/cwt for the dairy enterprise. To be competitive in today's economy requires a land base right-sized for the dairy herd, including cows and heifers.

A rule of thumb for dairy operations is 1.5 to 2.0 acres per cow, which includes the youngstock. Even on herds utilizing custom heifer raisers, acreage may still be limited for the cows and the reduced heifer numbers raised on the home farm (Table 1). This is not a sustainable model, and the cash flow plans are reflecting costs that are too high and not competitive. Last year in 2019, several challenges negatively impacted herd performance and are possibly going to derail any chance of improvement for 2020.

Forage quality, both corn silage and haylage, were not the best due to lower than ideal fiber digestibility. This has been reflected in lower milk production than expected and as a result lower milk income. Due to rainfall at undesirable times last spring, quantity of small grain silage was compromised, and corn was planted very late. Even though most farms are utilizing double cropping as a forage source, the yields were extremely low. The tonnage for small grain silage on an as-fed basis ranged from 2 to 10 tons/acre. Farms that are doing a good job typically are in the 6 to 8 tons/acre range. The farms with extremely low tonnage have extremely high unit costs. In most cases, the small grain silage was harvested late, and quality was not ideal for lactating cows.

Another common thread observed in herds of all sizes relates to heifer numbers. With the popularity of sexed semen and the low prices for cattle, more heifers are staying on the farm. This is turning into a liability because they require feed, which is draining the limited inventory. When evaluating heifer rations for the cash flow plans, it is no coincidence forages needed are not matching the forages purchased. Heifers are being short-changed due to cash flow issues.

Drilling down further, age at first calving is being extended beyond the recommended 24 months. The percentage of first-lactation animals is getting close to 50 percent of the milking herd, when the range should be around 38 to 40 percent. First-lactation animals do not perform to the level of mature cows and are another liability to the herd because of reduced milk income.

Profitability relies on having a solid foundation from which to build. Emphasis is usually on forage quality, which is important, but quantity is probably the more significant factor in many situations. Relying on purchased forage and grain to compensate for inadequate or inefficient home-raised feed production is a formula for disaster. This, coupled with a large heifer inventory, is putting a strain on the whole farm system. The best way to determine severity of the problem is to do an intensive cash flow assessment, including numbers from both the financial and production side of the operation. Now is the time to determine the best course of action to take advantage of an improved milk price for 2020.

Table 1. Animal units compared to acreage harvested for crops (owned and rented land) for an Amish producer.

Animal	Number	Bodyweight, lbs.	Animal unit[1]
Milk cows	44	1300	44.0
Dry cows	7	1350	7.3
Calves < 6 months	5	250	1.0
Heifers 7 to 12 months	5	600	2.3
Heifers >12 months	10	900	6.9
Horses/mules	12	1100	10.0
Total animal units			71.5

Total animal units: 71.5
Total harvestable acres: 57.0
Acres per animal: 1.25[2]

Note: A custom heifer raiser is used for some of the replacement animals.

[1]The milking herd average bodyweight is considered the standard bodyweight of 1.0. Example: dry cow bodyweight of 1350 divided by 1300 equals 1.038 times 7 dry cows equals 7.3 animal units.

[2]Recommended acres per animal is 1.5 to 2.0.

Action Plan for Evaluating the Whole Farm System

Goal – Complete a cash flow plan for the whole farm

Step 1: Using Penn State Extension's Excel spreadsheet, complete a year-end analysis for 2019 on both a cash and accrual basis.

Step 2: Compile income for the dairy and other sources, including crop sales or other farm income (custom work, hogs, birds, etc.).

Step 3: Compile expenses for the dairy, crops, feed, overheads, family living, and loan payments, including principal and interest.

Step 4: Include accounts payable. The usual areas are feed, seed, fertilizer, and vet expenses.

Step 5: Work with the appropriate consultants to discuss the farm's breakeven cost, comparing the whole farm to the dairy and crop enterprises.

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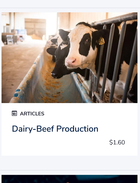
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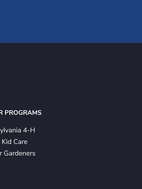
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Feeding management and characteristics of rations for high-producing dairy cows in freestall herds

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ABSTRACT

The objectives of this cross-sectional observational study were to 1) describe the feeding management and characteristics of rations for high-producing Holstein cows housed in freestall barns in Minnesota, 2) evaluate ration change over time, and 3) investigate herd-level risk factors for ration change. Each of 50 randomly selected freestall dairy herds was visited once during the study. Samples of TMR were collected from the high-production group feed bunk to represent the initial ration as delivered to the cows, 3 additional samples were collected every 2 to 3 h after feed delivery, and the accumulated orts were cleaned out of the feed bunk. Feeding management practices and TMR formulation were also collected at the time of visit. Seventy percent of herds fed once daily, 22% fed twice daily, and 8% fed 3 times daily. Frequency of feed push-up was 5.4 ± 2.3 times daily. Linear feed bunk space per cow was 0.45 ± 0.11 m. Sixty-two percent of the farms had 3-row pens and 38% had 2-row pens. Linear feed bunk space per cow was greater in 2-row pens (0.56 m/cow) than in 3-row pens (0.39 m/cow). Post and rail was the most common type of feed barrier; it was used by 60% of the herds. Headlocks were used by 28% of the herds, combination of post and rail with headlocks was used by 8%, and diagonal bars were used by 4%. Water trough linear space was 4.6 ± 2.1 cm/cow. Estimated dry matter intake was 24.3 kg/cow per day. The forage content of the formulated ration was 52% of the ration DM, and corn silage was the most commonly used forage. The NDF content of the analyzed ration was greater than the NDF content of the formulated ration (30.6 and 29.8%, respectively). In contrast, the CP content was lower (17.5 and 17.9%, respectively). Some feeding management practices (e.g., feeding frequency) were associated with ration NDF content change over time. This association may be minimized by implementing ration and management changes.

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Key words: feeding management, ration characteristic, particle size

INTRODUCTION

In recent decades, there has been a trend for housing dairy cows in freestall barns instead of tiestall barns in the upper Midwest to improve labor efficiency in dairy operations. With this change, cows are no longer fed individually; instead, they are fed as a group with a TMR, where forages and concentrates are mixed together. Feeding a TMR allows producers to incorporate all the required ingredients into a single ration to meet cows' nutritional requirements and optimize herd milk production. However, feeding cows as groups is more challenging because they can potentially sort the feed and individual preferences can lead to cows eating different diets. In addition, social interactions among cows at the feed bunk can affect individual cows' intake.

Several management and environmental factors have been shown to affect feeding behavior of dairy cows. Increasing feed bunk space per cow resulted in a reduction in displacements of subordinate cows by dominant cows while they were eating (Olofsson, 1999; DeVries et al., 2004). In addition, type and design of the feed barrier was shown to influence aggressive behavior between cows while they were eating (Huzzey et al., 2006). Similarly, water consumption is an important factor influencing milk production. Water intake could be affected by available space per cow at the water trough (Castle and Thomas, 1975). An assessment of feeding management practices used in Minnesota freestall herds has not been conducted in recent history.

Ration physical and chemical characteristics are important factors in meeting the nutritional requirements of high-producing dairy cows (NRC, 2001). Those characteristics have not been evaluated in a large data set of Minnesota freestall herds. The Penn State Forage and TMR Particle Separator is a field tool that can be used to describe physical characteristics of rations. An additional sieve measuring 1.18 mm was added recently (Kononoff et al., 2003); it allows for more accurate estimation of the average TMR particle size distribution.

Selective consumption or sorting of the TMR has been reported (Leonardi and Armentano, 2003; DeVries

et al., 2007). Observation of the feeding behavior and analysis of the orts revealed that cows typically sort against long particles (Leonardi and Armentano, 2003; DeVries et al., 2007), which could reduce the intake of physically effective NDF and increase the intake of the finer nonstructural carbohydrate fraction. This situation could affect the normal function of the rumen and increase the risk of SARA and displaced abomasum, result in fluctuations in feed intake, alter the immune function, increase the incidence of foot lesions, depress milk fat, and reduce rumination activity (Martin, 2000; Leonardi and Armentano, 2003). Recent studies have investigated sorting activity of cows housed in a freestall facility (DeVries et al., 2007; Leonardi and Armentano, 2007). Measuring feed sorting behavior in commercial herds is difficult, but better documenting changes to the ration in a large number of freestall facilities can be of interest and point to potential feed sorting activity.

The objectives of this observational study were to 1) document feeding management and characteristics of rations provided to high-producing Holstein cows housed in freestall barns in Minnesota; 2) evaluate ration NDF content change over time; and 3) investigate herd-level risk factors for ration NDF content change over time.

MATERIALS AND METHODS

On-Farm Data Collection

This cross-sectional observational study was performed in 50 freestall dairy farms in Minnesota between June and October 2004. Dairy farms were selected randomly from a list of herds having more than 150 cows situated within a geographical area where most of the dairy farms in Minnesota are located (central and southeast Minnesota). The list was obtained from the Minnesota Department of Agriculture (St. Paul). Herd owners were contacted by phone and asked about their willingness to participate in the study. The only criterion for enrollment was that cows were housed in freestall barns. All farms had Holstein cows as the predominant breed, but this was not a criterion for selection. Observation was focused on the high-production group. High-production group size was 117 ± 51 (mean ± SD) cows. Therefore, results from this study would represent the population of cows in the high-production group housed in freestall dairy farms with a herd size ≥150 cows.

Each farm was visited once during the study. Logistical limitations and the goal of visiting all herds during the same season did not allow for more than 1 visit per farm. On each farm, samples of the TMR were collected from 6 to 10 areas along the feed bunk of the high-production group pen and mixed together in a 5-gallon bucket to obtain a representative sample of the TMR along the feed bunk. Special care was taken to ensure that each grab sample of the TMR represented the remaining feed in the feed bunk in each sampled area. This process was repeated 5 times during the day as follows: sample 1 represented the initial TMR collected immediately after it was delivered; samples 2, 3, and 4 represented samples taken every 2 to 3 h after sample 1 (delivery time); and sample 5 was taken from the accumulated orts cleaned out of the bunk by the feed manager. We were unable to collect ration weights for delivered feed and orts. Most producers indicated feeding for a maximum of 5% orts (as fed), with some targeting 2 to 3%.

At every sampling time, an evaluation of the particle size distribution of the TMR was performed by the same person using the 3-sieve (19-, 8- and 1.18-mm) Penn State Forage and TMR Particle Size Separator and the methodology described by Kononoff et al. (2003). The procedure was performed in triplicate for each sampling time and the weight of the mass retained on each screen and the bottom pan was recorded in every replicate.

In addition, at each sampling time a representative subsample of the TMR was taken and kept frozen (−20°C) for the analysis of CP and NDF using standard methods. Samples were dried in a 60°C forced-air oven and ground in a Wiley mill (Swedesboro, NJ) to pass through a 1-mm screen. Final DM was determined by drying samples at 105°C for 8 h (AOAC, 1995). Samples were analyzed for NDF using the Ankom200 fiber system (Ankom Technology Corporation, Fairport, NY). Sodium sulfite and heat-stable α-amylase were included in the neutral detergent extraction, and heat-stable α-amylase was also added during the first 2 rinses (Hintz et al., 1996). Samples were analyzed for CP using a TrueSpec Protein Nitrogen Analyzer (Leco Corporation, St. Joseph, MI; AOAC, 1995).

Information on feeding frequency, frequency of feed push-up, and number of cows in the pen was obtained from the herd manager. The linear length of the feed bunk and water troughs was measured during the farm visit. A copy of the TMR formulation used for the high-production group at the time of visit was also obtained and used to determine the type and amount of forage in the ration, to describe the nutrient composition of the formulated diet, and to compare the nutrient formulation for CP and NDF with laboratory results. Milk production data were summarized from the nearest DHIA test date to the time of visit as management level milk (**MLM**) for each group on each farm. Management level milk adjusts the daily milk yield for 150 DIM, 3.5% fat, and 3.0% true protein. Milk fat and milk protein were reported as percentages.

Statistical Analysis

Descriptive statistics was used to characterize the distribution of the variables in the study using the MEANS and FREQ procedures of SAS (SAS Institute Inc., Cary, NC). *t*-Test was used to determine differences in the mean linear feed bunk space per cow between 2-row and 3-row pens. *t*-Test was also used to determine differences between DM, CP, and NDF of the formulated ration and the analyzed ration. These *t*-tests were performed using the MEANS procedure of SAS (SAS Institute Inc.). Differences were declared at $P < 0.05$.

Exploratory data analysis was performed using the GPLOT and UNIVARIATE procedures of SAS (SAS Institute Inc.). Mixed models were used to evaluate chemical (DM, NDF, and CP) changes of the ration across the 5 samples. Farms were included in these models as a random effect, and least squares means of the 5 samples were computed and compared using Bonferroni test for multiple comparisons. A random-effect mixed model was used to analyze the association of NDF content (percentage) over time (dependent variable) and the possible associated factors (explanatory variables), using farm as a random effect. Following the evaluation of the models using Akaike's and Bayesian information criteria, the final model that better fit the data included a random intercept and slope (time) by farm with an unstructured working correlation matrix within farm. The models were selected using the MIXED procedure of SAS (SAS Institute Inc.).

The following were initially used as explanatory variables: time after feed delivery when the sample was taken (hours); feed delivery frequency (grouped in 2 categories: 1 = once daily; 2 = twice or more daily); feed push-up frequency (grouped in 2 categories: 1 = 5 times or fewer daily; 2 = 6 times or more daily); feed bunk barrier design (grouped in 2 categories: 1 = predominantly headlock; 2 = predominantly post and rail); percentage of hay in the ration (DM basis); feed bunk space per cow (meters); and initial TMR DM content (percentge). Interactions between initial NDF content and percentage of hay in the ration and between initial NDF content and initial TMR DM content were also considered in the model. Stepwise backward elimination was used to remove nonsignificant terms from the model. The threshold value to keep a term in the model was $P \leq 0.05$. Model assumptions were evaluated using residual plots. The model was also used to calculate the BLUP for the random effects of the farm. Once the BLUP were ordered from highest to lowest, management and production characteristics were calculated for the 50th, 25th, and 10th percentiles.

RESULTS AND DISCUSSION

Feeding Management Practices

Seventy percent of herds fed once daily, 22% fed twice daily, and 8% fed 3 times daily. The frequency of feed push-up was 5.4 ± 2.3 times daily (range = 3–12 times daily). It was expected that farms that fed their cows only once daily would have higher frequency of feed push-up throughout the day; however, a single regression analysis showed that feed delivery frequency was not associated with feed push-up frequency. Some might expect that pushing up feed will increase feeding activity. However, DeVries et al. (2003) did not find differences in feeding activity when 2 extra push-ups were implemented during the late evening and early morning hours in a freestall herd fed twice daily. They concluded that fresh feed delivery and the milking process were more important in stimulating the feeding activity of dairy cows. In another study, DeVries and von Keyserlingk (2005) concluded that the feed delivery effect was more important than the milking effect. However, it is essential to push up feed to the cows various times during the day to provide them access to the feed because they tend to toss feed forward and no longer within reach when they eat at a feed bunk.

The linear feed bunk space per cow was 0.45 ± 0.11 m (range = 0.21–0.75 m). DeVries et al. (2004) showed that an increase in linear feed bunk space per cow reduced aggressive behavior among cows and improved feeding time, especially of more subordinate cows. Similarly, Olofsson (1999) reported that an increase in the level of competition at the feed bunk by increasing the number of cows per feeding station (4 times) resulted in an increase in the frequency of displacements from the bunk for subordinate cows. Additionally, the exposure to higher levels of competition at the feed bunk increased their consumption rate, reduced their time spent eating, and increased their time spent standing. The American Society of Agricultural Engineers recommended that linear feed bunk space per cow should be no less than 0.60 m (ASAE, 2001). In the current study, 92% of the high-production groups had less than the recommended feed bunk space, which indicates some level of overstocking in the pens as it relates to feeding space.

The linear feed bunk space per cow in freestall barns is a function of the number of cows in the pen and the length of the feed bunk, which is related to the pen configuration (2-row or 3-row). We found that 62% of the farms had 3-row pens and 38% had 2-row pens. The average linear feed bunk space per cow was greater ($P < 0.01$) in 2-row pens (0.56 ± 0.09 m/cow) than

Table 1. Characteristics of the TMR provided to high-producing Holstein cows in 50 freestall herds in Minnesota

Item[1]	Mean	SD	Minimum	Maximum
Forage content (DM basis), %	52.1	6.5	38.6	68.2
DMI, kg/cow per day	24.3	2.3	18.3	29.9
DM, %				
Formulated	51.9	4.3	40.4	62.9
Analyzed	52.3	4.8	39.3	62.1
NDF, % of DM				
Formulated	29.8[a]	1.6	25.4	32.8
Analyzed	30.6[b]	2.3	26.0	37.6
CP, % of DM				
Formulated	17.9[a]	0.5	16.9	18.6
Analyzed	17.5[b]	1.0	15.4	19.2
ADF, % of DM	19.8	1.0	17.9	22.0
Forage NDF, % of DM	22.2	1.9	18.9	27.7
Crude fat, % of DM	5.2	0.89	3.0	7.2
NFC, % of DM	39.3	1.6	36.4	42.0
Ca, % of DM	0.96	0.09	0.94	1.11
P, % of DM	0.43	0.04	0.36	0.52
NE_L, Mcal/kg of DM	1.71	0.42	1.63	1.83

[a,b]Means within a column and item with different superscripts differ ($P < 0.01$).

[1]Values for analyzed DM (%), analyzed NDF (%), and analyzed CP (% of DM) are laboratory results of samples collected immediately after feed delivery. Values for all other items are obtained from the formulated ration for the high-production group.

in 3-row pens (0.39 ± 0.08 m/cow). However, in both cases, the mean linear space per cow was less than 0.74 m for a 2-row pen and 0.46 m for a 3-row pen when the pen was stocked at 1 cow per stall (Mentink and Cook, 2006), indicating some level of overstocking. Mentink and Cook (2006) also reported a significant difference in feed bunk space between 2-row and 3-row pens (0.58 m and 0.42 m, respectively) in a field study with 10 dairy herds in Wisconsin.

Post and rail was the most common type of feed barrier; it was used by 60% of the herds. Headlocks were used by 28% of the herds, combination of post and rail with headlocks was used by 8%, and diagonal bars were used by 4%. Huzzey et al. (2006) showed that headlocks reduced aggressive behaviors between cows at the feed bunk, especially for more subordinate cows, compared with post and rail barriers. We speculate that producers preferred post and rail barriers for economic reasons.

The throat height at the feed bunk was 51.4 ± 8.8 cm (measure taken from the pen) and the feed table depth was 39.1 ± 7.0 cm (measure taken from the feed lane). Therefore, the feed bunk was 12.4 ± 8.2 cm higher than the pen. Observation of cows fed in feed troughs at different heights indicated that they prefer to eat from feed troughs placed at floor level with their heads down at the natural pasture position (Albright, 1993) or slightly (10 cm) above this level (ASAE, 2001). The position of head down reduced the feed tossing behavior and waste in comparison with elevated feed bunks (28 cm height on the bottom of the trough and 76 cm height on the top; Albright, 1993). Neck rail height was 122.9 ± 9.1 cm (including all types of feed barrier design), which was basically the recommendation (122.0 cm) for adult cows (ASAE, 2001). The opening between the curb and the neck rail on the feed lane was 71.5 ± 7.4 cm. All these measurements seemed appropriate for cows housed in freestall barns.

Water was provided mainly in water troughs with a linear space of 4.6 ± 2.1 cm/cow (range = 2.0–11.3 cm/cow). Behavioral studies have indicated that the recommended water trough space for milking cows should be from 3.2 to 5.3 cm/cow depending on the DM content of the ration (Castle and Thomas, 1975).

Ration Characteristics and Milk Production

All farms fed their high-production group a TMR. The ration formulation for the high-production group was obtained from 49 of the 50 farms that participated in this study. All rations were formulated to meet the nutrient requirements of lactating dairy cows (NRC, 2001). On average, rations were formulated for 40 kg of daily milk production and 625 kg of BW. Table 1 summarizes ration characteristics, including nutrient concentrations.

The estimated ration DMI was 24.3 kg/cow per day. The forage content of the formulated ration was 52% of the ration DM. Corn silage was the source of forage most commonly used in the formulation of the TMR, and only 1 farm did not include it in the ration formulation for the high-production group. The percentage of corn silage was 25.4 ± 7.9% of the ration DM and

Table 2. Daily milk production and milk composition of high-producing Holstein cows in 50 freestall herds

Item	Mean	SD	Minimum	Maximum
Daily milk yield, kg/cow	39.9	5.6	28.5	54.5
Milk fat, %	3.51	0.36	2.80	4.80
Milk protein, %	2.90	0.20	2.16	3.20

Table 3. Particle size distribution of the initial TMR of high-producing Holstein cows in 50 freestall herds

Particle size[1]	Mean	SD	Minimum	Maximum
>19.0 mm, %	10.8	8.4	3.5	47.7
19.0 to 8.0 mm, %	41.5	7.9	18.1	57.7
8.0 to 1.18 mm, %	35.0	6.0	24.3	50.7
<1.18 mm, %	12.6	4.1	1.0	19.9

[1]Measured with the Penn State Forage and TMR Particle Separator (Kononoff et al., 2003). Values shown in percentage of the material as fed retained on the sieve.

48.7 ± 14.2% of the total forage DM. The second most commonly used source of forage was alfalfa haylage, which was included in 47 of the rations at 22.6 ± 8.3% of the TMR and 43.4 ± 14.9 of the total forage. Hay was included in 31 of the rations at 6.9 ± 3.6% of the TMR and 13.4 ± 6.9% of the total forage. Straw was used in 7 rations at 0.74 ± 0.44% of the TMR and 1.4 ± 0.78% of the total forage. Additionally, 3 farms used other sources of forage such as barley silage (2) or sweet corn silage (1) at 3.4 ± 1.4% of the TMR and 6.9 ± 3.9% of the total forage.

Results of the laboratory analysis of the initial samples of TMR (sample 1) from the 50 farms are shown in Table 1. The estimated DM of the formulated ration was similar to the DM measured in the initial ration; however, the estimated NDF and CP of the formulated ration were different than the analyzed values. The NDF content of the analyzed ration was greater than the estimated NDF content of the formulated ration ($P < 0.01$); in contrast, the CP content of the analyzed ration was lower than the estimated CP of the formulated ration ($P < 0.01$). Because both NDF and CP contents of the rations were greater than the minimum recommended for high-producing dairy cows (25% NDF and 14.1% CP, assuming a perfect balance between RUP and RDP; NRC, 2001) and the difference between formulated and analyzed values was very small, it appears that these statistical differences would not represent biological differences and would have no effect on the cows' health or performance. Factors that could account for these small differences include sampling discrepancies and day-to-day variation in TMR mixing.

Daily milk production (MLM) for the 50 high-production groups was 39.9 ± 5.6 kg/d. Milk fat percentage was 3.51 ± 0.36 and milk protein percentage was 2.90 ± 0.2 (Table 2). Rations were formulated for 40 kg of milk/day and the average production indicated that this goal was reached for the average farm.

Heinrichs and Kononoff (2002) recommended that between 2 and 8% of the weight of the TMR (as fed basis) should be retained on the upper sieve (particles larger than 19 mm) of the Penn State Particle Separator. No rations in this study were below the lower recommended limit of 2%, whereas 52% of them were above the upper recommended limit of 8%; however, 84% of the rations were below 15% (Table 3). A high proportion of larger particles in the TMR would not necessarily represent a risk for normal rumen activity. However, increasing the proportion of larger particles in the ration could potentially lead to more sorting by the cows (Martin, 2000; Shaver, 2002).

The analysis of distribution of smaller particles showed that the percentage of farms with TMR particle size not meeting the recommendation (30–50%) for particles between 19 and 8 mm and between 8 and 1.18 mm was 22 and 24%, respectively. All rations included the recommended proportion for particles <1.18 mm (<20%).

We observed basically no change in the percentage material retained on the second sieve (>8 mm) of the Penn State Separator over time (Figure 1). Other sieves, especially the top sieve (>19 mm), had a noticeable change from the initial TMR to the orts. It appears that cows were less likely to select for or against particles between 19 and 8 mm. These results substantiate the recommendation by Kononoff et al. (2003) for less than 8% on the top sieve but 30 to 50% on the second sieve.

Ration Change Over Time

We observed an increase ($P < 0.01$) in NDF content and a decrease ($P < 0.01$) in CP and DM content over time (Table 4). The NDF content least squares means increased 6.75 percentage units from the initial ration to the orts ($P < 0.01$). In contrast, the least squares means of the CP content decreased 1.52 percentage units from the initial ration to the orts ($P < 0.01$). Some cows could be consuming a ration lower in NDF and higher in starch, which could lead to ruminal acidosis.

Studies have reported sorting of TMR against longer particles in favor of shorter particles in group-housed cattle. In the current observational study, complete data were not available to demonstrate that cows were indeed sorting the TMR. However, sorting activity against long particles could be a likely explanation for the changes in TMR NDF content. DeVries et al. (2007) used the Penn State Separator to investigate whether the amount of forage in the TMR of cows housed in a

Table 4. Least squares means of DM, NDF, and CP content of each TMR sample[1] for high-producing Holstein cows in 50 freestall herds

Item	1	2	3	4	5
DM, %	52.1[a]	50.3[bc]	49.9[bc]	50.5[b]	49.4[c]
NDF, %	30.6[a]	32.3[b]	33.3[c]	34.0[c]	37.4[d]
CP, %	17.5[a]	17.0[b]	16.9[b]	16.7[b]	15.9[c]

[a–d]Means within a row with different superscripts differ ($P < 0.01$).

[1]Sample 1 = initial TMR; samples 2, 3, and 4 = samples every 2 to 3 h; sample 5 = orts.

Table 5. Multivariate regression mixed model of the risk factors associated with TMR NDF content change over time for high-producing Holstein cows in 50 freestall herds

Risk factor	Coefficient	SE	*P*-value
Time after feed delivery, h	0.38	0.06	<0.001
Initial TMR DM content, %	−0.17	0.07	0.035
Feeding frequency, times/d			
1 vs. 2 or 3	1.59	0.75	0.018

freestall barn would affect feed sorting behavior and found that cows sorted against long particles in both diets (62.3 or 50.7% forage), but cows fed the lower forage diet had greater feed sorting activity. Martin (2000) evaluated change in the particle size distribution of the TMR in a freestall herd and found changes in the mass retained by the top screen and the bottom pan of the Penn State Particle Separator 23.5 h after feed delivery. The mass retained on the top screen increased 6.3-fold, whereas the mass on the bottom pan decreased 3.0-fold. Leonardi and Armentano (2007) found that cows housed in a freestall facility sorted their rations against longer particles, favoring finer particles. The intake of the longest particles, expressed as a percentage of the predicted intake, was 63.3%. Sorting was also evaluated when the same cows were housed in a tiestall barn. Their intake of the longest particles was 73.2% when fed individually, indicating that cows can sort even more when housed in a group.

Risk Factors for Ration NDF Content Change Over Time

Feed push-up frequency, percentage of hay in the ration, feed bunk barrier design, feed bunk space per cow, and all interaction effects were excluded from the statistical model because of lack of significance. Visual evaluation of the residual plots and the distribution of the random intercept and slopes did not indicate violations of the model assumptions. The presence of a few outlier observations did not change the main findings of the study; therefore, outliers were retained.

The analysis of the other risk factors showed that time after feed delivery ($P < 0.01$) and feeding frequency ($P < 0.05$) were associated with greater changes in NDF content over time. In contrast, initial TMR DM content ($P < 0.05$) was associated with lower NDF content change (Table 5).

Greater initial DM content (drier TMR) was associated with lower NDF content change over time. An increase of 1 percentage unit in DM content was associated with a reduction of 0.17 percentage units in NDF. The magnitude of the association was low and probably not biologically significant. In addition, there might be a confounding factor with drier rations in this data set having a greater percentage of dry hay. Leonardi et al. (2005) reported that adding water to the TMR decreased its DM content and reduced the sorting for shorter particles. It is suggested that drier TMR are more susceptible to being sorted because their particles are less likely attached to each other and the movement of the tongue and nose of the cows could then easily separate the ration by particle size.

The feed barrier design (headlocks or post and rail) was not associated with particle size change over time. Huzzey et al. (2006) found that headlocks reduced the aggression between cows at the feed bunk and concluded that the physical separation provided by headlocks could be used to reduce the competition for feed bunk space, thus possibly decreasing sorting activity. The data collected from this study did not allow us to reach that conclusion because sorting behavior could not be accurately measured.

Martin (2000) and Shaver (2002) recommended adding less dry hay to the ration to reduce the feed sorting activity of cows. We found that the hay content of the TMR was not associated with ration particle size

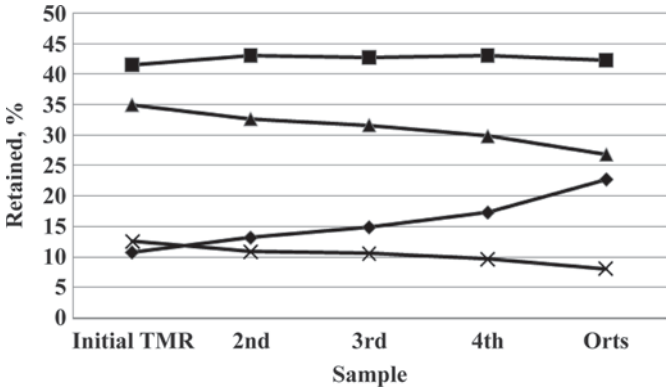


Figure 1. Average percentage of material retained on each sieve of the Penn State Forage and TMR Particle Size Separator over time [top (▲; >19 mm), second (■; >8 mm), third (♦; >1.18 mm), and bottom (×; <1.18 mm) pans] for 50 freestall herds in Minnesota. Samples represent the initial TMR collected at feed delivery; the second, third, and fourth samples collected every 2 to 3 h after feed delivery; and the orts.

Table 6. Management and production characteristics (averages) of the high-production groups of Holstein cows grouped in percentiles[1] according to the changes[2] of the TMR NDF content over time

	Low change			High change		
Variable	10th	25th	50th	50th	25th	10th
Forage in the ration,[3] %	47.68	50.30	50.0[a]	54.62[b]	55.97	53.18
Hay in the ration,[3] %	0.88	2.93	3.55	5.30	5.41	7.06
Linear space in feed bunk, m/cow	0.41	0.39	0.43	0.48	0.45	0.49
Particles >19 mm,[4] %	5.83[a]	8.10	10.5	11.49	10.33	13.76[b]
Particles <1.18 mm,[4] %	11.30	11.47	11.88	13.29	13.16	14.35
Daily milk yield, kg/cow	37.83	41.92	41.41[a]	38.26[b]	38.58	38.89
Milk fat, %	3.62	3.47	3.49	3.52	3.66	3.65
Milk protein, %	3.03	2.84	2.88	2.91	2.92	2.94

[a,b]Means within a percentile (e.g., 10th vs. 10th) with different superscripts differ ($P < 0.05$).

[1]Best linear unbiased prediction for random effect ordered from highest to lowest.

[2]Low change corresponds to smallest changes in TMR NDF content over time; high change corresponds to greatest changes.

[3]On DM basis.

[4]Measured with the Penn State Forage and TMR Particle Separator (Kononoff et al., 2003).

change over time; however, the use of hay as a source of forage was not very common in the rations evaluated. Hay inclusion ranged from 0 to 16% of the TMR, with an average of 4.4%. Martin (2000) and Shaver (2002) also recommended an increase in the frequency of fresh feed delivery and push-up to reduce the sorting of the TMR because pushing-up can result in some mixing of the feed. In the current study, the frequency of feed delivery was associated with NDF content change; herds that fed cows once daily had greater change than herds feeding 2 or 3 times daily.

Percentile Distribution for Rate of Change of NDF Content Over Time

The groups of cows on each farm were ranked based on the rate of change of the TMR NDF content over time by percentile distribution (Table 6) using the BLUP for the random effect of farm. Groups with a greater rate of NDF content change had greater proportions of longer particle material in the ration, greater percentage of forage in the ration, and lower milk production ($P < 0.05$) compared with groups that had a lower rate of change of NDF content over time.

Groups with higher rates of NDF change over time had lower daily milk yield. Cows in the top 50th percentile of high-production groups with greater rates of change in particle size produced approximately 3 kg/d less milk (adjusted for components and DIM) than cows in the 50th percentile for lower rates of change. It is possible that herds with less change in the TMR NDF content over time were herds with better overall management, which could result in better animal performance. Additionally, this observation could be confounded with feeding diets containing greater proportion of forage, and, therefore, relatively less milk production per cow. Milk composition (percentages of fat and protein) was similar among percentiles.

CONCLUSIONS

Information collected in this observational study indicated that the majority of freestall dairy farms in Minnesota fed cows once daily in 3-row pens with post and rail feed barriers, and provided 0.45 m of feed bunk space per cow. The main forage used in the ration was corn silage, and rations had adequate concentrations of NDF and CP. We could not measure feed sorting behavior because of the methodology used. However, we observed that ration NDF content increased over time. This chemical change in the TMR could potentially be detrimental to certain cows. Some feeding management practices and TMR characteristics were associated with the particle size change over time. Therefore this effect may be minimized by implementing management changes (e.g., increasing feeding frequency to twice daily).

This was an ecological type of study; therefore, the observations and conclusions based on groups of cows could not be extrapolated to an individual-cow level. Another limitation of this type of observational study was its inability to demonstrate a cause–effect relationship between the TMR NDF content change and the hypothetical risk factors. Controlled studies with groups of cows are needed to establish the causality relationship of these associations as well as a more in-depth analysis of the factors that affect particle size change and feed sorting behavior of cows.

ACKNOWLEDGMENTS

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REFERENCES

Albright, J. L. 1993. Feeding behavior of dairy cattle. J. Dairy Sci. 76:485–498.

AOAC. 1995. Official Methods of Analysis. 16th ed. Association of Official Analytical Chemists, Arlington, VA.

ASAE. 2001. Terminology and recommendations for freestall dairy housing, freestalls, feed bunks, and feeding fences. ASAE Standards. EP444.1 DEC99. http://asae.frymulti.com/standards.asp

Castle, M. E., and T. P. Thomas. 1975. The water intake of British Friesian cows on rations containing various forages. Anim. Prod. 20:181–189.

DeVries, T. J., K. A. Beauchemin, and M. A. G. Keyserlingk. 2007. Dietary forage concentration affects the feed sorting behavior of lactating dairy cows. J. Dairy Sci. 90:5572–5579.

DeVries, T. J., and M. A. G. von Keyserlingk. 2005. Time of feed delivery affects the feeding and lying patterns of dairy cows. J. Dairy Sci. 88:625–631.

DeVries, T. J., M. A. G. Von Keyserlingk, and K. A. Beauchemin. 2003. Short communication: Diurnal feeding pattern of lactating dairy cows. J. Dairy Sci. 86:4079–4082.

DeVries, T. J., M. A. G. Von Keyserlingk, and D. M. Weary. 2004. Effect of feeding space on the inter-cow distance, aggression, and feeding behavior of free-stall housed lactating dairy cows. J. Dairy Sci. 87:1432–1438.

Heinrichs, A. J., and P. J. Kononoff. 2002. Evaluating particle size of forages and TMRs using the new Penn State Forage Particle Separator. Tech. Bull. Penn. State Univ., Coll. Ag. Sci., Coop. Ext. DAS 02–42. Penn State University, PA.

Hintz, R. W., D. R. Mertens, and K. A. Albrecht. 1996. Effects of sodium sulfite on recovery and composition of detergent fiber and lignin. J. AOAC Int. 79:16–22.

Huzzey, J. M., T. J. DeVries, P. Valois, and M. A. G. von Keyserlingk. 2006. Stocking density and feed barrier design affect the feeding and social behavior of dairy cattle. J. Dairy Sci. 89:126–133.

Kononoff, P. J., A. J. Heinrichs, and D. R. Buckmaster. 2003. Modification of the Penn state forage and total mixed ration particle separator and the effects of moisture content on its measurements. J. Dairy Sci. 86:1858–1863.

Leonardi, C., and L. E. Armentano. 2003. Effect of quantity, quality, and length of alfalfa hay on selective consumption by dairy cows. J. Dairy Sci. 86:557–564.

Leonardi, C., and L. E. Armentano. 2007. Short communication: Feed selection by dairy cows fed individually in a tie-stall or as a group in a free-stall barn. J. Dairy Sci. 90:2386–2389.

Leonardi, C., F. Giannico, and L. E. Armentano. 2005. Effect of water addition on selective consumption (sorting) of dry diets by dairy cattle. J. Dairy Sci. 88:1043–1049.

Martin, R. 2000. Evaluating TMR particle size distribution: A series of on-farm case studies. Page 75 in Proc. Four-State Prof. Dairy Manag. Sem., Dubuque, IA.

Mentink, R. L., and N. B. Cook. 2006. Short communication: Feed bunk utilization in dairy cows housed in pens with either two or three rows of free stalls. J. Dairy Sci. 89:134–138.

NRC. 2001. Nutrient Requirements for Dairy Cattle. Natl. Acad. Sci., Washington, DC.

Olofsson, J. 1999. Competition for total mixed diets fed for ad libitum intake using one or four cows per feeding station. J. Dairy Sci. 82:69–79.

Shaver, R. D. 2002. Rumen acidosis in dairy cattle: Bunk management considerations. Page 75 in Proc. 12th Int. Symp. on Lameness in Ruminants, Orlando, FL. http://ruminantlameness.com/all.pdf

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Erratum to "Feeding management and characteristics of rations for high-producing dairy cows in freestall herds" (J. Dairy Sci. 93:822–829)

M. I. Endres and L. A. Espejo

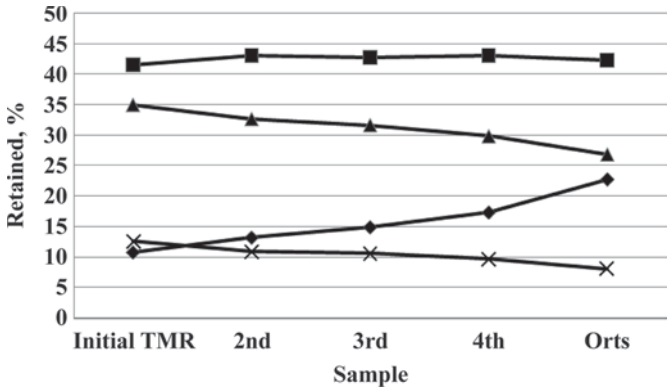


Figure 1. Average percentage of material retained on each sieve of the Penn State Forage and TMR Particle Size Separator over time [top (♦; > 19 mm), second (■; > 8 mm), third (▲; > 1.18 mm), and bottom (×; < 1.18 mm) pans] for 50 freestall herds in Minnesota. Samples represent the initial TMR collected at feed delivery; the second, third, and fourth samples collected every 2 to 3 h after feed delivery; and the orts.

The symbols for the top and third pans were switched in Figure 1. Data for the top pan are represented by diamonds and for the third pan by triangles. The corrected figure and caption are presented here. The authors regret the error.

Endres, M. I., and L. A. Espejo. 2010. Feeding management and characteristics of rations for high-producing dairy cows in freestall herds. J. Dairy Sci. 93(2):822–829.

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Regional carbon footprint analysis of dairy feeds for milk production in the USA

Felix Adom · Ashley Maes · Charles Workman · Zara Clayton-Nierderman · Greg Thoma · David Shonnard

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Abstract
Purpose A greenhouse gas emissions analysis (carbon footprint) was conducted for cultivation, harvesting, and production of common dairy feeds used for the production of dairy milk in the USA. The goal was to determine the carbon footprint (grams CO_2 equivalents (gCO_2e)/kg of dry feed) in the USA on a regional basis, identify key inputs, and make recommendations for emissions reduction.
Methods Commonly used dairy feeds in the USA, such as soybeans, alfalfa, corn, and others, were identified based on a recent literature review and information from dairy farm surveys. The following input data for the cultivation and harvesting of dairy feeds were collected for five US regions: crop production data, energy input, soil amendments, and crop protection chemicals. Life cycle inventory input data were mainly collected from the US Department of Agriculture National Agricultural Statistical Service on a state-by-state basis as well as from state extension services forage crop budget estimates. In addition to consulting other life cycle assessment studies and published articles and reports, this cradle-to-farm gate carbon footprint analysis was conducted using the Ecoinvent™ unit processes in SimaPro version 7.1© (PRé Consultants 2009).
Results The final carbon footprint results (gCO_2e/kg of dry dairy feed) varied regionally depending on a number of factors such as lime and fertilizer application rates. The average national US carbon footprint results of the main feeds were: corn grain (390), corn silage (200), dried distillers grains with solubles (910 dry mill, 670 wet mill), oats (850), soybeans (390), soybean meal (410), winter wheat (430), alfalfa hay (170), and forage mix (160).
Conclusions and recommendations The southeast dairy region generally showed a relatively high level of carbon footprint for most feeds, and this is attributable to the higher application rates of both synthetic fertilizers and lime. The highest contributor to carbon footprint for most regions (apart from soybeans and soybean meal) was due to the application of inorganic nitrogen fertilizer. Efficient transfer of knowledge to farmers with regards to fertilizer best management practices such as precision application of farm nutrients may contribute significantly to reducing regional crop carbon footprints.

Keywords Carbon footprint · Dairy · Feeds · Milk production

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1 Introduction

The issue of environmental sustainability has become a prominent factor in decision-making for industries in

addressing environmental challenges, such as global climate change. The United States (US) dairy industry inaugurated a study to analyze greenhouse gas (GHG) emissions from milk production in the USA. The US dairy milk supply chain can be divided into the following major stages: (a) feed production, (b) milk production, (c) milk delivery to processor, (d) processing, (e) packaging, (f) distribution, (g) retail activities, (h) milk consumption, and (i) disposal. In a comprehensive report, within which this article is a part, each stage was analyzed independently and combined to provide the carbon footprint for the dairy supply chain (Thoma et al. 2012). This article here focuses on the production of dairy feed in the USA using sources of data at the level of individual states and then aggregates that information into five dairy regions.

While there have been a number of life cycle assessment (LCA) studies on crops in Europe, there have been relatively few in the USA. The Ecoinvent™ (PRé Consultants 2009) database contains many food and forage crop inventory profiles, but these are from European data sources. Hayashi et al. (2006) reviewed the progress of LCA studies in Europe for areas like renewable energy, animal production, and horticulture. In the USA, there were several LCA studies conducted on single crops such as switchgrass, soybeans, and corn associated with bioenergy product analyses, including studies by Kim et al. (2009 a, b), Spatari et al. (2005), Landis et al. (2007), Shapouri et al. (2002), Sheehan et al. (1998), Pradhan et al. (2009), and Rotz et al. (2010). A review of this literature indicated that no previous LCAs considered a large number of crops and dairy feeds, and therefore, our study fills an important gap in the USA with respect to updated analyses for agricultural crops and other dairy feeds.

2 Life cycle assessment methodology

2.1 Dairy feeds, goal, and scope

In this study, ISO protocols were followed and all GHG emissions were expressed as equivalent emissions of carbon dioxide (CO_2e.). Commonly used feeds for US dairy production were identified based on a recent literature source (Mowrey and Spain 1999) and information obtained from a nationwide dairy producer survey regarding the composition of dairy feeds (and other related topics) (Thoma et al. 2012—see Appendix A of Electronic Supplementary Material). Over 5,000 surveys were sent to dairy farmers through their Co-ops from January to May 2009 and a second mailing was conducted in June 2009. Of those surveyed, 531 responded. The main relevancy of this survey to this carbon footprint study was the identification of commonly used dairy feeds in the USA. Responses from the dairy farmer survey and the collection of other crop data were organized on the basis of five regions as shown in Fig. 1. The definition of dairy milk production regions was done through consultation with dairy experts (Thoma et al. 2012). The basis for selection of these regions was a combination of production practices and climatic conditions. There are over 130 distinct dairy feedstuffs included in the results of that survey.

Goal The main goal of this study was to determine the carbon footprint from the cultivation and harvesting of US dairy feeds on a basis of 1 kg of feed harvested or produced in units of grams CO_2 equivalents (gCO_2e)/kg of dry feed. An additional goal was to identify dairy feed inputs with the highest environmental impact to serve as a source of information for improvement in production and as a benchmark against which progress can be measured in the dairy industry.

Scope The scope was a cradle-to-farm gate analysis. In this article, we report on grain, forage crops, and other coproducts [e.g., dried distillers grains with soluble (DDGS) and soybean meal) for which inventory data were available from US government and university extension sources. In this study, we did not consider all of the 130 or so dairy feeds identified in the survey by Thoma et al. (2012). Table 1 shows the three major categories of dairy feeds considered in this study, including grain crops, forage crops, and coproducts. This study includes application of inorganic fertilizers, effects of crop residues, manure application, crop protection chemicals, and energy inputs required for cultivation and harvesting. According to a study by Landis et al. (2007), seed production comprised less than 1% of GHG emissions for corn and soybean. This result was generalized for all dairy feeds analyzed in this study by assuming all

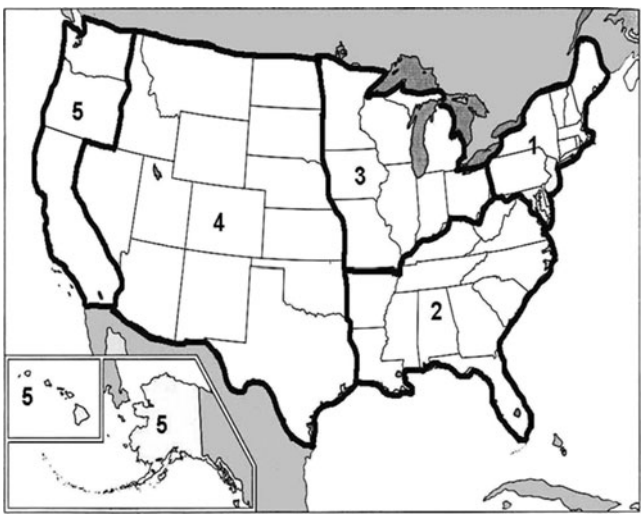


Fig. 1 Dairy production regions used for this study

Table 1 Dairy feeds analyzed in this study

Grain crops	Forage crops	Coproducts
	Alfalfa hay (16%)	
Oats (14%)	Alfalfa silage (16%)	
Soybean (13%)	Forage mix (16%)	DDGS, dry mill (10%)
Corn silage (65%)	Grain mix (15%)	DDGS, wet mill (60%)
Corn grain (15.5%)	Grass hay (16%)	Soybean meal (11%)
Winter wheat (13.5%)	Grass pasture (16%)	
	Grass silage (16%)	

Shown in parenthesis are the percentage moisture content for all feed analyzed in this study (NDSU 2011)

associated inputs for seed production were below cutoff criteria, and hence were excluded. Also, the scope of this carbon footprint analysis does not include incidental effects such as emissions from employee travel to or from the farm. Infrastructure elements, such as construction of buildings and farm equipment, were also excluded.

2.2 Functional unit

The functional unit for this carbon footprint study was 1 kg of dairy feed (grains, forage crops, and other coproducts) harvested or processed on dry matter basis.

2.3 Geographical boundaries

The geographical context of this carbon footprint study is the USA for dairy feeds grown and produced in the USA.

2.4 Allocation procedure

Most dairy feeds produced no coproducts, but for certain feeds, it was not possible to avoid allocation. For those feeds, allocations based on market value were used, as shown in Table 2. Section 3.1 explains the basis for allocation of nitrogen (N) inputs to corn and corn silage. Sections 3.1.1 and 3.1.2 explain in more detail the economic allocation to soybean oil and meal as well as wet and dried distillers grains with solubles. Five-year average commodity cost data from Illinois were used for economic allocation of soybean oil and meal, which was assumed to be representative of the national commodity market (USDA-IL 2010). Also, mass allocation based on a 5-year average yield provided by the National Oilseeds Processing Association was used for testing scenario cases, while economic allocation was adopted as the base case. Economic and mass allocation values for dried distillers grains with solubles from the thesis by Kodera (2007) were used in this study.

Table 2 Summary of allocation ratios and types used in this study

Coproduct	Economic allocation	Mass allocation
Soybean oil/meal/hulls	56.7:41.2:2.1	19.4:74:6.6[a]
DDGS dry/ethanol	30:70	52:48
DDGS wet/ethanol	24:76	51:49
Dairy feed/corn		Causal allocation
Corn/corn silage[b]		
Region 1		59:41
Region 2		91:9
Region 3		96:4
Region 4		95:5
Region 5		No data
		Causal relationship based on crop nitrogen requirements determined from reported yield

[a] CGB (2010)

[b] The large differences between regions are primarily determined by the relative production of each crop. More silage is grown in region 1 compared to corn grain than the other regions, and therefore, the allocation of shared inputs is not nearly equal

2.5 Inputs versus inventory data and possible limitations

Inputs such as fertilizer and fuel used for each crop production system were obtained from US government sources and the US literature. Inventory data underlying those inputs are largely from the Ecoinvent™ database (PRé Consultants 2009), which mostly represents European production. This presents a possible limitation to this study. However, European inventory data, while not geographically relevant, are technologically relevant for the inputs used in this US study because both US and European production uses modern technology. In addition, inventory data for many study inputs are simply not available yet based on US production.

3 Life cycle inventory analysis

A life cycle diagram describing the key inputs for each crop production system is shown in Fig. 2. The major inputs included: inorganic and organic fertilizer application on the farm, agrochemicals used to control pests, and farm energy use. Lime application on the farm was considered for some of the crops where data were available as well as effects of crop residues on direct and indirect nitrous oxide (N_2O) emissions. Energy use included gasoline, diesel, liquefied petroleum gas (LPG), natural gas, and electricity. GHG emissions for this analysis include: carbon dioxide (CO_2), methane (CH_4), N_2O, solvents, and refrigerants. Solvents and refrigerants were not directly included as

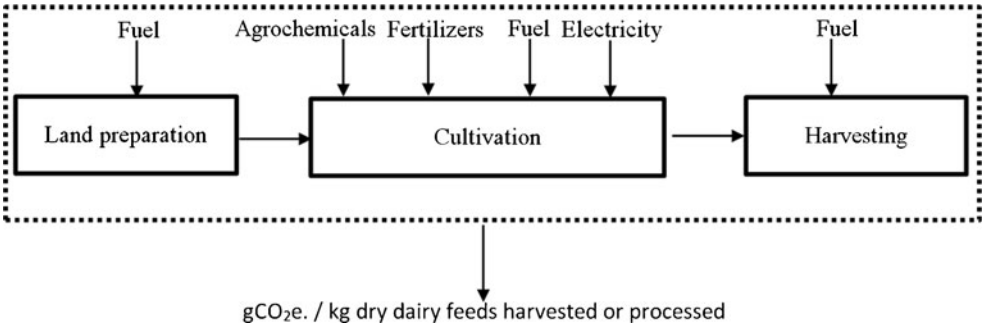


Fig. 2 Life cycle diagram for the cultivation and harvesting of dairy feed crops. *Dotted lines* represent the system boundary considered in this carbon footprint analysis

system inputs, rather these were incorporated by the use of Ecoinvent™ ecoprofiles (PRé Consultants 2009) for the various crop inputs. N_2O emissions from nitrogen fertilizer application for the degradation of crop residues and manure application were accounted for using IPCC (2006) guidelines for national GHG inventories (tier 1).

3.1 Production inputs and inventory for grains: corn, oats, soybeans, and winter wheat

Every year, the US Department of Agriculture (USDA) National Agricultural Statistical Service (NASS) conducts hundreds of farm surveys on cropping practice, chemical use, farm costs, and income. It is usually structured in a three-phase annual survey with specific goals. Phase I screens various farms for commodities and for potential inclusion in phases II and III, and this is done usually on a state-by-state basis. Phase II collects data on chemicals, fertilizer, and pesticides and has only one collection mode—personal interviews via-face-to-face contact. Phase III focuses on detailed economic information about the agricultural operation and the operator's household. Response rate from farmers has been highest for phase II with an average response rate of 80% from 2002 to 2006 and an average sample size of 5,465 according to the National Research Council (2008).

Table 3 summarizes the major crop databases and sources of the dairy grain crops. The USDA NASS databases were the primary source of crop production data for this study. Specific data obtained on a state-by-state basis included area harvested, yield, and total production. Average values for the harvested acres, yield, and production over the 5-year production period (2004–2008) were calculated and used. Annual crop production data for soybean, oats, wheat, corn grain, and silage for the 5-year period were obtained from the crop production summary reports from USDA NASS (2009a, 2007a). Appendix B of the Electronic Supplementary Material shows the computational spreadsheets of the major crops discussed here.

MacDonald et al. (2009) established that about 5% of US cropland receives animal manure, with corn land receiving over half of this applied manure. The percentage of planted acres receiving manure (manure share) was highest for corn and oats, being 11.6% and 9%, respectively. For all other grain crops, this area percentage for manure was approximately 1% or less. Therefore, we assume that only corn and oats receive manure as a fertilizer supplement. Dairy production regions needing supplementation with manure were identified by estimating the growth nitrogen requirements to meet crop production yields and comparing these with reported inorganic nitrogen inputs from the USDA NASS databases. The following sections explain in more details how the manure inputs were determined.

Corn Combined corn and silage input data for fertilizer and chemical application rates were obtained for states in regions 1, 2, 3, and 4, but no data were reported for region

Table 3 Crop databases and data sources for dairy grains

Summary of crop inventory and data source	
Soybean and soybean meal	Data sources
Area harvested/production data	USDA NASS (2009a, 2007a)
Fertilizer and agrochemical inputs	USDA NASS (2007b)
Lime input	Pradhan et al. (2009)
Energy inputs	Sheehan et al. (1998)
Oats	
Area harvested/production data	USDA NASS (2009a, 2007a)
Fertilizer and agrochemical inputs	USDA NASS (2006)
Lime input	Pradhan et al. (2009)
Energy inputs	Dartt and Schwab (2001)
Wheat	
Area harvested/production data	USDA NASS (2009a, 2007a)
Fertilizer and agrochemical inputs	USDA (2007b)
Energy inputs	Piringer and Steinberg (2006)
Corn	
Area harvested/production data	USDA NASS (2009a, 2007a)
Fertilizer and agrochemical inputs	USDA NASS (2006)
Energy inputs	Shapouri et al. (2002)
DDGS (dried distillers grains with solubles)	Hill et al. (2006)
	Wang (2001)
	Kodera (2007)
	Kim and Dale (2002)

5. USDA NASS database reported separate productivity data for corn grain and silage. Agrochemical chemical input data such as inorganic fertilizers and herbicides were reported for combined corn and silage land area. Productivity data indicated that region 5 contributed less than 1% toward the total corn production in the USA. MacDonald et al. (2009) in their report on manure usage for fertilizer estimated that 408 million kg of manure nitrogen was applied to corn grain and silage in the USA in 2007. The USDA NASS data for nitrogen application rates do not include manure contributions. In addition, the reported inorganic N application rates do not meet known crop requirements of approximately 0.54 kg N/bushel (bu) for corn grain and 5.19 kg N/mt for silage as defined by numerous crop production budgets (NDSU 1992). The amount of manure N required to reach the crop requirement was determined on a state-by-state basis using this equation: manure N = corn N growth requirement − synthetic N fertilizer application − residual N following rotation with soybeans. Using crop budgets for a corn–soybean rotation, it was estimated that approximately 23 kg N/ac was supplied in soybean residue (MSU 2010). The organic N from manure was applied in a manner to force the total N per crop to match the growth requirements mentioned above. Using a causal allocation based on the crop nitrogen requirements for both grain and silage, other crop inputs were allocated. Table 2 shows the allocation ratios used in this model for the various dairy production regions. Using this method, the total manure nitrogen applied to corn was approximately matched to the reported annual application rate of 408 million kg within a 4% margin. Specific inputs (e.g., lime) for the various crops are further explained in subsequent sections.

Soybeans In the case of soybeans, the USDA NASS (2009a, 2007a, b) had data such as quantity of inorganic fertilizer used, area harvested, crop productivity, chemical use, and other information for states in regions 2, 3, and 4. Soybean energy inputs and lime application rate data were obtained from Sheehan et al. (1998) and Pradhan et al. (2009), respectively. Inorganic nitrogen input data from USDA NASS (2007b) were included, while manure inputs were not because MacDonald et al. (2009) reported a manure share of approximately 1% of acres for soybean. Section 3.1.1 provides the sources of inventory data for the soybean meal–oil. The average of the carbon footprint in regions 2, 3, and 4 was used to represent regions 1 and 5 for which there were no data available.

Oats The primary source of data for fertilizer and chemical inputs for oats was from USDA NASS (2006). However, no input data (e.g., inorganic fertilizer and crop protection chemical) were reported for the states in region 2, and this is due to its relatively low oats productivity (5% of oats production). Due to the unavailability of input data for lime application for oat-producing states, the national average lime application rate for soybeans was assumed for the oats analysis (extension documents validated this estimate). Based on the N requirement recommendation of 0.5 kg N/bu and 40 kg N/ac (Beegle 1997), NASS reported inorganic N input data for dairy production regions 1 and 3 were low, requiring supplementation with manure. The reported inorganic N input data for regions 4 and 5 were sufficient to meet N requirement of oats. An estimated 20 kg N/ac of additional N from manure meets the reported yields, and this was applied to regions 1 and 3 on a state-by-state basis. This method does not take into account any nitrogen credit from prior rotation unlike in the case of manure GHG impact estimation for corn. Section 3.5 provides the details on energy inputs. Finally, due to lack of data for region 2, the inventory for this region was estimated by averaging regions 1, 3, 4, and 5.

Winter wheat This study focused on winter wheat because it accounts for 70% to 80% of the total wheat produced in the USA (USDA NASS 2009b) as compared to other types like durum and spring wheat. Productivity data were obtained from USDA NASS (2009a, 2007a); however, no data were available for the energy inputs on a state-to-state basis. Energy estimates for the production of wheat in the USA on a per hectare basis was obtained from Piringer and Steinberg (2006) for the wheat analysis. Manure impact was not considered for wheat primarily because it has less than 1% of acres applied with manure (MacDonald et al. 2009).

For all crops, input data for fuel and electricity consumption on the farm for crop production were obtained from the technical literature, state agricultural extension services, the US Department of Energy, the USDA, and other academic institutions (see Table 3). There are three regional interconnection grids in the USA, namely, Eastern Interconnection, Western Interconnection, and the Electric Reliability Council of Texas Interconnection. GHG emission factors (in gCO_2e/kWh) were constructed using Ecoinvent™ unit processes (PRé Consultants 2009) based on regional fuel mixes. Additionally, precombustion emissions and the transmission and distribution losses were included in the emission factor using regional interconnection grid data reported by Deru and Torcellini (2007). Section 3.5 of this article explains in more detail the assumptions and data sources for the specific crops for which energy input data were not available.

3.1.1 Soybean meal–oil–hull allocation

In the soybean meal analysis, additional processes were considered including transporting soybean to the crusher and crushing to recover oil and meal. The impact of

transporting soybean to the crusher was estimated as well as the impact of crushing with the use of data obtained from Sheehan et al. (1998), Pradhan et al. (2009), and Pollak (2010). The crushing and extraction energy required were updated based on a more recent study by Pradhan et al. (2009). Allocation to meal and oil were based on economic value of the coproducts from price data averaged over 2004–2008. The primary data source for prices was from Illinois, but is expected to be representative of the national commodity markets during the time period (USDA-IL 2010). Soybean meal allocation factors are shown in Table 2.

3.1.2 Dried distillers grains with solubles

Articles from the technical literature representing work done by LCA experts with corn ethanol and DDGS were used in this analysis. A thesis by Kodera (2007) performed a review of the effects of allocation method on LCA impacts of corn ethanol production by the dry milling process, for example, mass, energy, and value allocation as well as system expansion. Based on the allocation factor summary in this thesis and a study by Kim and Dale (2002), an allocation of the GHG burdens for corn ethanol production was made to DDGS in our model. As shown in Table 4, allocation factors varied widely and this resulted in some uncertainty for DDGS carbon footprint analysis. The DDGS GHG emissions values in this table were obtained using the allocation factors shown combined with GHG emissions for corn ethanol from three studies (Hill et al. 2006; Wang 2001; Shapouri et al. 2003) and DDGS production data from Hill et al. (2006). Detailed analysis of wet mill and dry mill DDGS can be found in Appendix B-6 of Electronic Supplementary Material.

3.2 Production inputs and inventory for forage crops: alfalfa, alfalfa silage, grass hay, grass pasture, and grass silage

To estimate the inventory for cattle forage production, crop production budgets produced by state agriculture extension specialists were collected and used as the primary source of input data. These budgets estimated the inputs needed to produce alfalfa, grass hay, silage, and pasture. These are not actual production records, but estimates prepared by agricultural extension agents with detailed knowledge of agronomic conditions in specific states. For this analysis, inventory data on fuel, electricity, fertilizers, soil amendments (N, P, K, sulfur, boron, and lime), and crop protection chemicals were used. When only purchase price for inputs was given, price was converted to quantity using information from budgets published on the same year that provided both price and quantity for the inputs in question. Pesticide application rates varied widely, depending on the type of pesticide. For budgets where only estimated pesticide purchase price was provided, available cost data were used to convert to quantities (Schnitkey 2004). MacDonald et al. (2009) reported that 6.9% (manure share) of hay and pasture land received manure as fertilizer. Because the budgets used to create the unit processes for these forage feeds report recommended total organic and inorganic nitrogen application rates together, it was assumed that 6.9% of the fertilizer applied was in the form of manure. In several cases, budgets provided total quantity of fertilizer, but did not specify the percentage breakdown for each. In this case, a ratio of 20:40:40 NPK for alfalfa was chosen, as it is a nitrogen fixer. For grass, we used 50:25:25.

Some budgets included custom costs for contracted services such as tilling, planting, or harvesting rather than providing explicit input estimates for each of these processes. Using figures from MSU Extension (MSU 2010) that showed custom costs per acre and fuel cost per acre for different practices, it was found that 16% of custom costs for tillage went to fuel, 12% to planting, 18% to fertilizers, and 18% of harvesting costs went to fuel. Over a 5-year period, a typical field is tilled and planted once, fertilized five times and harvested twice per year (10×); thus each practice was weighted by these estimated rates, giving tillage and planting a value of 1, fertilizing a value of 5, and harvesting a value of 10. As a result, a weighted average of 18% of custom costs was attributed to the consumption of diesel fuel.

There is a large difference in diesel use for hay, silage, and pasture. Most states provided budgets for hay, but fewer

Table 4 Allocation factors and GHG intensity of DDGS (see Appendix B-6)

	Energy	Mass	Economic	System expansion	References
Allocation factor to ethanol	0.57	0.48	0.70	0.80	Kim and Dale (2002); Kodera (2007)
Allocation factor to DDGS	0.43	0.52	0.30	0.20	
DDGS GHG emissions [kg CO_2e/kg DDGS (dry)]	1.60	2.30	0.91	0.53	
Corn ethanol (kg CO_2e/MJ ethanol)		0.0849			Hill et al. (2006)
		0.07			Wang (2001)
		0.062			Shapouri et al. (2003)

for pasture or silage. Using those few states that provided diesel use data for both (primarily regions 2 and 3), the average difference in diesel used to harvest hay or silage per short ton of crop was calculated. We assumed the dry matter yield was equivalent for pasture, hay, or silage. The only difference was harvesting and hauling. After finding the mean diesel use for hay for each region, we added ~1 gal per dry short ton of crop if harvested as silage and subtracted ~3 gal if kept as pasture.

3.3 Direct/indirect N_2O emissions

The IPCC (2006) tier 1 method was used to calculate direct and indirect N_2O emissions from managed soils for inputs such as synthetic and manure N fertilizer, N in crop residues (above and below ground residues) as well as CO_2 released by lime and urea-containing fertilizer. Direct N_2O release was estimated as 1% of N applied to soil released as N in N_2O. For indirect N_2O emissions, two major pathways were included. The first is the volatilization of N as NH_3 and oxides of N at a rate of 10% of applied N, and redeposition of these gases on water bodies where N_2O–N is emitted at a rate of 1% of the redeposited N. Leaching and runoff is the second pathway with a default leaching factor of 30% of applied N and an emission factor for N_2O–N of 0.75% of leached N. When urea ($CO(NH_2)_2$) is applied, it can be converted to ions like ammonium (NH_4^+) and bicarbonate (HCO_3^-) in the presence of urease enzymes and release CO_2. GHG emission from lime application is dealt with in Section 3.6. In this study, dinitrogen monoxide (N_2O) emissions for manure application is a combination of direct and indirect mechanisms as discussed above (see Appendix C of the Electronic Supplementary Material) including emissions from manure management systems (MMS).

The USDA NASS database does provide N fertilizer input data for crops (see Table 3); however, this database does not indicate the type of nitrogen fertilizer applied to crops. The production of different nitrogen fertilizers results in very different quantities of GHG emissions from their production. Therefore, an average US nitrogen fertilizer production profile was created for this study. Data on fertilizer consumption in the USA from the period of 2004–2007 was obtained and used to create the synthetic N ecoprofile for this analysis (Appendix D-1 and D-2 of Supplementary Documents). One of the N fertilizers, nitrogen solutions, was comprised of urea (35%), ammonium nitrate (40%), and water (25%) (Dyno Nobel Inc, MSDS 2010; Vitosh 1996).

For phosphorus fertilizer, a similar approach as for N fertilizer was taken by basing the mixture of phosphate fertilizers in proportion to their US production (USDA ERS 2009) as reported in Appendix D-3 of the Electronic Supplementary Material. Potassium and sulfur fertilizers as well as lime were treated similarly.

3.4 Crop protection chemicals

Insecticides, herbicides, and fungicides applied on the farm were considered in our analysis. In cases where the ecoprofile of a pesticide was not found in the Ecoinvent™ database in SimaPro 7.1© (PRé Consultants 2009), the chemical class was used. For instance, tebupirimphos which was not directly listed in the Ecoinvent™ database belongs to the organophosphorous class of compounds (PAN Pesticides Database 2009) and this was the ecoprofile used in our model. Rate of crop protection chemical application for soybean and winter wheat were all obtained from USDA NASS (2007b) while that of corn and oats were obtained from USDA NASS (2006). Forage crop protection data were obtained from state extension budgets as mentioned earlier.

3.5 On-farm energy

This analysis accounted for the following energy inputs on the farm: electricity, gasoline, diesel, LPG, and natural gas. Due to the lack of energy input information in the USDA NASS database, other sources were used to fill in the required data for the crop analysis. Energy input data for forage energy were from state extension documents as mentioned previously. Soybean energy input data were obtained from Sheehan et al. (1998) and represented 14 soybean-producing states, which together accounted for about 86% of the soybean produced in the USA. Additionally, energy input data for corn producing states were obtained from Shapouri et al. (2002) and represented about 80% of corn produced in the USA. In the case of oats, data for diesel use were obtained from Dartt and Schwab (2001). Due to lack of data on gasoline consumption for oats cultivation and harvesting, it was assumed that gasoline consumption was equal to one third of diesel consumption, based on diesel and gasoline inputs for other field crops, for example corn and soybeans. To fill data gaps, LPG and electricity inputs for corn and soybean were then averaged on a regional basis and used as an estimate for oats. Energy estimates for production of wheat in the USA on a per hectare basis was obtained from Piringer and Steinberg (2006).

3.6 Lime application

Lime application rates for soybean were obtained from Pradhan et al. (2009). In the case of oats, the national average of lime application rate for soybeans was assumed, which in our study (358 lb lime/acre) falls within the recommended range from two budgets that were obtained from

KSU (2003) and Crozier et al. (2004). Lime application data for corn grain and silage were estimated using a crop production budget (MSU 2010). While data on lime application rate were not available for wheat production, it appeared that lime was seldom used. For example, only 9% of wheat land area has ever been treated with lime based on a 1997 survey by USDA (Heimlich 2003). According to a US Geological Survey (USGS 2007) approximately 10.8 billion and 32 million kg of limestone and quicklime were applied in the US agricultural sector, respectively. As a result, every kilogram of an average US lime comprises 0.997 kg $CaCO_3$ and 0.003 kg of CaO. Final GHG intensity of lime accounts for both the production and its application on the field. Due to the on-farm application of calcium carbonate to acidic soils, CO_2 is released, which was accounted for in this study using the emission factor from the IPCC (2006) (see Section 3.8 for emission factor).

3.7 Crop residue effects on direct/indirect N_2O emissions

In this study, the 2006 IPCC guidelines for national GHG inventories (tier 1) was used to account for the N_2O emissions from the degradation of crop residues above and below ground. The average regional yields for various dairy feeds were converted on a dry weight basis to obtain a kilogram dry crop per harvested area. In addition, other parameters like the N content and weight of dry matter residue above and below ground allowed for the final estimation of kilogram N above and below ground of crop residue per kilogram of crop harvested. Appendix E of the Electronic Supplementary Material shows the detailed analysis of N_2O emissions of crop residues.

3.8 Emission factors for fertilizer, crop protection chemicals, and energy input

The emission factors are shown in Table 5 for the production and use of various fertilizers, lime, and energy inputs. Emission factors for pesticides are listed in the Electronic Supplementary Material (see Appendix F).

3.9 Data quality

The pedigree matrix derived from Frischknecht et al. (2007) was used to assess the quality of data, primarily fertilizer and other N_2O emissions, crop protection chemicals, and

Table 5 Emission factors for farm input: fertilizer, agrochemical, and energy

Farm inputs		Emission factors	Sources
Fertilizer	N	3.871 kg CO_2e/kg N in US mix N fertilizer due to manufacturing of N fertilizer	USDA ERS (2009)[a]
		0.633 kg CO_2e/kg N in US urea in US mix of N fertilizer due to field emissions CO_2	IPCC (2006)
		6.205 kg CO_2e/kg N in US mix of N fertilizer due to direct and indirect N_2O field emissions	Ecoinvent Database (PRé Consultants 2009)
	P	3.028 kg CO_2e/kg P in US mix P fertilizer due to manufacturing of P fertilizer (applied as P)	USDA ERS (2009)
			Ecoinvent Database (PRé Consultants 2009)
	K	0.573 kg CO_2e/kg K in US mix K fertilizer due to manufacturing of K fertilizer	USDA ERS (2009)
			Ecoinvent Database (PRé Consultants 2009)
	S	3.855 kg CO_2e/kg S in fertilizer	Ecoinvent Database (PRé Consultants 2009)
Agrochemicals	Lime	0.0158 kg CO_2e/kg lime due to manufacturing	USGS (2007)[b]
		0.4400 kg CO_2/kg $CaCO_3$ due to application on farm	
Fuel	Gasoline	10.96 kg CO_2e/gal	Deru and Torcellini (2007)
	Diesel	11.89 kg CO_2e/gal	
	LPG	7.66 kg CO_2e/gal	SEIT (2006)
	NG	7.72 kg CO_2e/CCF	
Electricity	US region	kg CO_2e/kWh	
	US Avg	0.823	Deru and Torcellini (2007)
	Eastern	0.867	
	Western	0.653	
	ERCOT	0.928	

LPG liquefied petroleum gas, *ERCOT* Electric Reliability Council of Texas, *NG* natural gas, *Avg* average

[a] Source: http://www.ers.usda.gov/Data/fertilizeruse/

[b] http://minerals.usgs.gov/minerals/pubs/commodity/stone_crushed/myb1-2007-stonc.xls and http://minerals.usgs.gov/minerals/pubs/commodity/lime/myb1-2007-lime.xls

energy inputs. Six characteristics of data quality were included: *reliability*, *completeness*, *temporal correlation*, *geographic correlation*, *further technological correlation*, and *sample size*. This was done by assigning a set of scores from 1 to 5 after a careful analysis of each data source (see Appendix G of Electronic Supplementary Material). Using some basic uncertainty (U_7) factors provided in Table 7.2 of Frischknecht et al. (2007) and assessing the data sources according to the six characteristics mentioned above, the square of geometric standard deviation (SD_{g95}) was calculated using Eq. 1:

Equation 1 For calculating SD_{g95}

$$SD_{g95} = \sigma_g^2 = \exp\sqrt{[\ln(U_1)]^2+[\ln(U_2)]^2+[\ln(U_3)]^2+[\ln(U_4)]^2+[\ln(U_5)]^2+[\ln(U_6)]^2+[\ln(U_7)]^2} \quad (1)$$

where U_1 = uncertainty factor of reliability, U_2 = uncertainty factor of completeness, U_3 = uncertainty factor of temporal correlation, U_4 = uncertainty factor of geographic correlation, U_5 = uncertainty factor of other technological correlation, U_6 = uncertainty factor of sample size, and U_7 = basic uncertainty factor.

By assuming a log-normal distribution of uncertainty, the estimated SD_{g95} was used to calculate an upper and a lower bound of the 95th percentile confidence interval for the various dairy feeds on a national basis (Table 6). The geometric mean (in micrograms) was used to estimate the lower and upper bound (gCO2e/kg feed) using Eqs. 2 and 3 (Frischknecht et al. 2007).

Equations 2 and 3 For calculating the lower and upper bound values of carbon footprint

$$\text{Lowerbound} = \frac{\mu_g}{\sigma^2{}_g} \quad (2)$$

$$\text{Upperbound} = \mu_g \times \sigma^2 g \quad (3)$$

4 Life cycle greenhouse gas impact assessment and interpretation of results

4.1 General assumptions for life cycle impact analysis

In estimating the carbon footprint, the GHG emissions were converted to CO_2 equivalents using global warming potentials (GWP) in the "IPCC 2006 100a" method in SimaPro 7.1© (PRé Consultants 2009); GWP is 1 for CO_2, 298 for N_2O, and 25 for CH_4 (Forster et al. 2007). The effects of other greenhouse gases emitted in minor amounts such as refrigerants, halons, and certain chlorinated solvents were also accounted for.

Table 6 Cradle-to-farm gate carbon footprint results of commonly used feeds by region and on national basis (gCO_2e/kg dry feed)

	Production region							
	1	2	3	4	5	Lower bound	Central bound (geometric mean)[a]	Higher bound
Alfalfa hay	190	270	140	140	150	140	170	210
Alfalfa silage	200	280	150	150	160	150	180	220
Corn grain	360	440	370	440	**400**	270	390	560
Corn silage	160	260	190	220	**210**	140	200	290
DDGS, dry mill	910	910	910	910	910	590	910	1,400
DDGS, wet mill	670	670	670	670	670	430	670	1,400
Forage mix	160	260	140	140	150	130	160	200
Grain mix	530	590	520	570	550	450	550	670
Grass hay	300	470	280	270	330	260	320	390
Grass pasture	240	410	250	220	280	130	270	560
Grass silage	310	480	290	280	340	270	330	410
Oats	800	**800**	580	1,000	1,140	580	850	1,240
Soybean	**410**	520	330	390	**410**	270	390	580
Soybean meal	460	540	400	430	450	420	460	490
Winter wheat	380	400	510	500	390	300	430	600

For crops with data presented in bold, no data for production was available; the average of results from other regions was adopted

[a] The geometric mean represents the US national greenhouse gas profiles for the various dairy feed with their respective ranges (lower/upper bound) estimated using the square of geometric standard deviation as shown in Eq. 2

4.2 Regional greenhouse gas emissions of dairy feeds

Table 6 summarizes the regional GHG emissions of dairy feeds on a per dry kilogram basis. Careful examination of the table reveals that there is significant variability among the regions for several feeds. Nearly all of the highest values are associated with region 2, and this appears to be driven primarily by greater nitrogen and lime inputs. The exception is the production of oats in region 5, which is nearly double the lowest value. This is as a result of much higher application rates for N reported in California; approximately three times the rates applied in other areas. This is partially offset by larger yields; however, the yield is only 1.5 to 1.7 times that of other regions. Grass has a higher carbon footprint than other forage crops and nearly as high as corn grain. Regional results for each feed analyzed were combined to estimate the national carbon footprint (see Table 6). Overall, processed coproducts like wet mill and dry mill DDGS and soybean meal show higher GHG emissions.

Results in Table 6 can be compared to recent literature values, though some of these studies occurred in different geographic contexts. Landis et al. (2007) modeled the agrosystem material flows for US corn and soybean by employing the greenhouse gases, regulated emissions, and energy use in transportation (GREET) model. The following results were obtained by Landis et al. (2007): 310–680 gCO_2e/kg of dry corn and 120–290 gCO_2e/kg of dry soybean. The carbon footprint results for corn and soybean at the farm stage from GREET (2010) were 290 and 200 gCO_2e/kg of dry crop, respectively. Two separate studies by Kim and Dale (2009a—40 counties in the USA) and Kim et al. (2009b—eight counties in the USA) estimated 360±100 and 540±290 gCO_2e/kg of dry corn grain, respectively, for US corn-producing counties. In our study, the national carbon footprint of corn grain was estimated to be 390 gCO_2e/kg of dry corn grain, with upper and lower bounds of 270 and 560 gCO_2e/kg of dry corn grain. Additionally, a value of 300 gCO_2e was estimated for 1 kg dry corn at field using the United States Life Cycle Inventory database in SimaPro (PRé Consultants 2009). The GHG emissions of 1 kg corn silage at the farm gate for the Swiss production processes using Ecoinvent Database was 190 gCO_2e/kg of dry corn silage, a value close to corn silage for our study in Table 6. A value of 620 gCO_2e/kg dry soybean was obtained from the Denmark LCA food database in SimaPro (Denmark LCA Food 2011 and PRé Consultants 2009). Dalgaard et al. (2008), using the EDIP 97 database (a Danish LCA methodology) in SimaPro (PRé Consultants 2009), analyzed the GWP of 1 kg (dry) of soybean meal to be 721 gCO_2e while Pelletier (2008) in the study of the environmental performance in the US broiler poultry sector estimated 297 gCO_2e. Finally, another European study by Van der Werf et al. (2005) estimated the GHG emissions for the production of 1 kg of wheat and barley to be 375 and 400 gCO_2e/kg of dry crop, respectively, while the Denmark LCA food database (PRé Consultants 2009) estimates 710 and 570 gCO_2e for 1 kg of dry wheat and oats, respectively. Taking into account the differences in modeling tools, study scope, and geographical context for the different studies, results from the literature are generally comparable to those obtained in this study. The following sections will display the results in more detail with regard to the relative importance of specific crop life cycle stages and inputs.

4.2.1 Soybean

Soybean showed a lower carbon footprint than some crops due to lower inorganic nitrogen fertilizer application, and this was largely due to the fact that it is a nitrogen-fixing crop. However, significant contributors to the various regional results are: lime application, gasoline, diesel, and N_2O emissions from soybean residues, as shown in Fig. 3. Together, they contributed about 70–86% of the overall GHG emissions in each productive dairy region. Interesting was the relative impact of lime input on the overall regional footprints. Lime input data for regions 2 and 3 for the soybean-producing states were relatively comprehensive (60% and 100% of states reporting, respectively). For region 4, data for lime application were available for just two states out of the six soybean-producing states. Another probable reason could have been the acidic nature of soils in regions 2 and 3 requiring more lime to increase soil pH for plant growth. Emissions of N_2O from crop residues were large compared to N_2O released from the application of N fertilizers for soybeans, a distinctly different feature compared to other crops. Approximately 65% of GHG emissions from N fertilizers were due to field application, with about 35% from manufacture, as also seen from the data in Table 5. Although it was not exactly clear why the states in the midwest (region 3) used relatively lower amounts of diesel, one possible reason was the effect of the Midwest Clean Initiative Diesel (EPA 2011) which encourages operational changes, technological improvements, and use of cleaner fuels for powering equipment. Finally, using the pedigree matrix, the standard deviation with 95% confidence interval for inorganic fertilizer, crop protection chemicals, and energy inputs was estimated to be 1.51, 1.21, and 1.57, respectively (see Appendix G-11 of the Electronic Supplementary Material).

4.2.2 Oats

The major contributors to the oats carbon footprint in the USA (Fig. 4) were identified to be inorganic nitrogen and phosphate fertilizers, manure, lime application, diesel, and the impact of N_2O emissions from oat residues, which together makes up approximately 72–92% of the overall

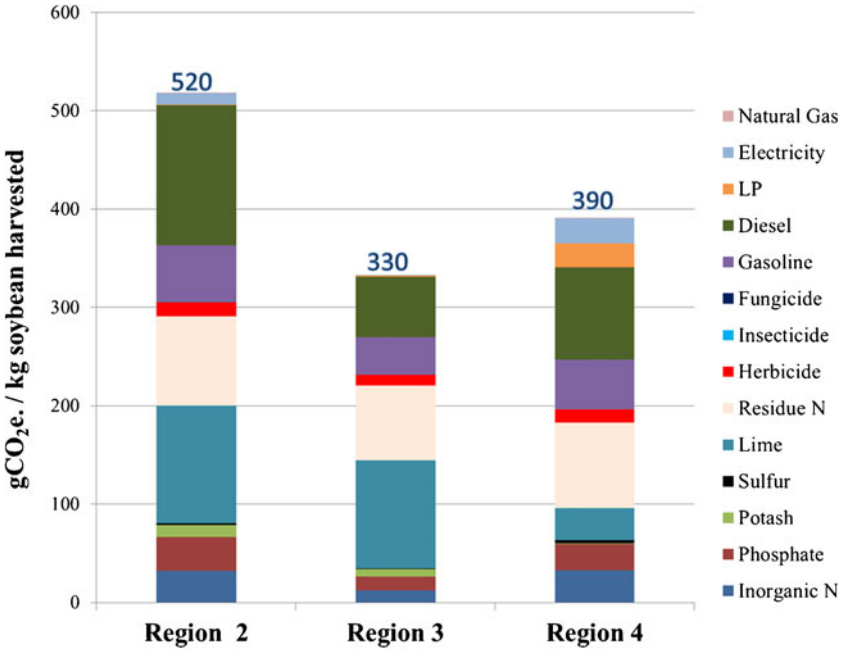


Fig. 3 Carbon footprint profile of soybeans harvested in the USA

footprint in each region. The regional variation in carbon footprint was due to the impact of fertilizer application rate. For example, dairy region 5 shows an unusually high carbon footprint of 1,100 gCO_2e/kg of oats harvested, due to high fertilizer N application. Furthermore, results from California in region 5 may not be representative of the other states in this region. About 65% of inorganic N fertilizer GHG emissions was from field application and 35% was due to manufacture.

The impact of crop residues remains fairly constant across the various regions for oats, contributing about 9% on national average towards the carbon footprints reported. However, the use of manure to supplement inorganic fertilizers in regions 1 and 3 contributed 21% and 26%, respectively, towards the regional footprints. Finally, in the case of oats, the standard deviation with 95% confidence for inorganic fertilizer, chemical protection, and energy inputs was estimated to be 1.51, 1.24, and 1.36, respectively (see Appendix G-11 of the Electronic Supplementary Material).

4.2.3 Corn grain and silage

Inorganic fertilizers, manure, phosphates, lime, diesel as well as the impacts of grain drying and N_2O emissions due to residues contributed approximately 80–90% towards the regional C footprint of corn grain (Fig. 5). In the corn silage analysis in Fig. 6, inorganic fertilizers, manure, phosphates, lime, diesel as well as the impacts of drying and N_2O emissions due to residues contributed about 73–90% towards the corn silage footprint for each dairy region. The

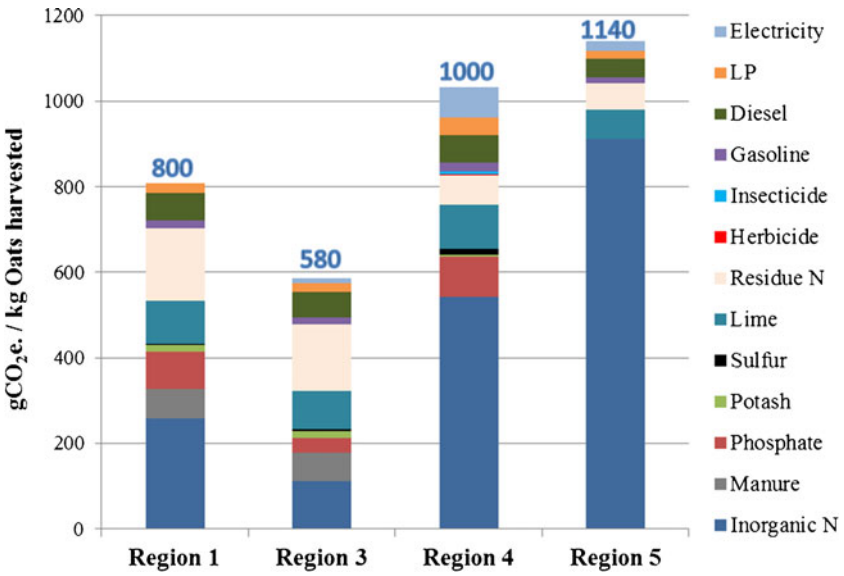


Fig. 4 Carbon footprint profile of oats harvested in the USA

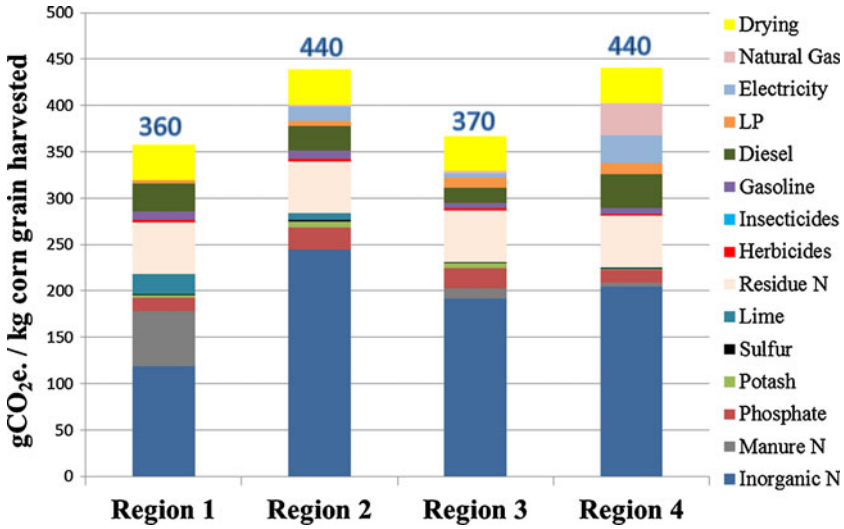


Fig. 5 Carbon footprint profile of corn grain harvested in the USA

contribution of the MMS to the GHG emissions for both crops was small (always <2%). Generally, the GHG emissions for corn grain with respect to the various dairy regions were about two times greater than for the corn silage. The comparatively larger emissions for corn grain compared to silage were mainly due to the allocation method applied from Section 3.1, under "Corn". Figure 5 shows high contributions of inorganic fertilizer from region 2, as this is the reason why additional manure was not added to supplement plant growth in this region. Interestingly, Fig. 6 shows a relatively high contribution for the use of natural gas for region 4 and this was primarily due to extremely high level of energy requirements from corn farms in Texas. In the final analysis, the standard deviation with 95% confidence for fertilizer, chemical protection, and energy inputs was estimated to be 1.51, 1.21, and 1.26, respectively, (see Appendix G-11 of the Electronic Supplementary Material) using the pedigree matrix.

4.2.4 Winter wheat

Regions 3 and 4 showed the highest carbon footprint (Fig. 7), largely due to the high rate of application of inorganic nitrogen fertilizers by farmers. Inorganic nitrogen and phosphate fertilizers, diesel, and the impact of N_2O releases contributed 93–95% of the overall GHG emissions in each dairy region. As in other crops, about 65% of inorganic N fertilizer GHG emissions was from field application and 35% was due to fertilizer manufacture.

On the whole, the carbon footprints for all dairy feed crops analyzed in this study were within the range 160–1140 gCO_2e/kg of dry feed. Various contributions of different farm inputs varied on a regional basis and this was mainly due to the different fertilizer, liming, and energy requirements depending on location, soil properties, and climate.

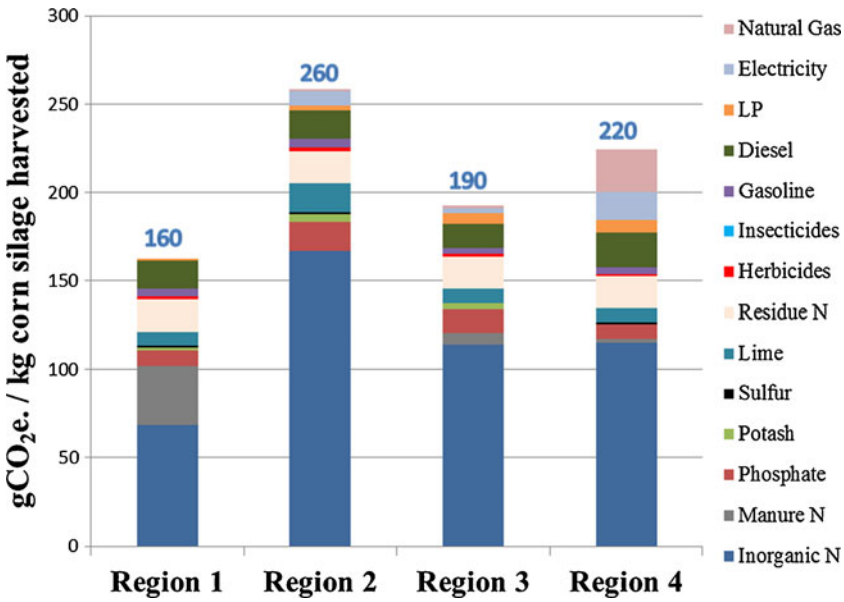


Fig. 6 Carbon footprint profile of corn silage harvested in the USA

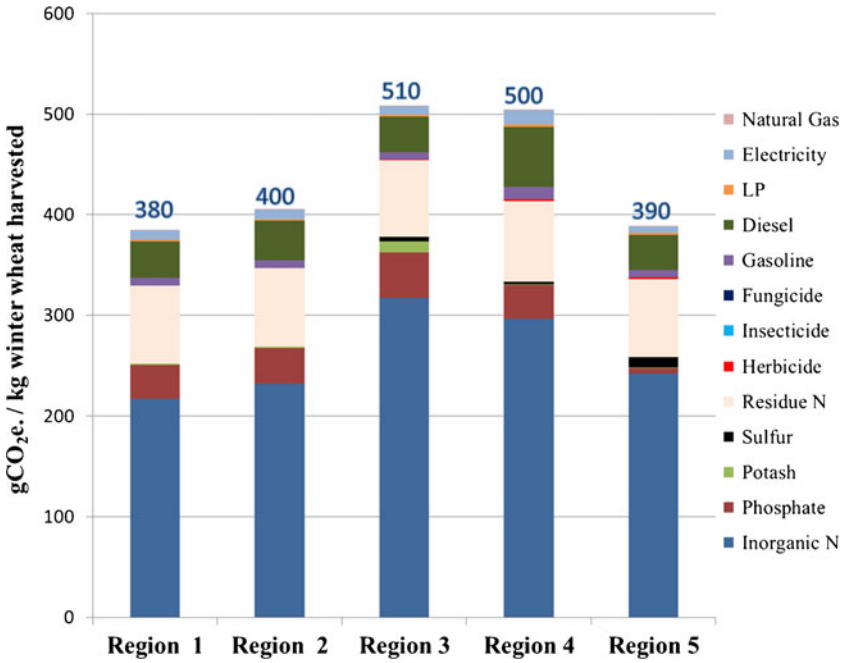


Fig. 7 Carbon footprint profile of winter wheat harvested in the USA

4.2.5 Forage crops: alfalfa hay, alfalfa silage, grass hay, grass pasture, and grass silage

The major contributors towards the regional footprints for both alfalfa hay and silage were identified to be due to crop residue, phosphate, lime, diesel, and electricity. In all regions, these factors contributed between 80% and 90% toward the overall regional footprint. However, impacts due to the application of potash, boron, crop protection chemicals, and use of gasoline were minimal ranging between 4% and 14% toward the carbon footprint for both alfalfa hay and silage. Contributions to carbon (GHG) footprint due to the application of inorganic fertilizer for both alfalfa hay and silage was less than 10% in all dairy production regions for which input data were available, and this low result was not surprising given that alfalfa is a nitrogen-fixing crop.

Grass showed a higher carbon footprint than other forage crops and nearly as high as the corn grain. Grass typically requires less maintenance and inputs, but produces lower yields than many other crops. In addition, there is much higher variability and uncertainty in actual yield than for other commodity crops. Region 2, which has the highest carbon footprint for grass and hay production, also had higher fuel, lime, and nitrogen use based on the available budget information. In all the different types of grass analyzed, inorganic fertilizers were the major contributors ranging from 34% to as high as 90% toward the footprint in the case of grass pasture. Lime contributions were significant for regions 1, 2, and 3, ranging between 13% and 19% for all grasses analyzed, but under 10% for regions 4 and 5. This reflects the acidic nature of soil in regions 1 to 3.

Finally, the standard deviation with 95% confidence for all inputs of alfalfa and grass were both estimated to be 1.22. Emission ranges varied significantly on a regional basis. The ranges reported in gCO_2e/kg dry forage feed were as follows: 140–270 (alfalfa hay), 150–280 (alfalfa silage), 270–470 (grass hay), 220–410 (grass pasture) and 280–410 (grass silage). The GHG emissions of 1 kg grass hay and silage at the farm gate for the Swiss production processes using Ecoinvent™ database (PRé Consultants 2009) were analyzed to be 180 and 220 gCO_2e/kg of dry feed, respectively, and somewhat lower than our results.

5 Conclusions and recommendations

In this carbon footprint study, the main goal was to estimate the GHG emissions from the cultivation and harvesting of dairy feeds on a basis of one dry kilogram of dairy feed harvested or produced (gCO_2e/kg of dry dairy feed). Table 6 shows the cradle-to-farm gate carbon footprint results obtained for all dairy feeds analyzed in this study. There were large differences in GHG emissions among the different dairy crops, with corn silage showing the lowest, while oats and DDGS displayed the highest. This variability was largely driven by fertilizer and energy utilization intensity as shown in Figs. 3, 4, 5, 6, and 7. There was some variability in carbon footprint for any crop from region to region, driven by regional differences in energy and lime use, but this variability was smaller than inter-crop variability.

The highest contributor to carbon footprint was the on-farm application of inorganic N fertilizer except for the leguminous feeds, whereas the fertilizer input categories P,

K, and S accounted for relatively small impacts for all crops. About 65% of inorganic N fertilizer GHG emissions was due to N_2O release upon application, whereas 35% was from fertilizer manufacture. N_2O emission contribution from crop residues was also significant for most crops. With N fertilizer input being the largest contributor to GHG emissions, much effort should be targeted toward lowering emissions associated with their production and use on the farm. Additionally, the efficient transfer of knowledge to farmers with regards to fertilizer best management practices might help reduce emissions on the farm. The use of crop protection chemicals was not so significant however, and energy use impacts varied widely from region to region, likely due to differences in climate, energy conservation programs, and need for crop drying. Finally, on the energy front, there is the need to promote the use of safe and cleaner forms of energy to help reduce climate active GHG emissions associated with the energy input needed by farmers.

This study highlights key crop inputs that are the drivers for emissions of greenhouse gases from the cradle-to-gate cultivation and harvesting for US dairy grain and forage crops. These crop results are equally applicable for uses other than dairy products; for example food production in general and bioenergy. Hopefully, these results will be useful for reducing GHG emissions by guiding efforts to modifying agricultural practices with respect to fertilizer application, use of manure, and energy consumption.

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References

Beegle D (1997) Estimating manure application rates. Agronomy fact sheet 55. Available at: http://juniataccd.org/programs/NMP/agronomy55.pdf

CGB (2010) CGG Enterprise Inc. http://www.cgb.com/browse.asp?page=339. Accessed 23 Jan 2010

Crozier CR, Osmond DS, Dunphy EJ, Fisher L, Heiniger RW, Johnson SE, Jordan DL, Weisz R, Hardy DH (2004) Lime and fertilizer suggestions—field, pasture, and hay crops. In 2012 North Carolina agricultural chemicals manual. The College of Agric. and Life Sci, North Carolina State Univ, Raleigh, p 40 Available: http://ipm.ncsu.edu/agchem/4-toc.pdf. Accessed 1 Dec 2010

Dalgaard R, Schmidt J, Halberg N, Christensen P, Thrane M, Pengue W (2008) LCA of soybean meal. Int J Life Cycle Assess 13:240–254

Dartt A, Schwab G (2001) Crops and livestock budgets estimates for Michigan. Agricultural economics report 609. Available at: http://www.aec.msu.edu/aecreports/budgets01.htm

Denmark LCA Food Database (2011). Available at http://www.lcafood.dk/products/crops/cashcrops.htm. Accessed 16 Jan 2011

Deru M, Torcellini P (2007) Source energy and emission factors for energy use in building, technical report NREL/TP-550-38617. Available at: http://www.nrel.gov/docs/fy07osti/38617.pdf

Dyno Nobel Inc, MSDS (2010) Material safety data sheet, Dyno Nobel Inc. MSDS # 1138. Available at: http://www.irmteam.com/Product_Sheets/MSDS-dynonobel-UAN32.pdf

EPA (2011) Environmental Protect Agency. USA http://www.epa.gov/midwestcleandiesel/. Accessed 23 Feb 2011

Forster P, Ramaswamy V, Artaxo P, Berntsen T, Betts R, Fahey DW, Haywood J, Lean J, Lowe DC, Myhre G, Nganga J, Prinn R, Prinn G, Raga G, Schulz M, Van Dorland R (2007) Changes in atmospheric constituents and in radiative forcing. In: Solomon S, Qin Min D, Manning M, Chen Z, Marquis M, Averyt KB, Tignor M, Miller HL (eds) Climate change 2007: the physical science basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge. Available at: http://www.ipcc.ch/pdf/assessment-report/ar4/wg1/ar4-wg1-chapter2.pdf

Frischknecht R, Jungbluth N, Althaus HJ, Doka G, Heck T, Hellweg S, Hischier R, Nemecek T, Rebitzer G, Spielmann M, Wernet G (2007) Overview and methodology. Ecoinvent report no 1. Swiss Centre for Life Cycle Inventories, Dübendorf

GREET (2010) The greenhouse gases, regulated emissions, and energy use in transportation model. Argonne National Laboratory, U.S. Department of Energy. Available at: http://greet.es.anl.gov/main. Version 1.8d. Accessed 10 Jan 2011

Hayashi K, Gaillard G, Nemecek T (2006) Life cycle assessment of agricultural production systems: current issues and future perspectives. In: Hu SH, Bejosano-Gloria C (eds) Good agricultural practice (GAP) in Asia and Oceania. Food and Fertilizer Technology Center, Taipei, pp 98–110

Heimlich R (2003) Agricultural resources and environmental indicators. Agriculture handbook no. AH722. Washington, DC: USDA Economic Research Service. Available at: http://www.ers.usda.gov/publications/arei/ah722/arei4_4/AREI4_4nutrientmgt.pdf

Hill J, Nelson E, Tilman D, Polasky S, Tiffany D (2006) Environmental, economic, energetic costs and benefits of biodiesel and ethanol biofuels. Proc Natl Acad Sci 103:1206–11210

IPCC (2006) Guidelines for national greenhouse gas inventories, prepared by the National Greenhouse Gas Inventories Programme. In: Eggleston H, Buendia L, Miwa K, Ngara Tand Tanabe K (eds). Available at: http://www.ipcc-nggip.iges.or.jp/public/2006gl/index.htm

Kim S, Dale B (2002) Allocation procedure in ethanol production system from corn grain: I. System expansion. Int J Life Cycle Assess 7:237–243

Kim S, Dale B (2009) Regional variations in greenhouse gas emissions of biobased products in the United States—corn-based ethanol and soybean oil. Int J Life Cycle Assess 14:540–546

Kim S, Dale B, Jenkins R (2009) Life cycle assessment of corn grain and corn stover in the United States. Int J Life Cycle Assess 14:160–174

Kodera K (2007) Analysis of allocation methods of bioethanol LCA, M.Sc. Thesis, CML, Leiden University, Netherlands, pp 23

KSU (2003) http://www.ksre.ksu.edu/library/crpsl2/mf2586.pdf. Accessed 1 Jan 2010

Landis E, Miller A, Theis L (2007) Life cycle of the corn−soybean agroecosystem for biobased production. Environ Sci Technol 41:1457–1464

MacDonald J, Ribaudo M, Livingston M, Beckman J, Huang W (2009) Manure use for fertilizer and for energy: report to congress. Administrative publication number: 037. Available at: http://www.ers.usda.gov/publications/ap/ap037/

Mowrey A, Spain N (1999) Results of a nationwide survey to determine feedstuffs fed to lactating dairy cows. J Dairy Sci 82:445–451

MSU (2010) Michigan State University Extension. https://www.msu.edu/user/steind/. Accessed 1 Jan 2010

National Research Council (2008) Understanding American agriculture: challenges for the agricultural resource management survey. Panel to review USDAs agricultural resource management survey. Committee on national statistics, division of behavioral and social sciences and education. The National Academies Press, Washington, DC

NDSU (North Dakota State University, USA) (1992) Fertilizing corn grain, popcorn, silage corn, and sweet corn. Available at: http://www.ag.ndsu.edu/pubs/plantsci/soilfert/sf722w.htm. Accessed 23 Feb 2011

NDSU (North Dakota State University, USA) (2011). Equivalent weights of grains and oilseeds. Available at: http://www.ag.ndsu.edu/pubs/ageng/machine/ae945w.htm. Accessed 23 Jan 2011

PAN Pesticides Database (2009) Available at: http://www.pesticideinfo.org/Search_Chemicals.jsp. Accessed 1 Jan 2009

Pelletier N (2008) Environmental performance in the US broiler poultry sector: life cycle energy use and greenhouse gas, ozone depleting, acidifying and eutrophying emissions. Agric Syst 98:67–73

Piringer G, Steinberg LJ (2006) Reevaluation of energy use in wheat production in the United States. J Ind Ecol 10:149–167

Pollak J (2010) Data update of soybean and soy feedstocks production and life cycle assessment of soy-based products and petroleum-based alternatives, peer reviewed final report. Omni Tech International and Four Elements Consulting. Available at: http://www.biodiesel.org/resources/reportsdatabase/reports/gen/20100201_GEN-422.pdf

Pradhan A, Shrestha S, Mc Aloon A, Yee W, Haas M, Duffield A, Shapouri H (2009) Energy life cycle assessment of soybean biodiesel. U.S. Department of Agriculture, Office of Energy Policy and New Uses. Agricultural economic report no. 845. 10/2002

PRé Consultants (2009) SimaPro 7.1 LCA software. http://www.pre.nl/. Accessed 1 Jan 2009

Rotz CA, Montes F, Chianese DS (2010) The carbon footprint of dairy production systems through partial life cycle assessment. J Dairy Sci 93:1266–1282

Schnitkey G (2004) Estimated cost of crop production in Illinois. Farm business management handbook. Available at: http://www.farmdoc.illinois.edu/manage/enterprise_cost/2004_crop_budgets.pdf

Shapouri H, Duffield JA, Wang M (2002) The energy balance of corn ethanol: an update: U.S. Department of Agriculture, Office of Energy Policy and New Uses. Agricultural economic report no. 813. 7/2002. Available at: http://www.transportation.anl.gov/pdfs/AF/265.pdf

Shapouri H, Duffield JA, Wang M (2003) The energy balance of corn ethanol revisited. U.S. Department of Agriculture, Office of Energy Policy and New Uses. Agricultural economic report number 813

Sheehan J, Camobreco V, Duffield JA, Graboski M, Shapouri H (1998) Life-cycle inventory of biodiesel and petroleum diesel for use in an urban bus. A joint study sponsored by U.S. Department of Agriculture and U.S. Department of Energy. NREL/SR-580-24089 Golden, CO: National Renewable Energy Laboratory. U.S. Department of Energy, 5/1998

Simplified Emission Inventory Tools - SEIT (2006). SEIT calculation workbook; v1.0. US Energy Information Administration, Washington, July 2006

Spatari S, Zhang Y, Maclean HL (2005) Life cycle assessment of switch and corn stover derived ethanol-fueled automobiles. Environ Sci Technol 39:9750–9758

Thoma G, Popp J, Shonnard D, Nutter D, Ulrich R, Matlock M, Kim D, Neiderman Z, East C, Adom F, Kemper N, Maes A (2012) Greenhouse gas emissions from production of fluid milk in the US. Int Dairy J (in press)

USDA NASS (2006) U.S. Department of Agriculture, National Agricultural Statistics Service. Agricultural chemical usage-field crops summary (2005). Available at: http://usda.mannlib.cornell.edu/usda/nass/AgriChemUsFC//2000s/2006/AgriChemUsFC-05-17-2006.pdf

USDA NASS (2007a) U.S. Department of Agriculture, National Agricultural Statistics Service. Crop production 2006 summary. U.S. Department of Agriculture, 11 Jan 2008. Available at: http://usda.mannlib.cornell.edu/usda/nass/CropProdSu//2000s/2007/CropProdSu-01-12-2007.pdf

USDA NASS (2007b) U.S. Department of Agriculture, National Agricultural Statistics Service. Agricultural chemical usage-field crops summary, 2006. Available at: http://usda.mannlib.cornell.edu/usda/nass/AgriChemUsFC//2000s/2007/AgriChemUsFC-05-16-2007_revision.pdf

USDA ERS (Economic Research Service) (2009) U.S. fertilizer use and price. Available at: www.ers.usda.gov/Data/FertilizerUse. Accessed 1 Jan 2009

USDA NASS (U.S. Department of Agriculture, National Agricultural Statistics Service) (2009a) Crop production 2008 summary. U.S. Department of Agriculture, 11 January 2008. Available at: http://usda.mannlib.cornell.edu/usda/nass/CropProdSu//2000s/2009/CropProdSu-01-12-2009.pdf

USDA NASS (2009b) U.S. Wheat classes. Available at: http://www.ers.usda.gov/briefing/wheat/background.htm. Accessed 14 Apr 2009

USDA-IL (2010) Illinois Department of Agriculture. Available at: http://www.agr.state.il.us/marketing/index.html. Accessed 23 Feb 2011

USGS (2007) United States Geological Survey 2007 available at: http://minerals.usgs.gov/minerals/pubs/commodity/stone_crushed/myb1-2007-stonc.xls http://minerals.usgs.gov/minerals/pubs/commodity/lime/myb1-2007-lime.xls

Van der Werf H, Petit J, Sanders J (2005) The environmental impacts of the production of concentrated feed: the case of pig feed in Bretagne. Agric Syst 83:153–177

Vitosh ML (1996) N-P-K fertilizers, Michigan State University Extension Bulletin. Available at: http://fieldcrop.msu.edu/sites/fieldcrop/files/E0896.pdf

Wang M (2001) Development and use of GREET 1.6 fuel-cycle model for transportation fuels and vehicle technologies. Tech. Rep. ANL/ESD/TM-163, Argonne National Laboratory, Argonne, IL, 2001. Available at: www.transportation.anl.gov/pdfs/TA/153.pdf

Frequently Asked Questions

FAQ

Frequently Asked Questions

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Frequently Asked Questions

FAQ 4.1 | How Will the Climate Change Over the Next Twenty Years?

The parts of the climate system that have shown clear increasing or decreasing trends in recent decades will continue these trends for at least the next twenty years. Examples include changes in global surface temperature, Arctic sea ice cover, and global average sea level. However, over a period as short as twenty years, these trends are substantially influenced by natural climate variability, which can either amplify or attenuate the trend expected from the further increase in greenhouse gas concentrations.

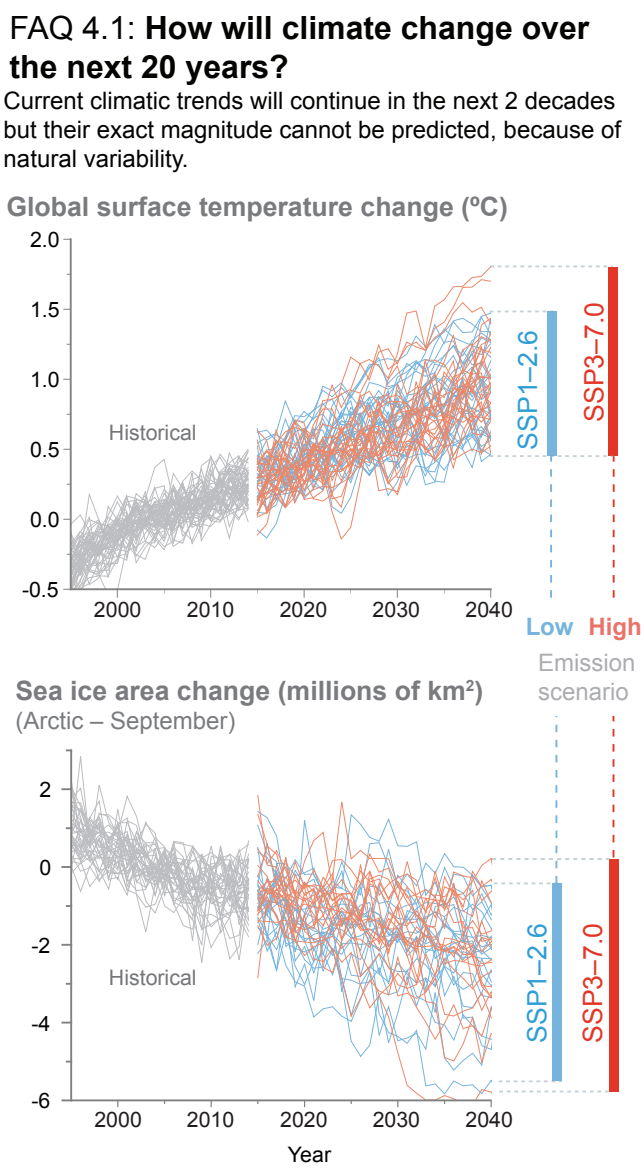
Twenty years are a long time by human standards but a short time from a climate point of view. Emissions of greenhouse gases will continue over the next twenty years, as assumed in all the scenarios considered in this Report, albeit with varying rates. These emissions will further increase concentrations of greenhouse gases in the atmosphere (see FAQ 4.2), leading to continued trends in global surface warming and other parts of the climate system, including Arctic sea ice and global average sea level (see FAQ 9.2). FAQ 4.1, Figure 1 shows that both global surface temperature rise and the shrinking of sea ice in the Arctic will continue, with little difference between high- and low-emissions scenarios over the next 20 years (that is, between the red and blue lines).

However, these expected trends will be overlain by natural climate variability (see FAQ 3.2). First, a major volcanic eruption might occur, such as the 1991 eruption of Mt. Pinatubo on the Philippines; such an eruption might cause a global surface cooling of a few tenths of a degree Celsius lasting several years. Second, both atmosphere and ocean show variations that occur spontaneously, without any external influence. These variations range from localized weather systems to continent- and ocean-wide patterns and oscillations that change over months, years, or decades. Over a period of twenty years, natural climate variability strongly influences many climate quantities, when compared to the response to the increase in greenhouse gas concentrations from human activities. The effect of natural variability is illustrated by the very different trajectories that individual black, red or blue lines can take in FAQ 4.1, Figure 1. Whether natural variability would amplify or attenuate the human influence cannot generally be predicted out to twenty years into the future. Natural climate variability over the next twenty years thus constitutes an uncertainty that at best can be quantified accurately but that cannot be reduced.

Locally, the effect of natural variability would be much larger still. Simulations (not shown here) indicate that, locally, a cooling trend over the next twenty years cannot be ruled out, even under the high-emissions scenario – at a small number of locations on Earth, but these might lie anywhere. Globally, though, temperatures would rise under all scenarios.

In summary, while the direction of future change is clear for the two important climate quantities shown here – the global surface temperature and the Arctic sea ice area in September – the magnitude of the change is much less clear because of natural variability.

FAQ 4.1 (continued)



FAQ 4.1, Figure 1 | Simulations over the period 1995–2040, encompassing the recent past and the next twenty years, of two important indicators of global climate change. (Top) Global surface temperature, and **(bottom)**, the area of Arctic sea ice in September. Both quantities are shown as deviations from the average over the period 1995–2014. The grey curves are for the historical period ending in 2014; the blue curves represent a low-emissions scenario (SSP1-2.6) and the red curves one high-emissions scenario (SSP3-7.0).

Frequently Asked Questions

FAQ 4.2 | How Quickly Would We See the Effects of Reducing Carbon Dioxide Emissions?

The effects of substantial reductions in carbon dioxide emissions would not be apparent immediately, and the time required to detect the effects would depend on the scale and pace of emissions reductions. Under the lower-emissions scenarios considered in this Report, the increase in atmospheric carbon dioxide concentrations would slow visibly after about five to ten years, while the slowing down of global surface warming would be detectable after about twenty to thirty years. The effects on regional precipitation trends would only become apparent after several decades.

Reducing emissions of carbon dioxide (CO_2) – the most important greenhouse gas emitted by human activities – would slow down the rate of increase in atmospheric CO_2 concentration. However, concentrations would only begin to decrease when net emissions approach zero, that is, when most or all of the CO_2 emitted into the atmosphere each year is removed by natural and human processes (see FAQ 5.1 and FAQ 5.3). This delay between a peak in emissions and a decrease in concentration is a manifestation of the very long lifetime of CO_2 in the atmosphere; part of the CO_2 emitted by humans remains in the atmosphere for centuries to millennia.

Reducing the rate of increase in CO_2 concentration would slow down global surface warming within a decade. But this reduction in the rate of warming would initially be masked by natural climate variability and might not be detected for a few decades (see FAQ 1.2, FAQ 3.2 and FAQ 4.1). Detecting whether surface warming has indeed slowed down would thus be difficult in the years right after emissions reductions begin.

The time needed to detect the effect of emissions reductions is illustrated by comparing low- and high-emissions scenarios (FAQ 4.2, Figure 1). In the low-emissions scenario (SSP1-2.6), CO_2 emissions level off after 2015 and begin to fall in 2020, while they keep increasing throughout the 21st century in the high-emissions scenario (SSP3-7.0). The uncertainty arising from natural internal variability in the climate system is represented by simulating each scenario ten times with the same climate model but starting from slightly different initial states back in 1850 (thin lines). For each scenario, the differences between individual simulations are caused entirely by simulated natural internal variability. The average of all simulations represents the climate response expected for a given scenario. The climate history that would actually unfold under each scenario would consist of this expected response combined with the contribution from natural internal variability and the contribution from potential future volcanic eruptions (the latter effect is not represented here).

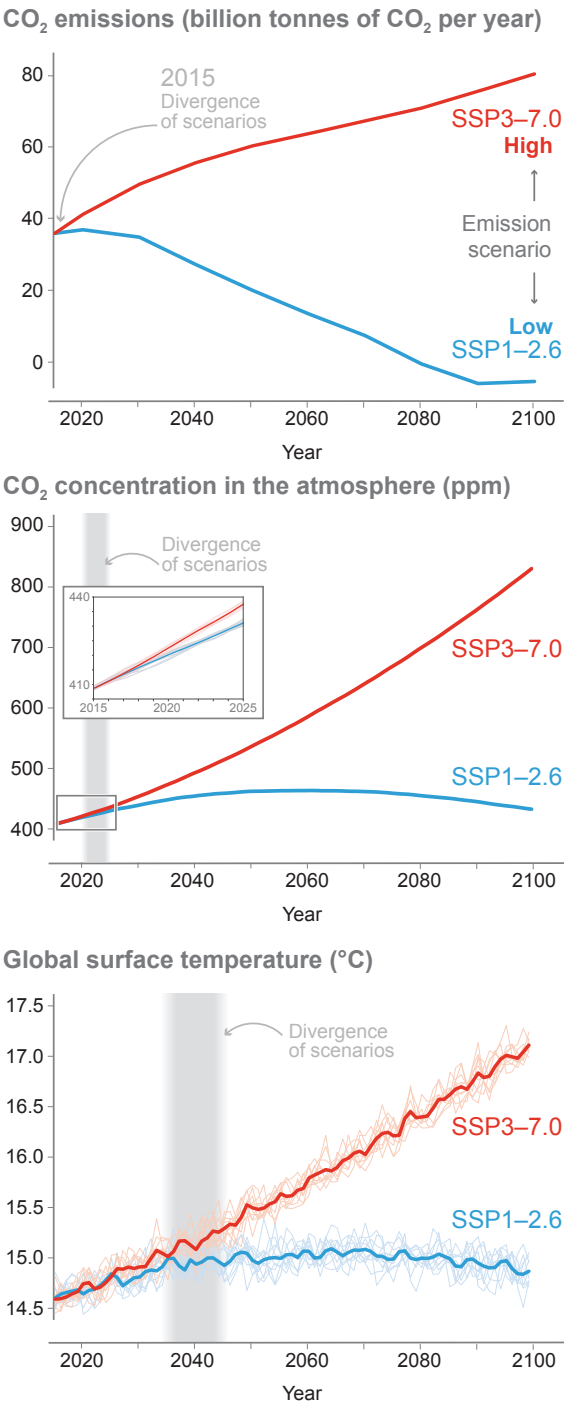
FAQ 4.2, Figure 1 shows that the atmospheric CO_2 concentrations differ noticeably between the two scenarios about five to ten years after the emissions have begun to diverge in year 2015. In contrast, the difference in global surface temperatures between the two scenarios does not become apparent until later – about two to three decades after the emissions histories have begun to diverge in this example. This time would be longer if emissions were reduced more slowly than in the low-emissions scenario illustrated here and shorter in the case of stronger reductions. Detection would take longer for regional quantities and for precipitation changes, which vary more strongly from natural causes. For instance, even in the low-emissions scenario, the effect of reduced CO_2 emissions would not become visible in regional precipitation until late in the 21st century.

In summary, it is only after a few decades of reducing CO_2 emissions that we would clearly see global temperatures starting to stabilize. By contrast, short-term reductions in CO_2 emissions, such as during the COVID-19 pandemic, do not have detectable effects on either CO_2 concentration or global temperature. Only sustained emissions reductions over decades would have a widespread effect across the climate system.

FAQ 4.2 (continued)

FAQ 4.2: **Detecting reduced CO_2 emissions**

Sustained reduction in carbon dioxide (CO_2) emissions would become apparent in atmospheric concentration after 5–10 years and in the temperature after 20–30 years.



FAQ 4.2, Figure 1 | Observing the benefits of emissions reductions. (Top) Carbon dioxide (CO_2) emissions, **(middle)** CO_2 concentration in the atmosphere and **(bottom)** effect on global surface temperature for two scenarios: a low-emissions scenario (SSP1-2.6, blue) and a high-emissions scenario (SSP3-7.0). In the low-emissions scenario, CO_2 emissions begin to decrease in 2020 whereas they keep increasing throughout the 21st century in the high-emissions scenario. The thick lines are the average of the 10 individual simulations (thin line) for each scenario. Differences between individual simulations reflect natural variability.

FAQ 4.3 | At a Given Level of Global Warming, What Are the Spatial Patterns of Climate Change?

As the planet warms, climate change does not unfold uniformly across the globe, but some patterns of regional change show clear, direct and consistent relationships to increases in global surface temperature. The Arctic warms more than other regions, land areas warm more than the ocean surface, and the Northern Hemisphere more than the Southern Hemisphere. Precipitation increases over high latitudes, tropics and large parts of the monsoon regions, but decreases over the subtropics. For cases like these, we can infer the direction and magnitude of some regional changes – particularly temperature and precipitation changes – for any given level of global warming.

The intensity of climate change will depend on the level of global warming. It is possible to identify certain patterns of regional climate change that occur consistently, but increase in amplitude, across increasing levels of global warming. Such robust spatial patterns of climate change are largely independent of the specific scenario (and pathway in time) that results in a given level of global warming. That is, as long as different scenarios result in the same global warming level, irrespective of the time when this level is attained in each scenario, we can infer the patterns of regional change that would result from this warming. When patterns of changes are robust, regional consequences can be assessed for all levels of global warming, for all future time periods, and for all scenarios. Temperature and precipitation show such robust patterns of changes that are particularly striking.

The high latitudes of the Northern Hemisphere are projected to warm the most, by two to four times the level of global warming – a phenomenon referred to as Arctic amplification (FAQ 4.3, Figure 1, left). Several processes contribute to this high rate of warming, including increases in the absorption of solar radiation due to the loss of reflective sea ice and snow in a warmer world. In the Southern Hemisphere, Antarctica is projected to warm faster than the mid-latitude Southern Ocean, but the Southern Hemisphere high latitudes are projected to warm at a reduced amplitude compared to the level of global warming (FAQ 4.3, Figure 1, left). An important reason for the relatively slower warming of the Southern Hemisphere high latitudes is the upwelling of Antarctic deep waters that drives a large surface heat uptake in the Southern Ocean.

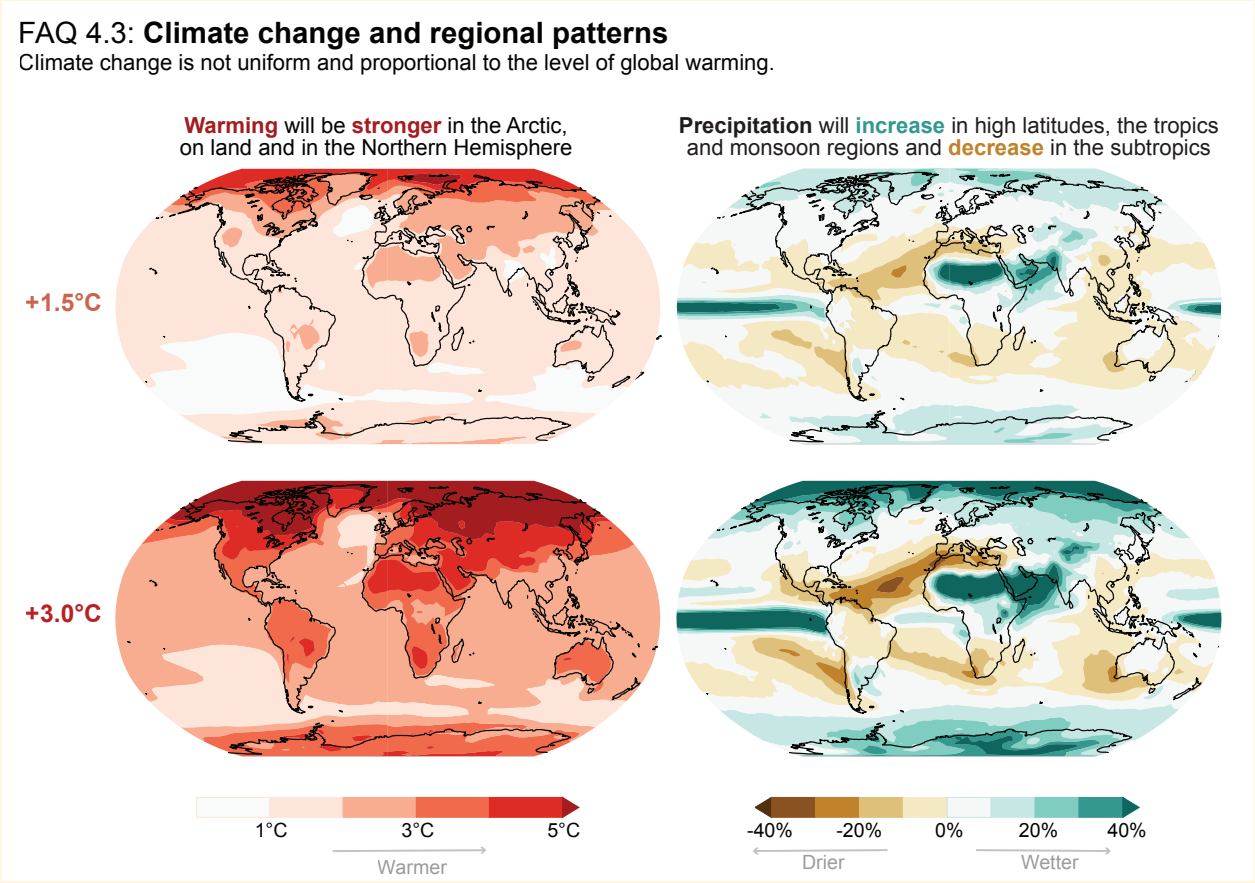
The warming is generally stronger over land than over the ocean, and in the Northern Hemisphere compared to the Southern Hemisphere, and with less warming over the central subpolar North Atlantic and the southernmost Pacific. The differences are the result of several factors, including differences in how land and ocean areas absorb and retain heat, the fact that there is more land area in the Northern Hemisphere than in the Southern Hemisphere, and the influence of ocean circulation. In the Southern Hemisphere, robust patterns of relatively high warming are projected for subtropical South America, southern Africa, and Australia. The relatively strong warming in subtropical southern Africa arises from strong interactions between soil moisture and temperature and from increased solar radiation as a consequence of enhanced subsidence.

Precipitation changes are also proportional to the level of global warming (FAQ 4.3, Figure 1, right), although uncertainties are larger than for the temperature change. In the high latitudes of both the Southern and Northern Hemispheres, increases in precipitation are expected as the planet continues to warm, with larger changes expected at higher levels of global warming (FAQ 4.3, Figure 1, right). The same holds true for the projected precipitation increases over the tropics and large parts of the monsoon regions. General drying is expected over the subtropical regions, particularly over the Mediterranean, southern Africa and parts of Australia, South America, and south-west North America, as well as over the subtropical Atlantic and parts of the subtropical Indian and Pacific Oceans. Increases in precipitation over the tropics and decreases over the subtropics amplify with higher levels of global warming.

Some regions that are already dry and warm, such as southern Africa and the Mediterranean, are expected to become progressively drier and drastically warmer at higher levels of global warming.

In summary, climate change will not affect all the parts of the globe evenly. Rather, distinct regional patterns of temperature and precipitation change can be identified, and these changes are projected to amplify as the level of global warming increases.

FAQ 4.3 (continued)



FAQ 4.3, Figure 1 | Regional changes in temperature (left) and precipitation (right) are proportional to the level of global warming, irrespective of the scenario through which the level of global warming is reached. Surface warming and precipitation change are shown relative to the 1850–1900 climate, and for time periods over which the globally averaged surface warming is 1.5°C **(top)** and 3°C **(bottom)**, respectively. Changes presented here are based on 31 CMIP6 models using the high-emissions scenario SSP3-7.0.

Irreversible climate change due to carbon dioxide emissions

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The severity of damaging human-induced climate change depends not only on the magnitude of the change but also on the potential for irreversibility. This paper shows that the climate change that takes place due to increases in carbon dioxide concentration is largely irreversible for 1,000 years after emissions stop. Following cessation of emissions, removal of atmospheric carbon dioxide decreases radiative forcing, but is largely compensated by slower loss of heat to the ocean, so that atmospheric temperatures do not drop significantly for at least 1,000 years. Among illustrative irreversible impacts that should be expected if atmospheric carbon dioxide concentrations increase from current levels near 385 parts per million by volume (ppmv) to a peak of 450–600 ppmv over the coming century are irreversible dry-season rainfall reductions in several regions comparable to those of the ''dust bowl'' era and inexorable sea level rise. Thermal expansion of the warming ocean provides a conservative lower limit to irreversible global average sea level rise of at least 0.4–1.0 m if 21st century CO_2 concentrations exceed 600 ppmv and 0.6–1.9 m for peak CO_2 concentrations exceeding ≈1,000 ppmv. Additional contributions from glaciers and ice sheet contributions to future sea level rise are uncertain but may equal or exceed several meters over the next millennium or longer.

dangerous interference | precipitation | sea level rise | warming

Over the 20th century, the atmospheric concentrations of key greenhouse gases increased due to human activities. The stated objective (Article 2) of the United Nations Framework Convention on Climate Change (UNFCCC) is to achieve stabilization of greenhouse gas concentrations in the atmosphere at a low enough level to prevent "dangerous anthropogenic interference with the climate system." Many studies have focused on projections of possible 21st century dangers (1–3). However, the principles (Article 3) of the UNFCCC specifically emphasize "threats of serious or irreversible damage," underscoring the importance of the longer term. While some irreversible climate changes such as ice sheet collapse are possible but highly uncertain (1, 4), others can now be identified with greater confidence, and examples among the latter are presented in this paper. It is not generally appreciated that the atmospheric temperature increases caused by rising carbon dioxide concentrations are not expected to decrease significantly even if carbon emissions were to completely cease (5–7) (see Fig. 1). Future carbon dioxide emissions in the 21st century will hence lead to adverse climate changes on both short and long time scales that would be essentially irreversible (where irreversible is defined here as a time scale exceeding the end of the millennium in year 3000; note that we do not consider geo-engineering measures that might be able to remove gases already in the atmosphere or to introduce active cooling to counteract warming). For the same reason, the physical climate changes that are due to anthropogenic carbon dioxide already in the atmosphere today are expected to be largely irreversible. Such climate changes will lead to a range of damaging impacts in different regions and sectors, some of which occur promptly in association with warming, while others build up under sustained warming because of the time lags of the processes involved. Here we illustrate 2 such aspects of the irreversibly altered world that should be expected. These aspects are among reasons for concern but are not comprehensive; other possible climate impacts include Arctic sea ice retreat, increases in heavy rainfall and flooding, permafrost melt, loss of glaciers and snowpack with attendant changes in water supply, increased intensity of hurricanes, etc. A complete climate impacts review is presented elsewhere (8) and is beyond the scope of this paper. We focus on illustrative adverse and irreversible climate impacts for which 3 criteria are met: (*i*) observed changes are already occurring and there is evidence for anthropogenic contributions to these changes, (*ii*) the phenomenon is based upon physical principles thought to be well understood, and (*iii*) projections are available and are broadly robust across models.

Advances in modeling have led not only to improvements in complex Atmosphere–Ocean General Circulation Models (AOGCMs) for projecting 21st century climate, but also to the implementation of Earth System Models of Intermediate Complexity (EMICs) for millennial time scales. These 2 types of models are used in this paper to show how different peak carbon dioxide concentrations that could be attained in the 21st century are expected to lead to substantial and irreversible decreases in dry-season rainfall in a number of already-dry subtropical areas and lower limits to eventual sea level rise of the order of meters, implying unavoidable inundation of many small islands and low-lying coastal areas.

Results

Longevity of an Atmospheric CO_2 Perturbation. As has long been known, the removal of carbon dioxide from the atmosphere involves multiple processes including rapid exchange with the land biosphere and the surface layer of the ocean through air–sea exchange and much slower penetration to the ocean interior that is dependent upon the buffering effect of ocean chemistry along with vertical transport (9–12). On the time scale of a millennium addressed here, the CO_2 equilibrates largely between the atmosphere and the ocean and, depending on associated increases in acidity and in ocean warming (i.e., an increase in the Revelle or "buffer" factor, see below), typically ≈20% of the added tonnes of CO_2 remain in the atmosphere while ≈80% are mixed into the ocean. Carbon isotope studies provide important observational constraints on these processes and time constants. On multimillenium and longer time scales, geochemical and geological

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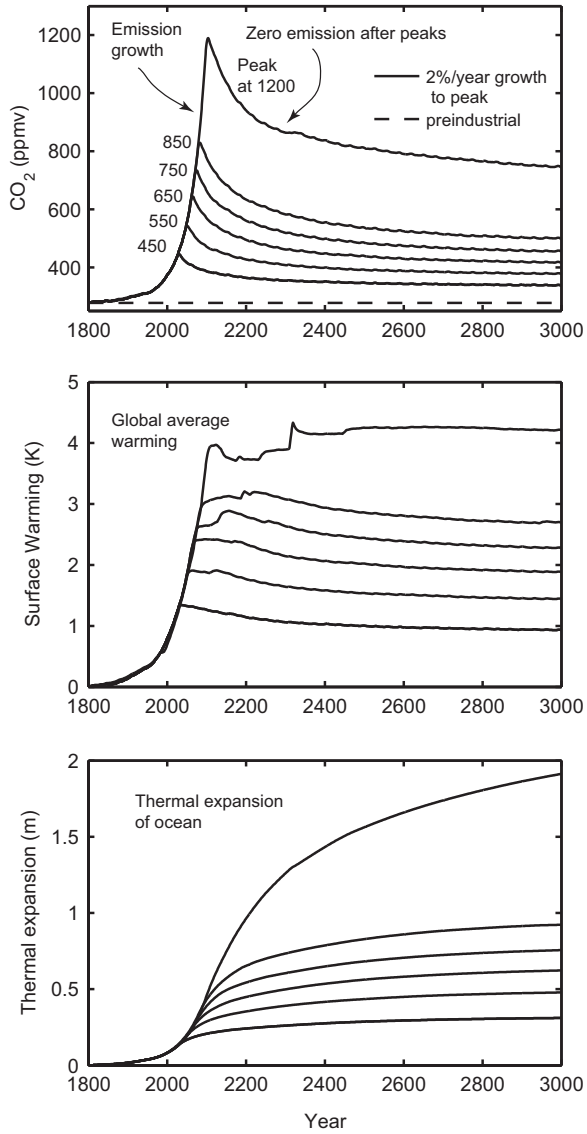


Fig. 1. Carbon dioxide and global mean climate system changes (relative to preindustrial conditions in 1765) from 1 illustrative model, the Bern 2.5CC EMIC, whose results are comparable to the suite of assessed EMICs (5, 7). Climate system responses are shown for a ramp of CO_2 emissions at a rate of 2%/year to peak CO_2 values of 450, 550, 650, 750, 850, and 1200 ppmv, followed by zero emissions. The rate of global fossil fuel CO_2 emission grew at ≈1%/year from 1980 to 2000 and >3%/year in the period from 2000 to 2005 (13). Results have been smoothed using an 11-year running mean. The 31-year variation seen in the carbon dioxide time series is introduced by the climatology used to force the terrestrial biosphere model (15). (*Top*) Falloff of CO_2 concentrations following zero emissions after the peak. (*Middle*) Globally averaged surface warming (degrees Celsius) for these cases (note that this model has an equilibrium climate sensitivity of 3.2 °C for carbon dioxide doubling). Warming over land is expected to be larger than these global averaged values, with the greatest warming expected in the Arctic (5). (*Bottom*) Sea level rise (meters) from thermal expansion only (not including loss of glaciers, ice caps, or ice sheets).

processes could restore atmospheric carbon dioxide to its preindustrial values (10, 11), but are not included here.

Fig. 1 illustrates how the concentrations of carbon dioxide would be expected to fall off through the coming millennium if manmade emissions were to cease immediately following an illustrative future rate of emission increase of 2% per year [comparable to observations over the past decade (ref. 13)] up to peak concentrations of 450, 550, 650, 750, 850, or 1,200 ppmv; similar results were obtained across a range of EMICs that were assessed in the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (5, 7). This is not intended to be a realistic scenario but rather to represent a test case whose purpose is to probe physical climate system changes. A more gradual reduction of carbon dioxide emission (as is more likely), or a faster or slower adopted rate of emissions in the growth period, would lead to long-term behavior qualitatively similar to that illustrated in Fig. 1 (see also Fig. S1). The example of a sudden cessation of emissions provides an upper bound to how much reversibility is possible, if, for example, unexpectedly damaging climate changes were to be observed.

Carbon dioxide is the only greenhouse gas whose falloff displays multiple rather than single time constants (see Fig. S2). Current emissions of major non-CO_2 greenhouse gases such as methane or nitrous oxide are significant for climate change in the next few decades or century, but these gases do not persist over time in the same way as carbon dioxide (14).

Fig. 1 shows that a quasi-equilibrium amount of CO_2 is expected to be retained in the atmosphere by the end of the millennium that is surprisingly large: typically ≈40% of the peak concentration enhancement over preindustrial values (≈280 ppmv). This can be easily understood on the basis of the observed instantaneous airborne fraction (AF^{peak}) of ≈50% of anthropogenic carbon emissions retained during their buildup in the atmosphere, together with well-established ocean chemistry and physics that require ≈20% of the emitted carbon to remain in the atmosphere on thousand-year timescales [quasi-equilibrium airborne fraction (AF^{equi}), determined largely by the Revelle factor governing the long-term partitioning of carbon between the ocean and atmosphere/biosphere system] (9–11). Assuming given cumulative emissions, EMI, the peak concentration, CO_2^{peak} (increase over the preindustrial value CO_2^0), and the resulting 1,000-year quasi-equilibrium concentration, CO_2^{equi} can be expressed as

$$CO_2^{peak} = CO_2^0 + AF^{peak} \cdot EMI \quad [1]$$

$$CO_2^{equi} = CO_2^0 + AF^{equi} \cdot EMI \quad [2]$$

so that

$$CO_2^{equi} - CO_2^0 = \frac{AF^{equi}}{AF^{peak}} (CO_2^{peak} - CO_2^0). \quad [3]$$

Given an instantaneous airborne fraction (AF^{peak}) of ≈50% during the period of rising CO_2, and a quasi-equilbrium airborne factor (AF^{equi}) of 20%, it follows that the quasi-equilibrium enhancement of CO_2 concentration above its preindustrial value is ≈40% of the peak enhancement. For example, if the CO_2 concentration were to peak at 800 ppmv followed by zero emissions, the quasi-equilibrium CO_2 concentration would still be far above the preindustrial value at ≈500 ppmv. Additional carbon cycle feedbacks could reduce the efficiency of the ocean and biosphere to remove the anthropogenic CO_2 and thereby increase these CO_2 values (15, 16). Further, a longer decay time and increased CO_2 concentrations at year 1000 are expected for large total carbon emissions (17).

Irreversible Climate Change: Atmospheric Warming. Global average temperatures increase while CO_2 is increasing and then remain approximately constant (within ≈ ±0.5 °C) until the end of the millennium despite zero further emissions in all of the test cases shown in Fig. 1. This important result is due to a near balance between the long-term decrease of radiative forcing due to CO_2 concentration decay and reduced cooling through heat loss to the oceans. It arises because long-term carbon dioxide removal

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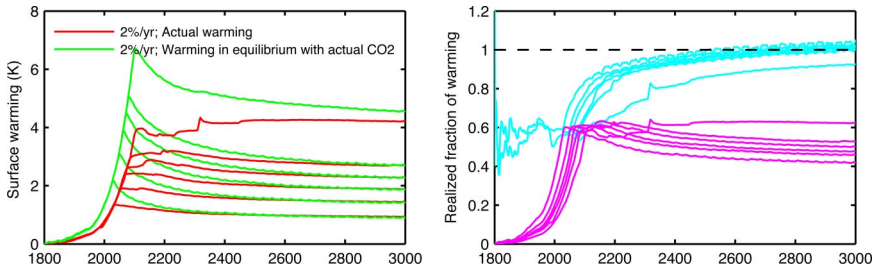


Fig. 2. Comparison between calculated time-dependent surface warming in the Bern2.5CC model and the values that would be expected if temperatures were in equilibrium with respect to the CO_2 enhancements, illustrative of 2%/year emission increases to 450, 550, 650, 750, 850, and 1,200 ppmv as in Fig. 1. (*Left*) The actual and equilibrium temperature changes (based upon the model's climate sensitivity at equilibrium). The cyan lines in *Right* show the ratio of actual and equilibrium temperatures (or realized fraction of the warming for the time-dependent CO_2 concentrations), while the magenta lines show the ratio of actual warming to the equilibrium temperature for the peak CO_2 concentration.

and ocean heat uptake are both dependent on the same physics of deep-ocean mixing. Sea level rise due to thermal expansion accompanies mixing of heat into the ocean long after carbon dioxide emissions have stopped. For larger carbon dioxide concentrations, warming and thermal sea level rise show greater increases and display transient changes that can be very rapid (i.e., the rapid changes in Fig. 1 *Middle*), mainly because of changes in ocean circulation (18). Paleoclimatic evidence suggests that additional contributions from melting of glaciers and ice sheets may be comparable to or greater than thermal expansion (discussed further below), but these are not included in Fig. 1.

Fig. 2 explores how close the modeled temperature changes are to thermal equilibrium with respect to the changing carbon dioxide concentration over time, sometimes called the realized warming fraction (19) (shown for the different peak CO_2 cases). Fig. 2 *Left* shows how the calculated warmings compare to those expected if temperatures were in equilibrium with the carbon dioxide concentrations vs. time, while Fig. 2 *Right* shows the ratio of these calculated time-dependent and equilibrium temperatures. During the period when carbon dioxide is increasing, the realized global warming fraction is ≈50–60% of the equilibrium warming, close to values obtained in other models (5, 19). After emissions cease, the temperature change approaches equilibrium with respect to the slowly decreasing carbon dioxide concentrations (cyan lines in Fig. 2 *Right*). The continuing warming through year 3000 is maintained at ≈40–60% of the equilibrium warming corresponding to the peak CO_2 concentration (magenta lines in Fig. 2 *Right*). Related changes in fast-responding atmospheric climate variables such as precipitation, water vapor, heat waves, cloudiness, etc., are expected to occur largely simultaneously with the temperature changes.

Irreversible Climate Change: Precipitation Changes. Warming is expected to be linked to changes in rainfall (20), which can adversely affect the supply of water for humans, agriculture, and ecosystems. Precipitation is highly variable but long-term rainfall decreases have been observed in some large regions including, e.g., the Mediterranean, southern Africa, and parts of southwestern North America (21–25). Confident projection of future changes remains elusive over many parts of the globe and at small scales. However, well-known physics (the Clausius–Clapeyron law) implies that increased temperature causes increased atmospheric water vapor concentrations, and changes in water vapor transport and the hydrologic cycle can hence be expected (26–28). Further, advances in modeling show that a robust characteristic of anthropogenic climate change is poleward expansion of the Hadley cell and shifting of the pattern of precipitation minus evaporation (*P–E*) and the storm tracks (22, 26), and hence a pattern of drying over much of the already-dry subtropics in a warmer world (≈15°-40° latitude in each hemisphere) (5, 26). Attribution studies suggest that such a drying pattern is already occurring in a manner consistent with models including anthropogenic forcing (23), particularly in the southwestern United States (22) and Mediterranean basin (24, 25).

We use a suite of 22 available AOGCM projections based upon the evaluation in the IPCC 2007 report (5, 29) to characterize precipitation changes. Changes in precipitation are expected (5, 20, 30) to scale approximately linearly with increasing warming (see Fig. S3). The equilibrium relationship between precipitation and temperature may be slightly smaller (by ≈15%) than the transient values, due to changes in the land/ocean thermal contrast (31). On the other hand, the observed 20th century changes follow a similar latitudinal pattern but presently exceed those calculated by AOGCMs (23). Models that include more complex representations of the land surface, soil, and vegetation interactively are likely to display additional feedbacks so that larger precipitation responses are possible.

Here we evaluate the relationship between temperature and precipitation averaged for each month and over a decade at each grid point. One ensemble member is used for each model so that all AOGCMs are equally weighted in the multimodel ensemble; results are nearly identical if all available model ensemble members are used.

Fig. 3 presents a map of the expected dry-season (3 driest consecutive months at each grid point) precipitation trends per degree of global warming. Fig. 3 shows that large uncertainties remain in the projections for many regions (white areas). However, it also shows that there are some subtropical locations on every inhabited continent where dry seasons are expected to become drier in the decadal average by up to 10% per degree of warming. Some of these grid points occur in desert regions that are already very dry, but many occur in currently more temperate and semiarid locations. We find that model results are more robust over land across the available models over wider areas for drying of the dry season than for the annual mean or wet season (see Fig. S4). The *Insets* in Fig. 3 show the monthly mean projected precipitation changes averaged over several large regions as delineated on the map. Increased drying of respective dry seasons is projected by >90% of the models averaged over the indicated regions of southern Europe, northern Africa, southern Africa, and southwestern North America and by >80% of the models for eastern South America and western Australia (see Fig. S3). Although given particular years would show exceptions, the long-term irreversible warming and mean rainfall changes as suggested by Figs. 1 and 3 would have important consequences in many regions. While some relief can be expected in the wet season for some regions (Fig. S4), changes in dry-season precipitation in northern Africa, southern Europe, and western Australia are expected to be near 20% for 2 °C warming, and those of southwestern North America, eastern South America, and southern Africa would be ≈10% for 2 °C of global mean warming. For comparison, the American "dust

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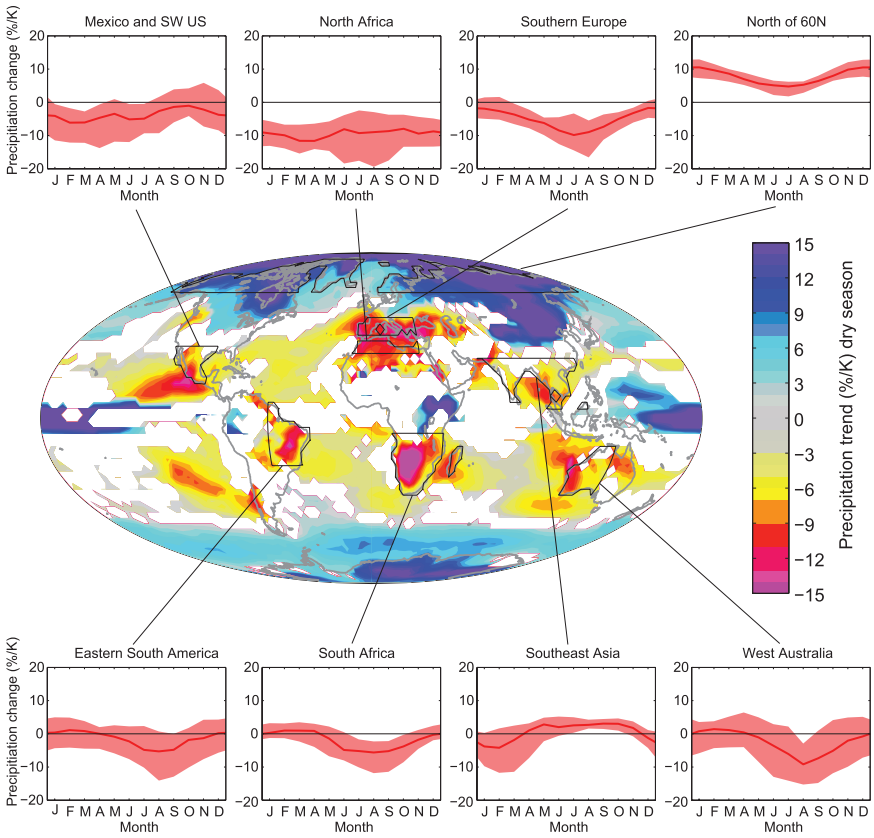


Fig. 3. Expected decadally averaged changes in the global distribution of precipitation per degree of warming (percentage of change in precipitation per degree of warming, relative to 1900–1950 as the baseline period) in the dry season at each grid point, based upon a suite of 22 AOGCMs for a midrange future scenario (A1B, see ref. 5). White is used where fewer than 16 of 22 models agree on the sign of the change. Data are monthly averaged over several broad regions in *Inset* plots. Red lines show the best estimate (median) of the changes in these regions, while the red shading indicates the ± 1-σ likely range (i.e., 2 of 3 chances) across the models.

bowl" was associated with averaged rainfall decreases of ≈10% over ≈10–20 years, similar to major droughts in Europe and western Australia in the 1940s and 1950s (22, 32). The spatial changes in precipitation as shown in Fig. 3 imply greater challenges in the distribution of food and water supplies than those with which the world has had difficulty coping in the past. Such changes occurring not just for a few decades but over centuries are expected to have a range of impacts that differ by region. These include, e.g., human water supplies (25), effects on dry-season wheat and maize agriculture in certain regions of rain-fed farming such as Africa (33, 34), increased fire frequency, ecosystem change, and desertification (24, 35–38).

Fig. 4 *Upper* relates the expected irreversible changes in regional dry-season precipitation shown in Fig. 3 to best estimates of the corresponding peak and long-term CO_2 concentrations. We use 3 °C as the best estimate of climate sensitivity across the suite of AOGCMs for a doubling of carbon dioxide from preindustrial values (5) along with the regional drying values depicted in Fig. 3 and assuming that ≈40% of the carbon dioxide peak concentration is retained after 1000 years. Fig. 4 shows that if carbon dioxide were to peak at levels of ≈450 ppmv, irreversible decreases of ≈8–10% in dry-season precipitation would be expected on average over each of the indicated large regions of southern Europe, western Australia, and northern Africa, while a carbon dioxide peak value near 600 ppmv would be expected to lead to sustained rainfall decreases of ≈13–16% in the dry seasons in these areas; smaller but statistically significant irreversible changes would also be expected for southwestern North America, eastern South America, and Southern Africa.

Irreversible Climate Change: Sea Level Rise. Anthropogenic carbon dioxide will cause irrevocable sea level rise. There are 2 relatively well-understood processes that contribute to this and a third that may be much more important but is also very uncertain. Warming causes the ocean to expand and sea levels to rise as shown in Fig. 1; this has been the dominant source of sea level rise in the past decade at least (39). Loss of land ice also makes important contributions to sea level rise as the world warms. Mountain glaciers in many locations are observed to be retreating due to warming, and this contribution to sea level rise is also relatively well understood. Warming may also lead to large losses of the Greenland and/or Antarctic ice sheets. Additional rapid ice losses from particular parts of the ice sheets of Greenland and Antarctica have recently been observed (40–42). One recent study uses current ice discharge data to suggest ice sheet contributions of up to 1–2 m to sea level rise by 2100 (42), but other studies suggest that changes in winds rather than warming may account for currently observed rapid ice sheet flow (43), rendering quantitative extrapolation into the future uncertain. In addition to rapid ice flow, slow ice sheet mass balance processes are another mechanism for potential large sea level rise. Paleoclimatic data demonstrate large contributions of ice sheet loss to sea level rise (1, 4) but provide limited constraints on the rate of such processes. Some recent studies suggest that ice sheet surface mass balance loss for peak CO_2 concentrations of 400–800 ppmv may be even slower than the removal of manmade carbon dioxide following cessation of emis-

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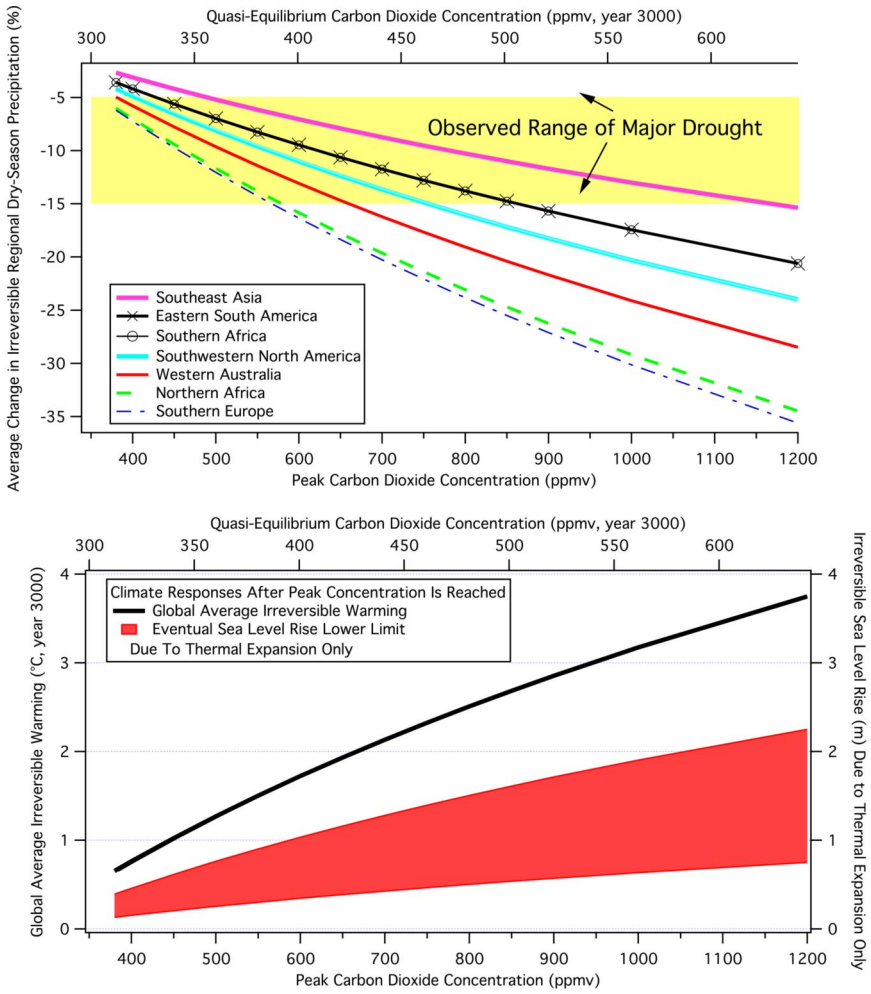


Fig. 4. Illustrative irreversible climate changes as a function of peak carbon dioxide reached. (*Upper*) Best estimate of expected irreversible dry-season precipitation changes for the regions shown in Fig. 3, as a function of the peak carbon dioxide concentration during the 21st century. The quasi-equilibrium CO_2 concentrations shown correspond to 40% remaining in the long term as discussed in the text. The precipitation change per degree is derived for each region as in Fig. 3; see also Fig. S3. The yellow box indicates the range of precipitation change observed during typical major regional droughts such as the ''dust bowl'' in North America (32). (*Lower*) Corresponding irreversible global warming (black line). Also shown is the associated lower limit of irreversible sea level rise (because of thermal expansion only based upon a range of 0.2–0.6 m/°C), from an assessment across available models (5). Smaller values (by ≈30%) for expected warming, precipitation, and thermal sea level rise would be obtained if climate sensitivity is smaller than the best estimate while larger values (by ≈50%) would be expected for the upper end of the estimated likely range of climate sensitivity (49).

sions, so that this loss could contribute less than a meter to irreversible sea level rise even after many thousands of years (44, 45). It is evident that the contribution from the ice sheets could be large in the future, but the dependence upon carbon dioxide levels is extremely uncertain not only over the coming century but also in the millennial time scale.

An assessed range of models suggests that the eventual contribution to sea level rise from thermal expansion of the ocean is expected to be 0.2–0.6 m per degree of global warming (5). Fig. 4 uses this range together with a best estimate for climate sensitivity of 3 °C (5) to estimate lower limits to eventual sea level rise due to thermal expansion alone. Fig. 4 shows that even with zero emissions after reaching a peak concentration, irreversible global average sea level rise of at least 0.4–1.0 m is expected if 21st century CO_2 concentrations exceed 600 ppmv and as much as 1.9 m for a peak CO_2 concentration exceeding ≈1,000 ppmv. Loss of glaciers and small ice caps is relatively well understood and is expected to be largely complete under sustained warming of, for example, 4 °C within ≈500 years (46). For lower values of warming, partial remnants of glaciers might be retained, but this has not been examined in detail for realistic representations of glacier shrinkage and is not quantified here. Complete losses of glaciers and small ice caps have the potential to raise future sea level by ≈0.2–0.7 m (46, 47) in addition to thermal expansion. Further contributions due to partial loss of the great ice sheets of Antarctica and/or Greenland could add several meters or more to these values but for what warming levels and on what time scales are still poorly characterized.

Sea level rise can be expected to affect many coastal regions (48). While sea walls and other adaptation measures might combat some of this sea level rise, Fig. 4 shows that carbon dioxide peak concentrations that could be reached in the future for the conservative lower limit defined by thermal expansion alone can be expected to be associated with substantial irreversible commitments to future changes in the geography of the Earth because many coastal and island features would ultimately become submerged.

Discussion: Some Policy Implications

It is sometimes imagined that slow processes such as climate changes pose small risks, on the basis of the assumption that a choice can always be made to quickly reduce emissions and

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thereby reverse any harm within a few years or decades. We have shown that this assumption is incorrect for carbon dioxide emissions, because of the longevity of the atmospheric CO_2 perturbation and ocean warming. Irreversible climate changes due to carbon dioxide emissions have already taken place, and future carbon dioxide emissions would imply further irreversible effects on the planet, with attendant long legacies for choices made by contemporary society. Discount rates used in some estimates of economic trade-offs assume that more efficient climate mitigation can occur in a future richer world, but neglect the irreversibility shown here. Similarly, understanding of irreversibility reveals limitations in trading of greenhouse gases on the basis of 100-year estimated climate changes (global warming potentials, GWPs), because this metric neglects carbon dioxide's unique long-term effects. In this paper we have quantified how societal decisions regarding carbon dioxide concentrations that have already occurred or could occur in the coming century imply irreversible dangers relating to climate change for some illustrative populations and regions. These and other dangers pose substantial challenges to humanity and nature, with a magnitude that is directly linked to the peak level of carbon dioxide reached.

Materials and Methods

The AOGCM simulation data presented in this paper are part of the World Climate Research Program's (WCRP's) Coupled Model Intercomparison Project phase 3 (CMIP3) multimodel data set (29) and are available from the Program for Climate Model Diagnosis and Intercomparison (PCMDI) (www-pcmdi.llnl.gov/ipcc/about_ipcc.php), where further information on the AOGCMs can also be obtained. The EMIC used in this study is the Bern2.5CC EMIC described in refs. 7 and 15; it is compared to other models in refs. 5 and 7. It is a coupled climate–carbon cycle model of intermediate complexity that consists of a zonally averaged dynamic ocean model, a 1-layer atmospheric energy–moisture balance model, and interactive representations of the marine and terrestrial carbon cycles.

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1. Hansen J, *et al.* (2007) Dangerous human-made interference with climate: a GISS modelE study. *Atmos Chem Phys* 7:2287–2312.
2. Ramanathan V, Feng Y (2008) On avoiding dangerous anthropogenic interference with the climate system: formidable challenges. *Proc Natl Acad Sci USA* 105:14245–14250.
3. Schellnhuber HJ (2008) Global warming: Stop worrying, start panicking? *Proc Natl Acad Sci USA* 105:14239–14240.
4. Oppenheimer M, Alley RB (2004) The West Antarctic ice sheet and long term climate policy. *Clim Change* 64:1–10.
5. Meehl GA, *et al.* (2007) Global climate projections. *Climate Change 2007: The Physical Science Basis*, eds Solomon S, *et al.* (Cambridge Univ Press, Cambridge, UK, and New York), pp 747–845.
6. Matthews HD, Caldeira K (2008) Stabilizing climate requires near-zero emissions. *Geophys Res Lett* 35:L04705, 10.1029/2007GL032388.
7. Plattner GK, *et al.* (2008) Long-term climate commitments projected with climate−carbon cycle models. *J Clim* 21:2721–2751.
8. Parry ML, *et al.* (2007) *Climate Change 2007: Impacts, Adaptation, and Vulnerability. Contribution of Working Group 2 to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* (Cambridge Univ Press, Cambridge, UK, and New York).
9. Revelle R, Suess HE (1957) Carbon dioxide exchange between atmosphere and ocean and the question of an increase of atmospheric CO_2 during the past decades. *Tellus* 9:18–27.
10. Archer D, Kheshgi H, Maier-Reimer E (1997) Multiple timescales for neutralization of fossil fuel CO_2. *Geophys Res Lett* 24:405–408.
11. Montenegro A, Brovkin V, Eby M, Archer D, Weaver AJ (2007) Long term fate of anthropogenic carbon. *Geophys Res Lett* 34:L19707, 10.1029/2007GL030905.
12. Archer D, Brovkin V (2008) The millennial atmospheric lifetime of anthropogenic CO_2. *Clim Change* 90:283–297 10.1007/s10584-008-9413-1.
13. Raupach MR, *et al.* (2007) Global and regional drivers of accelerating CO_2 emissions. *Proc Natl Acad Sci USA* 94:10288–10293.
14. Forster P, *et al.* (2007) Changes in atmospheric constituents and in radiative forcing. *Climate Change 2007: The Physical Science Basis*, eds Solomon S, *et al.* (Cambridge Univ Press, Cambridge, UK, and New York), pp 747–845.
15. Joos F, *et al.* (2001) Global warming feedbacks on terrestrial carbon uptake under the Intergovernmental Panel on Climate Change (IPCC) emission scenarios. *Global Biogeochem Cycles* 15:891–907.
16. Schmittner A, Oschlies A, Matthews HD, Galbraith ED (2008) Future changes in climate, ocean circulation, ecosystems, and biogeochemical cycling simulated for a business-as-usual CO_2 emission scenario until year 4000 AD. *Global Biogeochem Cycles* 22:GB1013, 10.1029/2007GB002953.
17. Eby M, *et al.* (2008) Lifetime of anthropogenic climate change: millennial time-scales of potential CO_2 and surface temperature perturbations. *J Clim*,10.1175/2008JCLI2554.1, in press.
18. Flueckiger J, Knutti R, White JWC (2006) Oceanic processes as potential trigger and amplifying mechanisms for Heinrich events. *Paleoceanography* 21:PA2014, doi:10.1029/2005PA001204.
19. Stouffer RJ (2004) Time scales of climate response. *J Clim* 17:209–214.
20. Allen MR, Ingram WJ (2002) Constraints on future changes in climate and the hydrologic cycle. *Nature* 419:224–232.
21. Trenberth KE, *et al.* (2007) Observations: surface and atmospheric climate change. *Climate Change 2007: The Physical Science Basis*, eds Solomon S, *et al.* (Cambridge Univ Press, Cambridge, UK), pp 747–845.
22. Seager R, *et al.* (2007) Model projections of an imminent transition to a more arid climate in southwestern North America. *Science* 316:1181–1184.
23. Zhang X, *et al.* (2007) Detection of human influence on twentieth-century precipitation trends. *Nature* 448:461–465.
24. Gao X, Giorgi F (2008) Increased aridity in the Mediterranean region under greenhouse gas forcing estimated from high resolution simulations with a regional climate model. *Global Planet Change* 62:195–209.
25. Burke EJ, Brown SJ, Christidis N (2006) Modelling the recent evolution of global drought and projections for the 21st century with the Hadley Centre climate model. *J Hydrometeorol* 7:1113–1125.
26. Held IM, Soden BJ (2006) Robust responses of the hydrological cycle to global warming. *J Clim* 19:5686–5699.
27. Manabe S, Stouffer RJ (1980) Sensitivity of a global climate model to an increase of CO_2 concentration in the atmosphere. *J Geophys Res* 85:5529–5554.
28. Kutzbach JE, Williams JW, Vavrus SJ (2005) Simulated 21st century changes in regional water valance of the Great Lakes region and links to changes in global temperature and poleward moisture transport. *Geophys Res Lett* L17707, 10.1029/2005GL023506.
29. Meehl GA, *et al.* (2007) The WCRP CMIP3 multi-model dataset: a new era in climate change research. *Bull Am Meteorol Soc* 88:1383–1394.
30. Mitchell TD (2003) Pattern scaling: an examination of the accuracy of the technique for describing future climates. *Clim Change* 60:217–242.
31. Stouffer RS, Manabe S (1999) Response of a coupled ocean-atmosphere model to increasing atmospheric carbon dioxide: sensitivity to the rate of increase. *J Clim* 12:2224–2237.
32. Narisma GT, Foley JA, Licker R, Ramankutty N (2007) Abrupt changes in rainfall during the twentieth century. *Geophys Res Lett* 34:L06710, 10.1029/2006GL028628.
33. Lobell DB, *et al.* (2008) Prioritizing climate change adaptation needs for food security in 2030. *Science* 319:607–610.
34. Easterling W, *et al.* (2007) Food, fibre, and forest products. *Climate Change 2007: Impacts, Adaptation, and Vulnerability*, eds Parry ML, *et al.* (Cambridge Univ Press, Cambridge, UK), pp 273–313.
35. Fischlin A, *et al.* (2007) Ecosystems, their properties, goods and services. *Climate Change 2007: Impacts, Adaptation, and Vulnerability*, eds Parry ML, *et al.* (Cambridge Univ Press, Cambridge, UK), pp 211–272.
36. Williams JW, Jackson ST, Kutzbach JE (2007) Projected distributions of novel and disappearing climates by 2100 AD. *Proc Natl Acad Sci USA* 104:5738–5742.
37. Scholze M, Knorr W, Arnell NW, Prentice IC (2006) A climate-change risk analysis for world ecosystems. *Proc Natl Acad Sci USA* 103:13116–13120.
38. Westerling AL, Hidalgo HG, Cayan DR, Swetnam TW (2006) Warming and earlier spring increase western US forest wildfire activity. *Science* 313:940–943.
39. Bindoff NL, *et al.* (2007) Observations: oceanic climate change and sea level. *Climate Change 2007: The Physical Science Basis*, eds Solomon S, *et al.* (Cambridge Univ Press, Cambridge, UK), pp 747–845.
40. Rignot E, Kanagaratnam P (2006) Changes in the velocity structure of the Greenland ice sheet. *Science* 311:986–990.
41. Joughin I, *et al.* (2008) Seasonal speedup along the western flank of the Greenland ice sheet. *Science* 320:781–783.
42. Pfeffer WT, Harper JT, O'Neel S (2008) Kinematic constraints on glacier contributions to 21st-century sea level rise. *Science* 321:1340–1343.
43. Holland DM, Thomas RH, De Young B, Ribergaard MH, Lyberth B (2008) Acceleration of Jakobshaven Isbrae triggered by warm subsurface ocean waters. *Nat Geosci* 1:659–664.
44. Charbit S, Paillard D, Ramstein G (2008) Amount of CO_2 emissions irreversibly leading to the total melting of Greenland. *Geophys Res Lett* 35:L12503, 10.1029/2008GL033472.
45. Parizek BR, Alley RB (2004) Implications of increased Greenland surface melt under global warming scenarios: ice sheet simulations. *Quat Sci Rev* 23:1013–1027.
46. Raper SCB, Braithwaite RJ (2006) Low sea level rise projections from mountain glaciers and icecaps under global warming. *Nature* 439:311–313.
47. Lemke P, *et al.* (2007) Observations: changes in snow, ice, and frozen ground. *Climate Change 2007: The Physical Science Basis*, eds Solomon S, *et al.* (Cambridge Univ Press, Cambridge, UK), pp 747–845.
48. Nicholls RJ, *et al.* (2007) Coastal systems and low lying areas. *Climate Change 2007: Impacts, Adaptation, and Vulnerability*, eds Parry ML, *et al.* (Cambridge Univ Press, Cambridge, UK), pp 315–357.
49. Knutti R, Hegerl G (2004) The equilibrium sensitivity of the Earth's temperature to radiation changes. *Nat Geosci* 1:735–743.

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Effect of methane mitigation on global temperature under a permafrost feedback

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ABSTRACT

Earth systems may fall into an undesirable system state if 1.5 °C of warming is exceeded. Carbon release from substantial permafrost stocks vulnerable to near-term warming represents a positive climate feedback that may increase the risk of 1.5 °C warming or greater. Methane (CH_4) is a short-lived but powerful greenhouse gas with a global warming potential 28.5 times that of carbon dioxide (CO_2) over a 100 year time span. Because permafrost thaw in the coming centuries is partly determined by the warming in the 21st century, rapid reductions in methane emissions early in the 21st century could have far reaching effects. We use a reduced complexity carbon cycle model and a permafrost feedback module to explore the possibility that accelerating reductions in methane emissions could help avoid long-term warming by limiting permafrost melt. We simulate three extended Representative Concentration Pathway (RCP) emission scenarios (RCP 2.6, 4.5, and 6) through the year 2300 and impose methane mitigation strategies where we reduce CH_4 emissions by 1%, 5% or 10% annually until the long-term scenario emission level is reached. We find that accelerated rates of methane mitigation do not sufficiently alter the global temperature anomaly to prevent or delay a permafrost feedback, nor do they result in meaningful long term reductions in temperatures. We find that the long-term magnitude of methane mitigation (i.e., long-term emission level) and not the rate of reduction, corresponds to long-term temperature change. Further study of methane-climate dynamics is necessary to fully resolve this question.

1. Introduction

There is increasing recognition and concern that multiple intrinsic positive feedbacks in the Earth system may lead to “tipping points” whereby the Earth system state may rapidly transition into a new undesirable one once some threshold of global mean warming is passed. Such feedbacks include ice sheet loss, permafrost melt, Atlantic ocean circulation, and Amazon rainforest dieback (Lenton et al., 2019). Without these feedbacks, previous estimates for “safe warming” ranged between 2-3 °C. With the inclusion of positive, interacting feedbacks, Lenton et al. (2019) concluded that warming must be limited to 1.5 °C. Warming past 1.5 °C may cause runaway feedback effects. Therefore, a full assessment of mitigation pathways to avoid crossing undesirable climate boundaries should explicitly include major feedbacks.

Among the many positive climate feedbacks, permafrost melt and subsequent carbon emissions may have the greatest effect on climate in the coming centuries due to the vast amounts of carbon stored within the permafrost and vulnerability to temperature perturbation (Crichton et al., 2016). Because long-term warming is primarily a function of *cumulative* carbon emissions (Pierrehumbert, 2014; Global, 2022) the concept of the carbon budget was developed. It describes a total cumulative amount of carbon that can be emitted to limit global mean warming (with some degree of confidence) to a given level, e.g. 1.5 °C. Each year, anthropogenic CO_2 emissions take roughly 9 gigatonnes of carbon (GtC) off the budget. In 2019, there was an estimated 136 GtC left in the budget for 1.5 °C, (Lenton et al., 2019; Rogelj et al., 2019) but more recent estimates from 2021 posit that only 120 GtC remain (Friedlingstein et al., 2022).

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The permafrost may be the most impactful near-term feedback because of high net carbon content and sensitivity to degradation with increased warming. As temperatures rise, permafrost emissions could rapidly exhaust the carbon budget. As of 2014, it has been estimated that circumpolar permafrost at a depth of 0-3 meters stored 1035 GtC (Hugelius et al., 2014). Several existing studies have estimated permafrost carbon emissions under Representative Concentration Pathway (RCP) emissions scenarios used by the Intergovernmental Panel on Climate Change (IPCC), namely RCP 2.6, RCP 4.5, RCP 6.0, and RCP 8.5, with the number corresponding to the change in radiative forcing the Earth experiences in the year 2100 (e.g., under RCP 8.5, the Earth will experience +8.5 Watts/m^{-2} of radiative forcing). Under RCP 8.5, 33-114 GtC may be released from the permafrost by 2100, contributing to an additional warming of 0.04-0.23 °C (Schneider Von Deimling et al., 2012), and by 2300, half the vulnerable permafrost carbon stock could be released. While the RCP 8.5 is a high-end scenario, there is still a great deal of uncertainty regarding permafrost carbon stocks, thawing processes, and subsequent microbial decomposition to CO_2 and CH_4, as well as other potential feedbacks (Schneider Von Deimling et al., 2012). Another study found that the permafrost feedback effect reduces the carbon budget for avoiding 2 °C warming by 100 GtC (Gasser et al., 2018), accounting for roughly 24% of the remaining carbon budget (Friedlingstein et al., 2022). Therefore, permafrost feedback is the primary positive climate feedback we examine in this paper.

Methane is a powerful greenhouse gas and is responsible for about 1.19 W/m^{-2} of radiative forcing since 1750. Given that warming is a function of multiple anthropogenic greenhouse gas emissions, mitigating methane emissions will play an important role in avoiding the climate boundary (Dreyfus et al., 2022; Rogelj et al., 2014; Harmsen et al., 2020; Xu and Ramanathan, 2017; Christensen et al., 2019). However, multiple authors have argued that methane mitigation is not a substitute for immediate decarbonization and will not "buy us time" as we work towards net-zero carbon (Pierrehumbert, 2014; Rogelj et al., 2014; Bowerman et al., 2013; Myhre et al., 2011). These conclusions hinge on the fundamentally different climate effects of short-lived and long-lived greenhouse gases.

Because near term climate forcers like methane have relatively short atmospheric lifetimes, the annual emissions *rate* of these substances is far more relevant than cumulative emissions over time (Pierrehumbert, 2014): There is no long-term "methane budget". We are concerned with net cumulative emissions of CO_2 because it is a long-lived millennial gas, where in contrast, methane oxidizes to CO_2 in the presence of hydroxyl radicals (OH), and has a perturbation lifetime of approximately 12.4 years (IPCC, 2023). Therefore, mitigation efforts should make their focus limiting annual methane emissions rather than limiting a net cumulative amount.

How to best plan methane mitigation in the coming years remains an open question. Although there is uncertainty regarding how much, there is general agreement that some warming can be avoided in this century by implementing methane mitigation plans (Smith and Mizrahi, 2013; Dreyfus et al., 2022), with methane mitigation especially valuable for limiting near term warming rates and magnitude by mid-century (Ocko et al., 2021). However, McKeough (2022) concluded that mitigation could be postponed to as late as 2050-2080 with limited impact on the temperature anomaly at 2100 (McKeough, 2022). Nevertheless, methane mitigation is understudied in relation to its long-term effects (past 2100), especially in relation to positive climate feedbacks. That is, because feedbacks such as permafrost may be sensitive to near-term temperature changes that are strongly influenced by methane emissions rates early in the twenty-first century, rapid methane mitigation could be a higher priority than previously realized.

We address the question of the rate of methane mitigation: Is there any benefit to an accelerated emissions reduction plan in the presence of a permafrost carbon feedback? We are interested in the possibility that the mitigation of methane could prevent some release of CO_2, as well as CH_4, from the permafrost, and therefore mitigate long-term warming. Because methane has considerable short term temperature effects and can strongly influence the short-term rate of warming, it warrants examination in relation to the permafrost feedback.

We use a reduced complexity model that represents the most relevant Earth systems to understand the dynamics between reducing annual CH_4 emissions and long term temperature changes from CO_2 and CH_4, as well as nitrous oxide (N_2O), due to its interaction with methane. Radiative forcing attributable to our three greenhouse gases is described with IPCC formulas, and the associated temperature change is determined by a two-box ocean layer heat transfer model from Pierrehumbert (2014). We develop a simplified carbon cycle model based on Glotter et al. (2014) and Hartin et al. (2016, 2015) that describes flux between three terrestrial biota compartments and two ocean compartments. Increased carbon uptake due to CO_2 fertilization and CO_2 buffering with acidification are included. We model permafrost decomposition via a linear decrease in permafrost extent with rise in temperature and subsequent release of emissions as exponential decay. This is based on the model of Kessler (2017), where permafrost carbon mobilization to a labile carbon pool increases linearly with temperature. Carbon in this labile pool is then emitted to the atmosphere as a mix of CO_2 and CH_4 according to exponential dynamics with an e-folding time of about 70 years. These simplified representations of Earth systems describe the relationship of emissions to temperature perturbation. Finally, we drive the model using RCP CO_2 emission time-series while varying rates of methane mitigation to determine the impact on long term temperature.

2. Methods

We use a reduced complexity climate model implemented as a system of coupled first order differential equations. These equations model the carbon cycle with carbon fluxes between atmospheric, terrestrial, and ocean layers, along with ocean carbonate chemistry. We use a simple two-box temperature response model to calculate the effects of radiative forcing from CO_2, N_2O, and CH_4 on surface temperature. We include a two-part linear permafrost feedback using a differential equation that responds to increases of the global mean temperature. The temperature and carbon cycle model can be driven either by imposed atmospheric GHG concentrations (when driving the model with historical data) or with GHG emissions (and resulting modeled concentrations) when projecting the model forward.

2.1. The carbon cycle

2.1.1. Terrestrial carbon stores

The terrestrial carbon stores included in our model are the vegetation, detritus and soil. Together, these have a significant interaction with atmospheric carbon. We use a differential equation to describe each major box, where C_V is the carbon of the vegetation layer, C_D is the carbon in the detritus layer, and C_S is the carbon in the soil layer. Each box (Equations (1), (2), (3)) has a source term representing net primary productivity (NPP), where autotrophs store some of amount of carbon. Each layer has loss and source terms to describe the transfer of carbon from one layer to another. The vegetation box's loss term represents the transfer of carbon to the detritus ($C_V f_{vd}$) and soil ($C_V f_{vs}$) layers. The detritus box's loss term describes the carbon transfer to the soil layer ($C_D f_{ds}$). The soil and detritus boxes have loss terms for heterotrophic respiration (RH), where microbial activity releases carbon into the atmosphere. Finally, each layer has a term representing losses of carbon due to land use change (F_{LC}).

We use formulas from Hartin et al. (2015) given by

$$\frac{dC_V}{dt} = NPP f_{nv} - C_V(f_{vd} + f_{vs}) - F_{LC} f_{lv}\,, \tag{1}$$

$$\frac{dC_D}{dt} = NPP f_{nd} + C_V f_{vd} - C_D f_{ds} - RH_{det} - F_{LC} f_{ld}\,, \tag{2}$$

$$\frac{dC_S}{dt} = NPPf_{ns} + C_V f_{vs} + C_D f_{ds} - RH_{soil} - F_{LC} f_{ls} \,. \tag{3}$$

Any land use change alters the CO_2 content of the terrestrial stores. If land is deforested, each layer releases carbon into the atmosphere. If x GtC are released due to land use change, a certain proportion of those emissions comes from each of the different layer represented by the portions f_{lv}, f_{ld}, and f_{ls} (Table 1).

Heterotrophic respiration (RH) from the detritus and soil layers feeds into the atmosphere. RH is a function of the current carbon content of the respective strata and the respiration factor Q_{10} which is the factor by which respiration increases for a 10 degree increase in temperature. For soil and detritus, we use a ten-year average of global mean temperature perturbation divided by ten. A running average is used to represent the slow change in temperature from the surface of the Earth to the lower layers of soil.

Net primary productivity (NPP) is a function of current atmospheric carbon levels compared to pre-industrial carbon levels in ppm scaled by the carbon fertilization parameter, β. The value for β varies depending on the region (Hartin et al., 2016), but we use a single value to represent the whole earth system. The total NPP is subtracted from our atmospheric carbon, reflecting the carbon uptake by all terrestrial sinks, and is added to terrestrial stores by a factor f_{nv}, f_{nd}, f_{ns} (Table 1). Therefore, we determine NPP and RH by

$$\mathrm{NPP}(t) = \mathrm{NPP}_0 \times f(C_{atm}, \beta) \tag{4}$$

$$f(C_{atm}, \beta) = 1 + \beta \times log\left(\frac{C_{atm}}{C_0}\right) \tag{5}$$

$$\mathrm{RH}_{s,d}(t) = C_{s,d} \times f_{rs,rd} \times Q_{10}^{T(t)/10}. \tag{6}$$

2.1.2. Oceanic carbon stores

Ocean carbon flows and buffering chemistry are modeled using the Bolin and Erikson Adjusted Model (BEAM) (Glotter et al., 2014), where CO_2 cycles between the atmosphere, upper ocean, and lower ocean.

We represent the carbon in the atmosphere, upper ocean, and lower ocean boxes as C_A, C_U, and C_L respectively. Important parameters include δ_d and δ_a, where δ_d represents the ratio of the moles of the lower (deep) ocean to the moles of the upper ocean. Then, δ_a is the ratio of moles between the atmosphere and the upper ocean. Given the ocean is approximately 500 times the size of the atmosphere, we set δ_d to 50 and solve for δ_a using known values for atmospheric and ocean moles. We use k_a for the turnover time for the upper ocean, k_d for the turnover time for the deep ocean, and k_H for Henry's constant. Lastly, the anthropogenic emissions stream $E(t)$ is added directly to C_A.

To model the carbon chemistry of the ocean, we look at the dynamics of how atmospheric carbon is absorbed into the different ocean layers. The loss of carbon in the atmosphere to the upper ocean is represented by $-k_a C_A$, and its flux back into the atmosphere is described with the expression $k_a \frac{k_H}{\delta_a} C_U$. Carbon flux in the upper ocean is described with the same expressions with opposite signs. Additionally, there is an exchange between the upper and lower ocean given by $-k_d C_U + \frac{k_d}{\delta_d} C_L$. These flows can be represented by the equations (Glotter et al., 2014)

$$\frac{dC_A}{dt} = -k_a C_A + k_a \frac{k_H}{\delta_a} C_U + E(t) \,, \tag{7}$$

$$\frac{dC_U}{dt} = k_a C_A - k_a \frac{k_H}{\delta_a} C_U - k_d C_U + \frac{k_d}{\delta_d} C_L \,, \tag{8}$$

$$\frac{dC_L}{dt} = k_d C_U - \frac{k_d}{\delta_d} C_L \,. \tag{9}$$

However, this does not completely model the dynamics between the ocean and the atmosphere. We must take into account the dynamic ocean chemistry as atmospheric CO_2 is dissolved in saltwater into the forms of bicarbonate (HCO_3^-) and carbonate (CO_3^{2-}). The dissociation of carbon into its compounds occurs with dissociation constants k_1 and k_2 (see Table 1). This dynamic equilibrium is represented by (Glotter et al., 2014)

$$CO_2 + H_2O \overset{k_1}{\rightleftharpoons} HCO_3^- + H^+ \overset{k_2}{\rightleftharpoons} CO_3^{2-} + 2H^+, \text{ where} \tag{10}$$

$$k_1 = \frac{[HCO_3^-][H^+]}{[CO_2(aq)]} \text{ and } k_2 = \frac{[CO_3^{2-}][H^+]}{[HCO_3^-]} \,. \tag{11}$$

Because CO_2 is a weak acid that reduces the ocean's capacity to absorb additional carbon dioxide, we must determine what the ocean's carbon storage capacity is at a given time. We use Λ as this "carbon storage factor", representing the ratio of the equilibrium of total dissolved inorganic carbon to CO_2 (aq). Because we have the dissociation constants k_1 and k_2, Λ also can be described as a function of hydrogen ion concentrations at a given time, and we get the following (Glotter et al., 2014):

$$\Lambda(t) = \frac{[CO_2] + [HCO_3^-] + [CO_3^{2-}]}{[CO_2]} = 1 + \frac{k_1}{[H^+]} + \frac{k_1 k_2}{[H^+]^2}. \tag{12}$$

Here, Λ is the ratio of the equilibrium of sum of dissolved inorganic carbon (DIC) relative to CO_2 (aq). To find Λ at a given time, we must know the concentration of hydrogen ions. By definition, we have the total dissolved inorganic carbon as

$$[DIC] = [\mathrm{CO}_2(aq)] + [HCO_3^-] + [CO_3^{2-}] \,. \tag{13}$$

After some simple algebraic manipulation of the equations for k_1 and k_2 on (11) and plugging into our $[DIC]$ on (13), we get

$$[DIC] = [\mathrm{CO}_2(aq)] \left(1 + \frac{k_1}{[H^+]} + \frac{k_1 k_2}{[H^+]^2}\right) \,. \tag{14}$$

Because the charges of the ions must be balanced, we can calculate the $[H^+]$ concentration using the alkalinity (Alk) as

$$Alk = [HCO_3^-] + 2[CO_3^-] = [\mathrm{CO}_2(aq)] \left(\frac{k_1}{[H^+]} + \frac{2k_1 k_2}{[H^+]^2}\right) \tag{15}$$

$$= \frac{C_U}{\Lambda} \left(\frac{k_1}{[H^+]} + \frac{k_1 k_2}{[H^+]^2}\right) \,. \tag{16}$$

Therefore, we find the concentration of hydrogen ions by solving the quadratic

$$[H^+]^2 + [H^+]k_1\left(1 - \frac{C_U}{Alk} + k_1 k_2 \left(1 - \frac{2C_U}{Alk}\right)\right) = 0 \tag{17}$$

where we take the positive root to be our hydrogen concentration.

The ability to store carbon decreases significantly as the pH increases. Our whole ocean carbon chemistry and flux can be represented with

$$\frac{dC_A}{dt} = -k_a C_A + k_a \frac{k_H}{\delta_a \Lambda} C_U + E(t) \,, \tag{18}$$

$$\frac{dC_U}{dt} = k_a C_A - k_a \frac{k_H}{\delta_a \Lambda} C_U - k_d C_U + \frac{k_d}{\delta_d} C_L \,, \tag{19}$$

$$\frac{dC_L}{dt} = k_d C_U - \frac{k_d}{\delta_d} C_L \,. \tag{20}$$

2.2. Model outline

Fig. 1 provides a simplified representation of our model's dynamics. Anthropogenic emissions, from fossil fuels and land use change, and the permafrost feedback, are the primary sources of CO_2 and CH_4 emissions, our primary warming agents. Biogenic methane emissions are included as a baseline, non-mitigable CH_4 source that contributes to warming, set at a constant 300 Mt CH_4 per year, between the 220-368 Mt estimated by Jackson et al. (2020). CO_2 circulates between the terrestrial and ocean compartments. Temperature perturbation is calculated from the change in radiative forcing from emissions which warm the upper and, in turn, the lower ocean. This temperature increase then

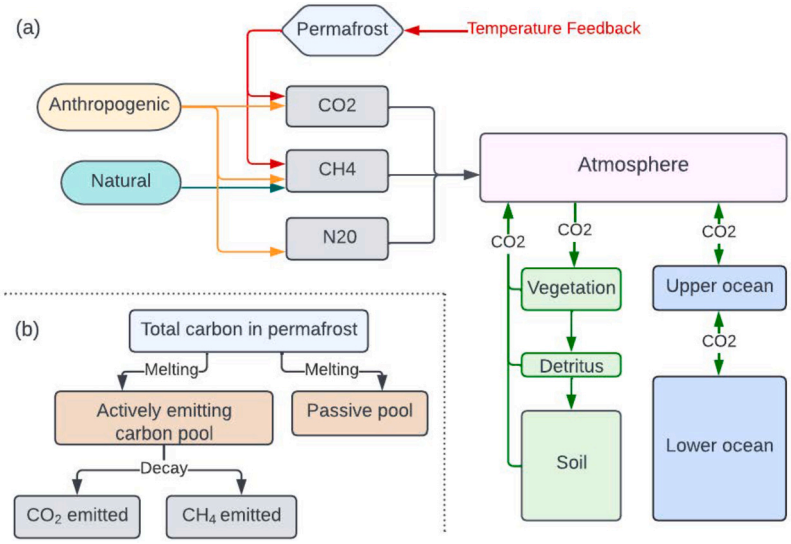


Fig. 1. Simplified Model Dynamics. Model outline: (a) The model includes CO_2, CH_4, and N_2O emissions into the atmosphere. Note, methane emissions are from anthropogenic and biogenic (natural) sources, and from permafrost emissions. CO_2 is from anthropogenic sources and the permafrost. N_2O is only from anthropogenic emissions. Carbon cycles between the atmosphere (as CO_2), terrestrial boxes (the vegetation, detritus, and soil), and the ocean boxes (upper and lower). Increases in temperature amplify permafrost emissions. (b) Permafrost sub-model schematic. Total carbon in the permafrost (C_{PF}, see Equation (31)) melts to expose soil. In the exposed soil, there is an actively emitting labile carbon pool (L_C and L_M, see Equations (34) and (35)), and a passive or non-labile carbon pool. From the actively emitting carbon pool, carbon is released as CO_2 or CH_4 in constant proportion.

feeds back into the permafrost module, causing permafrost melt and subsequent release of methane and CO_2.

2.3. Radiative forcing

Radiative forcing (RF) is calculated for each greenhouse gas using equations provided in the IPCC's Fifth Assessment Report (Myhre et al., 2014). RF from CO_2 has a log-linear temperature response to excess carbon past pre-industrial conditions (C_0). CH_4 and N_2O have interacting RF due to infrared band overlap (Myhre et al., 1998, 2014). Formulas for RF (W m^{-2}) are as follows:

$$\Delta N_{CO_2} = \alpha \times \ln\left(\frac{C}{C_0}\right)$$

where $\alpha = 5.35$ (21)

$$\Delta N_{CH_4} = \alpha \times (\sqrt{M} - \sqrt{M_0}) - (f(M, N_0) - f(M_0, N_0),$$

where $\alpha = 0.036$ (22)

$$\Delta N_{N_2O} = \alpha \times (\sqrt{N} - \sqrt{N_0}) - (f(M_0, N) - f(M_0, N_0), \text{ where } \alpha = 0.12 \quad (23)$$

$$f(M, N) = 0.47 \times \ln[1 + 2.01 \times 10^{-5}(MN)^{0.75} + 5.31 \times 10^{-15} M(MN)^{1.52}] \quad (24)$$

C, M, and N refer to current atmospheric concentrations of CO_2 in ppm, CH_4 in ppb, N_2O in ppb respectively. C_0, M_0 and N_0 refer to concentrations in 1750. The α term is the radiative forcing coefficient with units of $\frac{W}{m^2}$ and varies with each equation as indicated.

We also include differential equations for CH_4 and N_2O concentrations as a function of emissions and a fixed decay rate to reflect their atmospheric perturbation lifetimes as given by the IPCC (Myhre et al., 2014). We assume CO_2 does not decay from the atmosphere in the same way, but cycles into various ocean and terrestrial stores as described by the carbon cycle equations. The changes in CH_4 and N_2O are represented by

$$\frac{dCH_4}{dt} = E_{anthro} + E_{bio} + E_{pf} - \frac{CH_4}{\nu_1} \quad (25)$$

$$\frac{dN_2O}{dt} = E_{anthro} - \frac{N_2O}{\nu_2}, \quad (26)$$

where ν_1 is 12 years and ν_2 is 114 years. These perturbation lifetimes are approximations, as the lifetime for CH_4 is varied and depends on atmospheric conditions. We assume these rates to be constant.

2.4. Temperature response

Our model uses a two-box temperature response model described by Pierrehumbert (2014). This gives an accurate temperature response based on historical atmospheric concentrations of greenhouse gases and for projected emission streams (see 2).

We use T_{mix} to describe the temperature perturbation of the upper, or mixed, layer of the ocean. This model uses the mixed ocean layer temperature perturbation as a proxy for Earth surface temperature perturbation because ocean temperatures largely dictate surface temperature. T_{deep} represents the temperature perturbation of the deep ocean. The model describes the heat transfer between the two layers. We use μ to represent the heat capacity of each layer. The model uses γ for the heat transfer coefficient between the mixed and deep layers, and $\hat{\lambda}$ for the climate sensitivity parameter, both in units of $\frac{W}{m^2 K}$.

Temperature changes are driven by the change in radiative forcing, ΔN. The radiative forcing for each greenhouse gas is calculated and added together as a net ΔN, giving the following:

$$\mu_{mix}\frac{dT'_{mix}}{dt} = -\hat{\lambda}T'_{mix} - \gamma(T'_{mix} - T'_{deep}) + \Delta N(t) \quad (27)$$

$$\mu_{deep}\frac{dT'_{deep}}{dt} = \gamma(T'_{mix} - T'_{deep}) \quad (28)$$

2.5. Permafrost feedback

A permafrost feedback is included in our model, as it is one of the major short term climate feedbacks. Fig. 1 shows how a portion of carbon in the permafrost becomes vulnerable as the permafrost thaws. This now vulnerable pool is subject to decomposition by microbial activity and thus emitted into the atmosphere as CO_2 or CH_4. A portion of the permafrost carbon is considered fixed or "passive", as it is non-labile and will not be released during the timescales of our study. We make the assumption that the extent of the permafrost decreases linearly with

Table 1
Model parameters. Terrestrial and oceanic carbon cycle values are used to calculate carbon flux between the terrestrial stores, oceanic stores, and the atmosphere. Rows without units are unitless values. In our model, we convert all masses (GtC) to moles. Parameters k_1 and k_2 were converted to mole fraction by multiplying by 18/1000. (⋆) We raised the alkalinity parameter by a factor 1.02 to better match pre-industrial CO2 uptake rates. This is still within the reported experimental range for ocean alkalinity. Temperature response parameters come from Pierrehumbert (2014). We also convert γ and $\hat{\lambda}$ from watts to joules per year when running the model.

Model Parameters			
Parameter	Value	Unit	Description
Terrestrial Carbon Parameters (Hartin et al. (2016))			
f_{ds}	0.60		fraction of detritus carbon that transfers to the soil
f_{ld}	0.01		fraction land use carbon that enters detritus
f_{ls}	0.89		fraction land use carbon that enters soil
f_{lv}	0.10		fraction land use carbon that enters vegetation
f_{nd}	0.60		fraction of NPP carbon that enters the detritus
f_{ns}	0.05		fraction of NPP carbon that enters the soil
f_{nv}	0.35		fraction of NPP carbon that enters the vegetation
f_{rd}	0.25		fraction of respiration carbon that enters the detritus
f_{rs}	0.02		fraction of respiration carbon that enters the soil
f_{vd}	0.034		fraction of vegetation carbon that enters the detritus
f_{vs}	0.001		fraction of vegetation carbon that enters the soil
β	0.36		carbon fertilization parameter
Q_{10}	2.45		Q_{10} respiration factor
Oceanic Carbon Parameters (Glotter et al. (2014))			
k_1	8.00×10^{-7}	mol/kg	disassociation constant
k_2	4.63×10^{-10}	mol/kg	disassociation constant
k_a	0.2	yrs $^{-1}$	turnover time for upper ocean
k_d	0.05	yrs $^{-1}$	turnover time for deep ocean
k_H	1.23×10^{3}		Henry's constant
Alk	767.0⋆	GtC	alkalinity of the ocean
δ_d	50		ratio between upper and lower ocean
δ_a	calculated		ratio between upper ocean and atmosphere
AM	1.77×10^{20}	moles	moles of the atmosphere
OM	7.8×10^{22}	moles	moles of the ocean
Temperature Parameters (Pierrehumbert (2014))			
μ_{mix}	3.154×10^{8}	J m^{-2} K^{-1}	heat capacity of mixed layer
μ_{deep}	6.307×10^{9}	J m^{-2} K^{-1}	heat capacity of deep ocean
$\hat{\lambda}$	1.2	W m^{-2} K^{-1}	climate sensitivity parameter
γ	1.2	W m^{-2} K^{-1}	heat transfer coefficient
Permafrost Parameters (Kessler (2017))			
C_{PF}	1035	GtC	total GtC in the permafrost
τ	70	years	e-folding time for decomposition
β	0.172		coefficient for permafrost melt rate
η	0.40		fraction of non-labile carbon
ω	0.023		fraction of carbon released as methane

increase of global mean temperature and that carbon content of the permafrost is spatially homogeneous (Kessler, 2017).

We follow the logic of Kessler's model (Kessler, 2017) but adapted into differential equation form. The total carbon in the permafrost is C_{PF}. L_c and L_m combine to form the actively releasing labile carbon pool, where L_c is the proportion that is destined to be released as CO_2, and L_m is the proportion that is emitted as CH_4. Together, they represent the labile portion of the pool of carbon that is now vulnerable due to a decrease in permafrost extent. L_c and L_m each have their own emission stream $E(t)$. These pools are assumed to be 0 when initializing the model at year 2010. The proportion of carbon that is emitted as CO_2 or CH_4 is determined by the proportion parameter ω.

We describe the intact frozen carbon in the permafrost as the total carbon pool at initial time t_0 times the proportion of the permafrost left (PF_{extent}):

$$C_{frozen} = C_{PF}(t_0) PF_{extent}(t). \tag{29}$$

We describe the extent of permafrost at time t as

$$PF_{extent}(t) = 1 - \beta \times (T(t) - T(t_0)), \tag{30}$$

where the permafrost extent decreases linearly with rise in global mean temperature (T) above an equilibrium temperature ($T(t_0)$) (Kessler, 2017). In our model, we use the temperature at year 2010 as $T(t_0)$, while Kessler uses the temperature at the year 2000 as t_0, so our model gives slightly less melting. Additionally, the model does not allow C_{PF} to increase by permafrost refreezing.

As temperature increases, the extent of the permafrost decreases, and there is newly thawed soil that is now vulnerable to microbial decomposition. We represent this decomposition as exponential decay (Kessler, 2017).

The loss of carbon from the labile pools is represented by the exponential decay term $-\frac{1}{\tau}$. The carbon that has decayed from the permafrost is then added into our emissions stream. This is the same for

the active labile carbon pool being emitted as methane, because it is the remaining proportion (ω), and it shares the same decay rate $-\frac{1}{\tau}$.

The Kessler equations adapted into differential equation form are represented as

$$\frac{dC_{PF}}{dt} = C_{frozen}(t) - C_{PF} = \rho : \quad \rho \leq 0 \tag{31}$$

$$\frac{dL_C}{dt} = -\rho \times (1-\eta) \times (1-\omega) - \frac{1}{\tau} L_C \tag{32}$$

$$\frac{dL_M}{dt} = -\rho \times (1-\eta) \times \omega - \frac{1}{\tau} L_M \tag{33}$$

$$E_{PF\,C}(t) = \frac{1}{\tau} L_C \tag{34}$$

$$E_{PF\,M}(t) = \frac{1}{\tau} L_M \quad . \tag{35}$$

Summary of atmospheric carbon With the permafrost emissions added, we generalize our atmospheric carbon pool as follows:

$$\frac{dC_A}{dt} = E_{anthro} + E_{PF} + E_{LC} + F_T + F_O, \tag{36}$$

where E_{anthro} is fossil fuel emissions, E_{PF} is the emissions from the permafrost, E_{LC} is land use emissions, F_T is the flux of carbon between the terrestrial stores from net primary productivity and respiration ($-NPP + RH_{det,soil}$ see Equations (1), (2) and (3)), and F_O is the flux of carbon into the oceanic sinks ($-k_a C_A + k_a \frac{k_H}{\delta_a \Lambda} C_U$ see Equations (18)).

2.6. Validation and initial conditions

At the outset, we obtain pre-industrial initial conditions by imposing atmospheric CO_2 concentration at 1750 levels and running the model for a few thousand years to allow the levels of carbon in the ocean and terrestrial stores to stabilize. We then use these stabilized values as our initial conditions at 1750 for the vegetation, detritus, soil, upper ocean and lower ocean boxes.

We validated our model's temperature response and carbon cycle modules using historical data (Stocker et al., 2013). Our initial conditions for 1750 are given in Table 2. We drove the model from 1750 to 2010 using historical emissions data from the AR5 report (Stocker et al., 2013), allowing our model to calculate atmospheric CO_2 concentrations based on its carbon cycle modules (Fig. 2 (b)). The model also calculated temperature from the radiative forcing from atmospheric CO_2 concentrations (Fig. 2 (a)), which shows a reasonably similar temperature result for 2010 (Morice et al., 2021).

To obtain initial conditions for the year 2010, we drove the rest of model using imposed historical CO_2, CH_4, and N_2O atmospheric concentrations (Stocker et al., 2013) After so running the model to 2010, we took the carbon content of our upper ocean, lower ocean, vegetation, detritus, and soil boxes, along with the temperatures, as the initial conditions for projecting the model forwards.

2.7. Future emission scenarios

To determine the impact of methane mitigation strategies on permafrost climate feedbacks, we projected our model forward using the AR5's extended RCP 2.6, 4.5, and 6.0 CO_2 and N_2O emission streams (Meinshausen et al., 2011). We combine these RCP CO_2 and N_2O emission streams with our own calculated CH_4 emission stream based on different annual reduction plans. All our CH_4 emission streams start at 2010 with 330 Mt of CH_4 emitted that year and extend to 2300. To examine the impact of just the rate of phase-out, not magnitude, we take our initial value of 330 Mt and reduce it by a given percentage annually until it reaches the same "floor" level of the given RCP. For example, RCP 2.6's projected methane emission stream falls from 330 Mt/year to 142 Mt/year by 2100, where it then remains until 2300. Therefore, we take 330 Mt, and reduce it by a given percentage annually until it reaches 142 Mt and then hold that level constant. We can then compare varying accelerated rates of phase-out to the given "baseline" RCP scenario. For reference, the floor values for RCPs 4.5 and 6.0 are 266 Mt/year and 252 Mt/year, respectively.

To compare magnitude of phase-out, we take our projected methane emission streams to a lower final value than the RCP.

3. Results

We began by generating temperature time series for all scenarios. First, to see the effect of the permafrost module, we ran our "baseline" unaltered RCP emission scenarios from 2010 to 2300, and then ran the same scenarios again with the permafrost module in effect. We saw a significant change in temperatures with the permafrost module in effect, which can be seen in Fig. 3. Each RCP scenario has two main temperature projections, with the higher branch showing the permafrost feedback module in effect.

We also compared each RCP scenario with a rapid 10% annual methane emission reduction plan, shown by the dashed lines in Fig. 3. Once the 10% reduction plan reached the target methane emission rate of the given RCP, emissions were then held constant. For example, we compared the baseline RCP 2.6 with our RCP 2.6 with the 10% annual methane phase-out; both reached the same final target of 142 Mt CH_4 emitted annually (but at different times), and remained at this level through 2300. This comparison was made with and without the permafrost feedback. A 10% phase-out is considered very accelerated, and the target emission rate was reached within less than 5 years.

We compared our accelerated methane mitigation plans to the RCP's standard methane projections. For each RCP scenario, we used the IPCC's CO_2 emission projections, shown in gigatonnes of carbon in Fig. 4 (a), (c), and (e). We included each RCP's given N_2O emission projections to accurately calculate methane's radiative forcing by taking into account the band overlap explained in Section 2.3. We then compared the results of our methane mitigation plans with the baseline RCP scenarios. For RCP 2.6, we only considered 5% and 10% methane reduction rates, as a 1% annual reduction was actually slower than the baseline RCP 2.6. For RCP 4.5 and 6.0, we used a 1% and 10% annual reduction rate, seen in Fig. 4 (b), (d), and (f). Fig. 4 shows these different emissions pathways.

3.1. RCP 2.6

We ran the model under the RCP 2.6 scenario with and without the permafrost module to the year 2300 (see Fig. 5 (a)). Without permafrost, the final temperature perturbation in 2300 reaches 1.38 °C above pre-industrial levels. With the permafrost feedback, temperature reached 1.61 °C, a difference of 0.23 °C. Additionally, the model gives 97.7 GtC emitted from the permafrost by 2300.

Using the RCP 2.6 scenario, we examined two highly accelerated methane reduction scenarios, where we reduced anthropogenic methane from 330 Mt in 2010 by 5% or 10% annually until we reached a constant emission rate of 142 Mt of CH_4 per year. The baseline RCP 2.6 scenario reaches a minimum or "target" level of 142 MtCH_4 per year at 2100, and remains at this level through 2300. Therefore, these accelerated mitigation scenarios only differed from RCP 2.6 in how long it took to reach that target.

We found that the rate of methane mitigation had a negligible effect on temperature at 2300, but had a noticeable effect before 2100. The largest difference in temperature occurs at 2050, where there is a 0.06 °C difference between the standard RCP 2.6 scenario compared to the 10% phase-out (see SI 4).

At the year 2300, cumulative 97.7 GtC was emitted from the permafrost under the baseline RCP 2.6, while 95.3 GtC was emitted under a 5% accelerated methane reduction plan, and 94.4 GtC was emitted with a 10% methane reduction plan. This may be because under RCP 2.6's aggressive CO_2 mitigation scenario, CH_4 emission mitigation has a

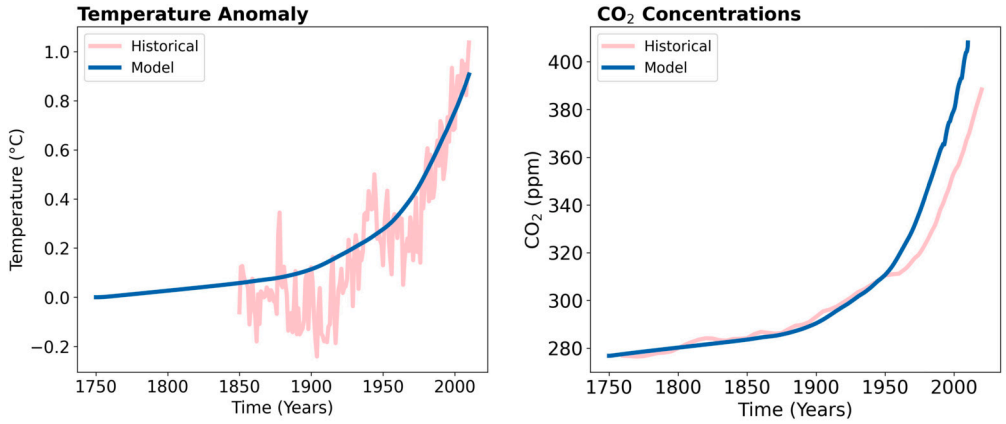


Fig. 2. Validation of the model against historical temperatures and atmospheric CO_2 concentrations. (a) Historical temperature anomaly data is given in pink. The blue line gives the temperature anomaly as predicted by our model, driven by emissions data while solving for atmospheric carbon. (b) shows atmospheric carbon concentrations from historical data in pink, versus our solved carbon concentrations in blue. The overshoot in modeled CO_2 concentration past 1950 may be due to an unaccounted for increase in biotic carbon uptake.

Table 2
Initial conditions for the year 2010, either found by driving the model with historical atmospheric concentration data or from other works (reference given in this case). These are the initial conditions used for our projections.

Initial Conditions					
Variable	Unit	Year		Description	Notes
		1750	2010		
T_{mix}	$C°$	0	0.81	surface temperature	
T_{deep}	$C°$	0	0.22	lower ocean temperature	
C_A	GtC	587.92	824.91	carbon in atmosphere	Glotter et al. (2014)
C_U	GtC	725.39	740.35	carbon in upper ocean	
C_L	GtC	36263.18	36310.28	carbon in lower ocean	
C_v	GtC	500	536.95	carbon in vegetation	Hartin et al. (2016)
C_D	GtC	55.29	59.73	carbon in detritus	
C_S	GtC	1808.82	1767.11	carbon in soil	
CH_4	ppb	N/A	1798.0	methane concentration	EEA (2019)
N_2O	ppb	N/A	323.7	nitrous oxide concentration	
C_{pf}	GtC	N/A	1035	carbon (frozen) in permafrost	Kessler (2017)
L_C	GtC	N/A	0	labile carbon	
L_M	GtC	N/A	0	labile methane (as carbon)	

Table 3
Temperature perturbation at year 2100 and 2300, with and without the permafrost feedback effect under different RCP scenarios. Note that these results do not include accelerated methane phase-outs.

Temperature Anomaly from Permafrost			
Year	RCP 2.6	RCP 4.5	RCP 6
2100, without PF (°C)	1.73	2.60	3.15
2100, with PF (°C)	1.86	2.77	3.31
Difference (°C)	0.13	0.17	0.16
% Difference	7.5%	6.5%	5.1%
2300, without PF (°C)	1.38	3.44	4.66
2300, with PF (°C)	1.61	3.9	5.13
Difference (°C)	0.23	0.46	0.47
% Difference	16.7%	13.4%	10.1%

relatively strong effect: We find that rapid methane mitigation has less effect on permafrost carbon release under other RCP scenarios.

Atmospheric concentrations of CO_2 are largely the same for all scenarios, and atmospheric concentrations for CH_4 reflect our differing reduction strategies, as well as slightly different permafrost emissions courses (see Fig. 5 (c) and (d).

3.2. RCP 4.5

We evaluated the impact of rate of mitigation under the RCP 4.5 emission scenario using the same basic procedures. First, we looked at temperature perturbation of the baseline RCP 4.5 scenario with and without a permafrost feedback effect. At 2300, the baseline RCP 4.5 resulted in a temperature anomaly 2300 of 3.44 °C, and with the permafrost module, 3.9 °C (see Table 3). 277.8 GtC was emitted from the permafrost by year 2300.

The target value of CH_4 emissions per year was set to 266 $MtCH_4$ per year, consistent with the value the RCP 4.5 reaches at 2100 and remains constant at through 2300. We performed a 1% or 10% methane mitigation plan to reduce emissions from 330 to 266 Mt CH_4 per year. In Fig. 6 (d), the atmospheric concentrations of CH_4 are shown for the different scenarios. The mitigation plans reduced atmospheric methane concentrations compared to the baseline RCP before year 2100. After the year 2100, atmospheric concentrations remained the same between all scenarios, as expected since our reduction plans meet the same target value as the RCP 4.5.

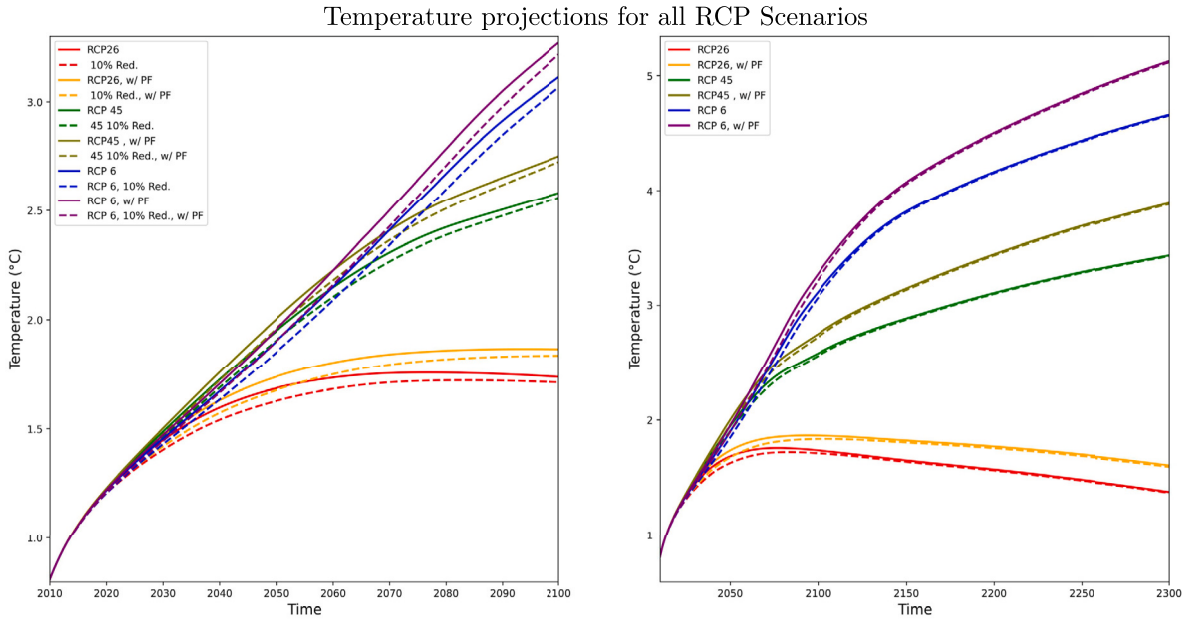


Fig. 3. Temperature responses for RCP 2.6, 4.5, and 6 emission scenarios, with and without a permafrost feedback effect, (a) from 2010-2100 and (b) from 2010-2300. Dashed lines show a 10% annual methane phase-out for the given scenario while solid lines show the baseline RCP scenario. Greatest differences in temperature between baseline RCP and 10% annual phase-out are seen before 2100. From 2100-2300, the projections with and without the rapid 10% methane reduction plans are largely the same, with or without the permafrost feedback in effect.

The 1% and 10% phase-out schemes yield effectively the same final temperature perturbation, although there was a transient temperature difference before year 2100 (see Fig. 3). The temperature projections converged and were virtually identical by the year 2300 (see Table 6).

3.3. RCP 6

We evaluated methane mitigation plans compared with baseline RCP 6 projections (Figure 9) and found results qualitatively similar with those of RCP 4.5. Temperature perturbation at the year 2300 without the permafrost module was 4.66 °C, and 5.13 °C with the permafrost module (see Table 3). 392.9 GtC was emitted from the permafrost by the year 2300. The target methane emission rate for RCP 6 was 252 $MtCH_4$ yearly. Our methane mitigation scenarios went from 330 $MtCH_4$ emitted in year 2010, reduced by 1% or 10% annually until reaching 252 $MtCH_4$ and were then held constant for future years.

Significantly lower atmospheric concentrations of methane from 2010-2100 under the mitigation strategies did not effect temperature projections or significantly impact permafrost emissions (see Supplemental Information for figure). Permafrost emissions were only marginally lower (by 1.7 GtC) in the year 2100 from the 10% mitigation scenario compared to the baseline RCP 6.

3.4. Final magnitude versus rate of mitigation

We compared the effect of the final magnitude and rate of methane mitigation on final temperature perturbation at the year 2300 while including the permafrost feedback module. We used the RCP 4.5 scenario for this comparison. We ran the model with methane reduction rates between 0.1% and 10% to targets between 125 Mt CH_4 and 275 Mt CH_4 per year to obtain a temperature perturbation at the year 2300.

Importantly, reduction rates below 0.5% never reached the low end target of 125 Mt CH_4 emissions per year at 2300. If emissions were reduced by less than 0.5% annually, there was not enough time from 2010 to 2300 to reduce emissions from 330 Mt CH_4 per year to 125 Mt CH_4 per year. For example, with a reduction rate of 0.1%, there was still 246 Mt CH_4 being emitted at the year 2300, and with 0.25% reduction rate, there was 160 Mt CH_4 emitted at 2300. This accounts for the difference in temperature perturbation at the year 2300 between the rates of 0.1 and 0.25% (see the slight bend on the left-hand side in Fig. 7) and the higher rates which converge to 3.7 °C. We found temperature perturbation responded highly linearly to the magnitude of mitigation, and not rate of reduction.

4. Discussion

4.1. Findings

4.1.1. Overall

We used a simplified climate model to assess the long-term impact of methane emission mitigation rates in the context of permafrost feedback. While the urgency of mitigating CO_2 emissions is well-established due to the long atmospheric residence time of CO_2, methane mitigation priorities remain less clear (Pierrehumbert, 2014; Global, 2022; Dreyfus et al., 2022; Nisbet et al., 2020). Although methane has a short atmospheric residence time, its potency suggests a potential need for accelerated phase-out (Myhre et al., 2014). Our model indicates that, despite a strong permafrost feedback, the rate of methane mitigation may be relatively unimportant for long-term temperature perturbation. However, further investigation is necessary to account for unmodeled methane-climate feedbacks and dynamics.

4.1.2. Permafrost feedback impact

We observed a notable difference in global mean temperature anomaly attributable to the permafrost feedback before considering methane mitigation. At year 2100, we observed a difference of 0.13-0.15 °C (4.7-7.5%) between all RCP scenarios, and at 2300, a difference of 0.23-0.47 °C (10.1-16.7%) (see Table 3). The permafrost feedback is significant and should be included in future climate modeling.

4.1.3. Accelerated methane mitigation scenarios vs. IPCC baseline

Contrasting our methane mitigation scenarios with the baseline RCP scenarios, we found that our accelerated mitigation scenarios did not substantially impact long-term permafrost thaw or temperature perturbation. Rather, we found that long term temperature perturbation was largely determined by the (final) magnitude of methane mitigation. Our

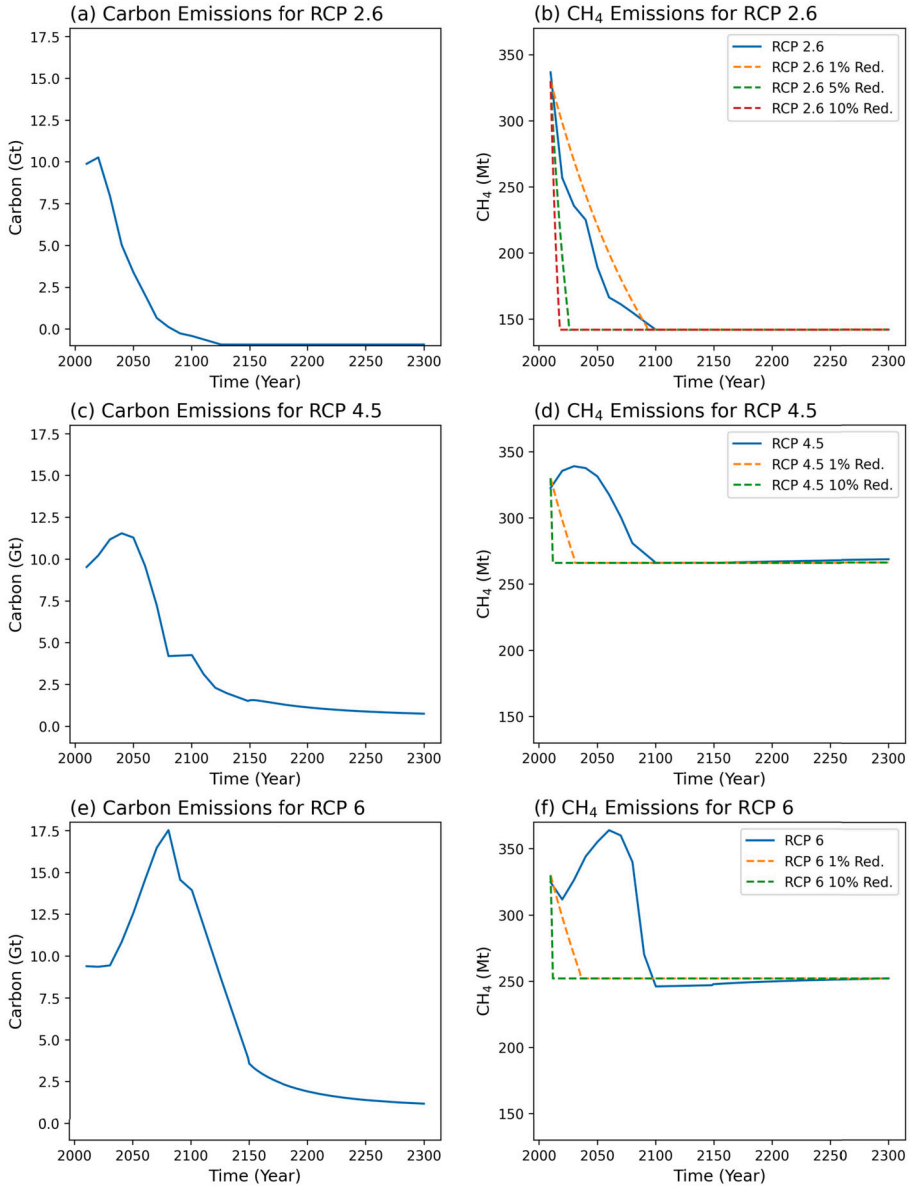


Fig. 4. Emissions streams for all RCP scenarios and RCP scenarios with accelerated methane phase-out. Solid lines represent baseline RCP scenarios, while dashed lines represent our imposed methane mitigation scenarios. Figures show total imposed emissions per year, not including permafrost feedback emissions. In Figures (a), (c), and (e), carbon emissions in gigatonnes are shown, as given by the RCP projection. In Figures (b), (d), and (f), CH_4 emissions in megatonnes are shown for the baseline RCP and our reduction scenarios.

findings showed that mitigation must be sufficiently swift to achieve lower target levels by year 2300, but beyond that, the impact of rate was negligible. Our most rapid methane mitigation scenario, reaching target levels within 10 years with a 10% annual reduction, showed a slight difference in temperature this century (see Fig. 3). This, however, was transient, and CO_2 ultimately determined the long-term temperature course.

4.2. Model limitations

4.2.1. Other emissions

We aimed to capture the essential dynamics between anthropogenic emissions and permafrost thaw and decomposition, not conclusively predict future temperature anomalies. Therefore, we included radiative forcing only from CO_2, CH_4, and N_2O, with which were able to adequately recreate surface temperature up to the year 2010, and from which we start our future projections. Black carbon, aerosols, halocarbons, ozone and other compounds could be included although they are not expected to make significant changes in the qualitative results, as historically, the cooling from aerosols has masked the warming from these other compounds (Dreyfus et al., 2022). Also, as CO_2 is mitigated, co-emitted aerosols will decline (Dreyfus et al., 2022). However, with less cooling to mask other greenhouse gases, methane could end up being relatively more important.

We also do not explicitly include fossil methane which oxidizes to new atmospheric CO_2, although upon testing inclusion at a constant 25% rate, we found negligible difference in our results (0.02 °C difference at 2300 under RCP 4.5, see Supplemental Information 6).

4.2.2. Permafrost uncertainty

There are major uncertainties still in permafrost modeling, primarily concerning microbial decomposition and spatial heterogeneity (Schneider Von Deimling et al., 2012). Our use of global mean temperature perturbation does not reflect regional temperature differences or spatial heterogeneity in carbon stores. Additionally, there is uncertainty to the rate of microbial decay of permafrost carbon, or “e-folding” time.

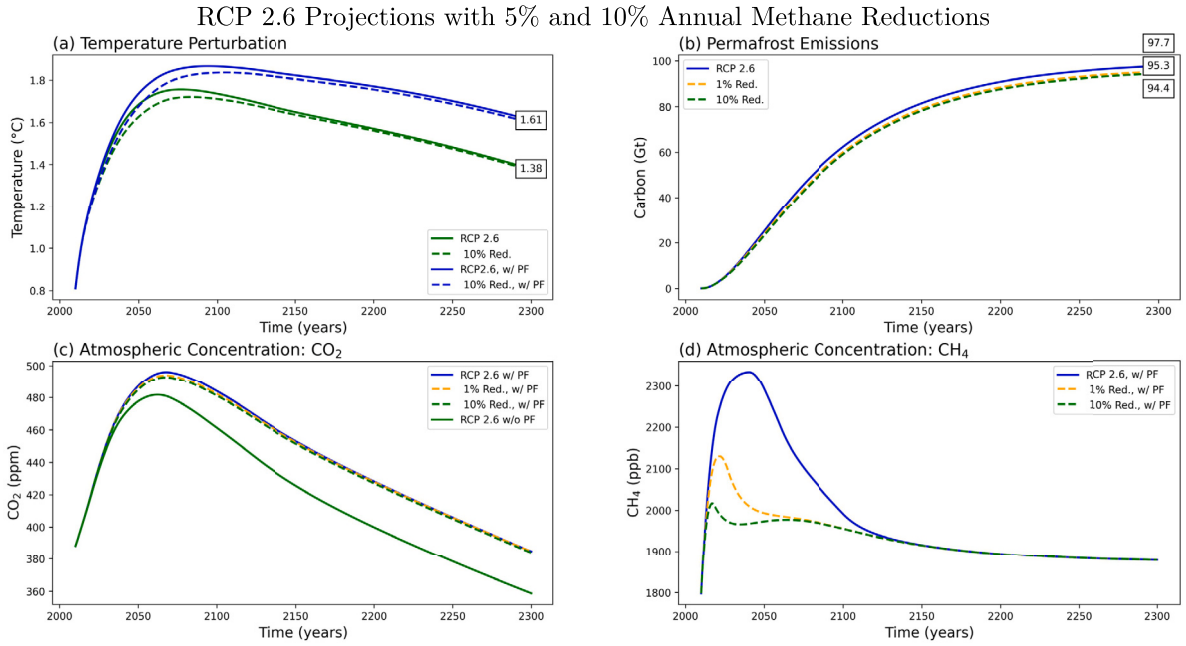


Fig. 5. Results for 5% and %10 methane phase-out strategies using the RCP 2.6 CO_2 scenario. Dotted lines represent our imposed methane mitigation scenarios, while solid lines represent the "baseline" RCP 2.6 scenario. We look at temperature perturbation at the year 2300 in (a), permafrost emissions at the year 2300 in (b), and atmospheric concentrations of CO_2 and CH_4 in (b) and (c).

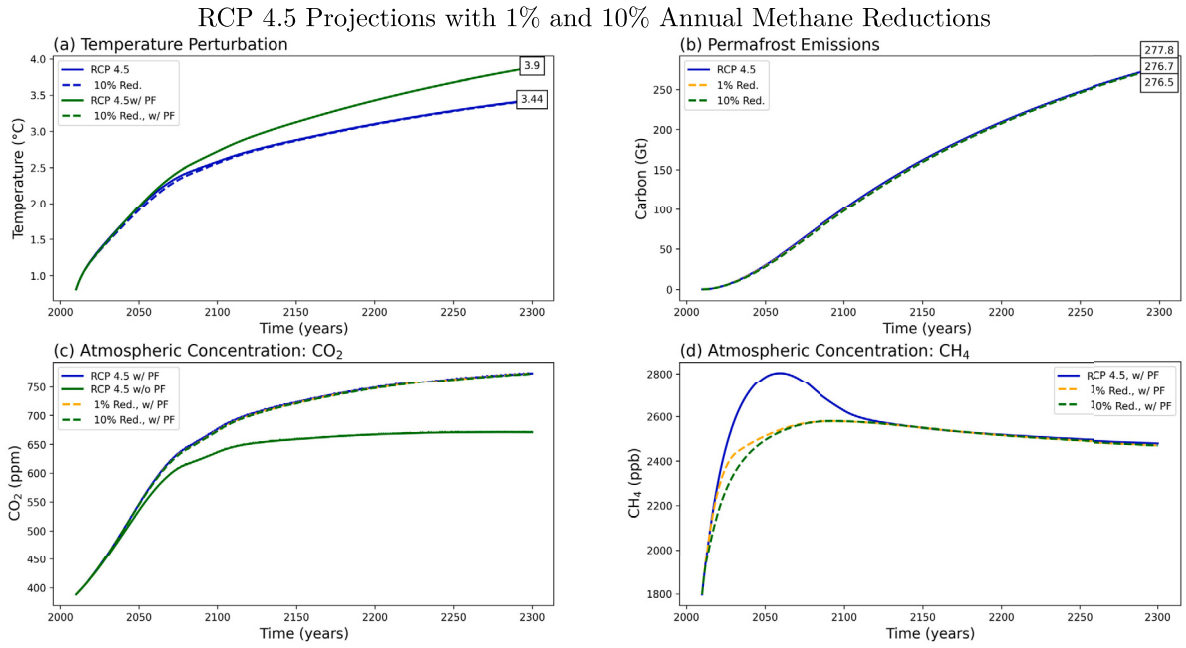


Fig. 6. RCP 4.5 results for 1% and %10 reduction rates to annual methane emissions. (a) shows the final temperature perturbations with and without the permafrost feedback module in effect, with the dashed line showing the 10% reduction scenario. (b) shows the permafrost emissions in gigatonnes of carbon for the baseline RCP scenario compared to the 1% and 10% reduction plans. (c) and (d) show atmospheric concentrations of CO_2 and CH_4 respectively over time.

We use 70 yr^{-1}, but it could be between 0-200 yr^{-1} and may be variable (Kessler, 2017). We found our results insensitive to the decay rate (see: Supplemental Information 5).

4.2.3. Impact of variable nitrogen oxide (NOx) emissions

The quantity of nitrogen oxides (NOx) in the atmosphere affects the rate of methane breakdown and therefore impacts atmospheric methane concentrations. Atmospheric NOx increases the oxidizing capacity of the atmosphere via increased hydroxyl radicals (OH), and hence decreases methane lifetime. Thus, decreases in anthropogenic NOx emission rates can lead to higher methane concentrations, as seemed to have happened during 2020 COVID-19 lockdowns (Stevenson et al., 2022). Both NOx and methane emissions decreased during COVID-19 lockdowns and yet, despite lower anthropogenic methane emissions, the atmospheric methane growth rate spiked sharply. Decreased OH as a result of lower NOx emissions and increased natural wetlands methane emissions were likely of roughly equal importance in explaining this spike (Peng et al., 2022). Indeed, methane growth rates saw the largest increase since NOAA began record keeping in 1984 (Stevenson et al., 2022).

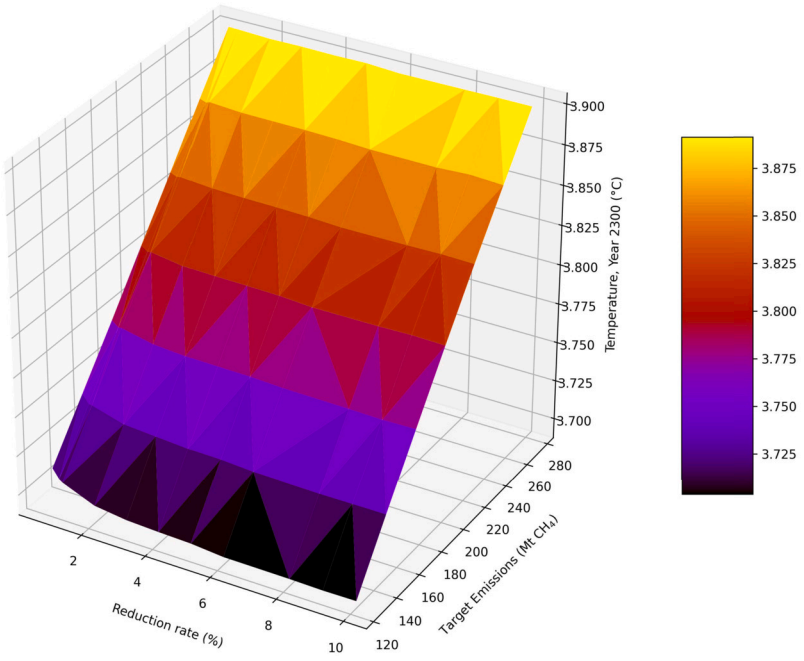


Fig. 7. The effect of reduction rate and target emission level on temperature perturbation at year 2300. Reduction rates vary between 0.5% and 10% and target emission levels vary between 125 and 275 Mt CH_4. Time span is from 2010 to 2300, and the RCP 4.5 CO_2 emission scenario is used.

Our model, focused on the response of methane concentrations to direct emissions alone, would not have captured this abrupt rise. Methane concentrations depend not only on the methane emissions pathway, but also on NOx and other greenhouse gas emissions pathways, the rate of other methane-climate feedbacks such as the wetlands, and temporal trends (Cheng and Redfern, 2022; Peng et al., 2022; Stevenson et al., 2022). Importantly, we assume methane concentrations to be stabilized when our rates of anthropogenic methane emissions have stabilized to a target value. However, further research must be done to understand how different anthropogenic CH4 and NOx emissions pathways can influence the rates of natural CH4 sources and sinks. Therefore, there is need for refinement in our underlying assumption about the relationship of anthropogenic methane emissions and overall methane concentrations to fully answer our guiding question.

4.2.4. Methane-climate variability

There are other methane-climate feedbacks which we have left unmodeled that are potentially of importance. These feedbacks operate on varying timescales and may depend on the rate of change of global mean temperature, rather than absolute changes in temperature (Cheng and Redfern, 2022). Variable rates in temperature increase and even precipitation may impact the intensity and rapidity of methane-climate feedbacks, particularly the wetland-climate feedback (Peng et al., 2022). This wetland feedback is particularly important, as demonstrated by the sharp spike in atmospheric methane growth in 2020 (Stevenson et al., 2022).

However, other methane-climate feedbacks may be sensitive to the rate of change of temperature. A faster rate of change in global mean temperature (and even rate of change in precipitation over time) may intensify the wetland-climate feedback. While our permafrost model is indirectly affected by the rate of temperature change (i.e., a faster increase causes more warming early in time), there is no direct interaction with the rate. Permafrost thaw is expected to respond to the overall change in the temperature gradient; however, there may be other factors involved in process that could have some dependence on the rate of temperature change, such as heterotrophic respiration (Brown and Markewitz, 2018; Nissan et al., 2023). It is important to emphasize that the addition of other methane-climate feedbacks that are more explicitly rate-dependent may qualitatively affect our results and conclusions.

4.2.5. Methane-concentration variability

As discussed above, atmospheric methane concentrations depend on more than the stabilized rates of methane emissions. We used simplified anthropogenic emission scenarios in our study to simulate the effect of different timelines on stabilized lower CH4 emission rates. As seen in 2020-2021, natural CH_4 and anthropogenic NOx emissions were unprecedentedly high and low respectively, resulting overall in a surge in the atmospheric methane growth rate (Feng et al., 2023). Variability in atmospheric methane concentration not explained by anthropogenic emissions could suggest a higher priority for anthropogenic methane mitigation, although it is unclear if this would affect our basic conclusions regarding the importance of the rate of methane mitigation.

These other important methane-climate dynamics should be included in future studies (Fig. 8) to fully answer our motivating question.

4.2.6. Hysteresis and path dependence

We also note that our study does not address the importance of early mitigation under all mechanisms for possible path dependence and hysteresis in the Earth System, beyond the hysteresis in the permafrost model considered. Numerical experiments on Earth system models of intermediate complexity suggest significant temperature change irreversibility when a large cumulative CO_2 course is followed by large-scale negative emissions (Jeltsch-Thömmes et al., 2020). In such scenarios, temperature overshoot could permanently destabilize permafrost with long lasting consequences (De Vrese and Brovkin, 2021). The AR5 emissions scenarios we have considered do not include large-scale negative carbon emissions (RCP 2.6 does posit smaller-scale negative emissions later in time); therefore, in this study, we are primarily concerned with the forward path and the effect of mitigation rates on the ultimate temperature perturbation under the forward path. Whether mitigation rates are of greater importance when a backward path of negative emissions is taken therefore remains an open question. In particular, the SSP1-1.9 scenario in the newer Sixth Assessment Report (Intergovernmental Panel on Climate Change, 2023) does include appreciable negative emissions after 2050, and both Earth system hysteresis and methane mitigation rates could be of more importance in this setting.

We may also draw an analogy between potential hysteresis in the Earth system with respect to *cumulative* CO_2 emissions, and potential hysteresis with respect to the *rate* of methane emissions. That is, it is

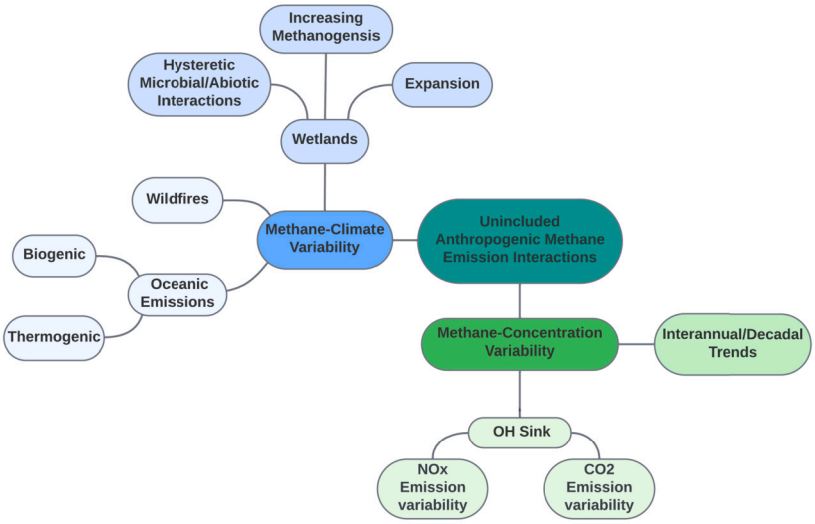


Fig. 8. Additional Important Methane-Climate Processes. Unmodeled factors, such as variable nitrogen oxide (NOx) emissions, contribute to atmospheric methane concentrations, influencing breakdown rates and oxidizing capacity of the atmosphere. Recent anomalies, like the surge in 2020 methane growth rates, demonstrate the need to consider NOx and other greenhouse gas emissions pathways, as well as additional methane-climate feedbacks like those associated with wetlands (Qu et al., 2022; Peng et al., 2022; Feng et al., 2023). Variability in methane-climate feedbacks, influenced by changing global mean temperatures and precipitation rates, can significantly impact outcomes (Zhang et al., 2023; Chang et al., 2021; Schaefer, 2019). The rising relevance of other methane sources, such as wildfires, in the 21st century, adds complexity (Qu et al., 2022). Understanding these dynamics is crucial for refining our assumptions about anthropogenic methane emissions and addressing the complexities of emission mitigation priorities.

generally agreed that the long-term cumulative emission of the former, and emissions rate of the latter, determine the climate impact, yet overshoot of either may affect be of importance. This work suggests that relatively modest increases in anthropogenic methane emissions followed by a decline (e.g., as in RCP 6) do not result in any hysteresis effect via the permafrost. This is but one of multiple relevant processes, and other methane-climate feedbacks have been shown to be pathway-dependent (Chang et al., 2021; Cheng and Redfern, 2022). Other climate feedbacks, such as Atlantic meridional overturning circulation (AMOC) shutdown may also be irreversible (Jackson et al., 2020), and some authors have expressed concern over cascading feedbacks (Lenton et al., 2019). Further study is required to understand whether the hysteresis in methane emissions *rates* (and not just cumulative CO_2 emissions) implies a greater need for more rapid methane phaseout.

4.3. Model comparisons

4.3.1. Permafrost feedback

Our model suggests warming over the next century attributable to permafrost within the range of other works. Macdougall et al. used a modified version of the Earth System Climate Model (ESCM) and found temperature difference attributable to permafrost thaw at 2100 to be 0.1-0.8 °C, estimated at 0.27 °C (consistent across different emission scenarios) (MacDougall et al., 2012). Crichton et al. added a permafrost-carbon module to the Earth System Model of Intermediate Complexity (EMIC), CLIMBER-2, and found increases of 10-40% of the maximum temperature change (Crichton et al., 2016). Burke et al. used the land surface model JULES (Joint UK Land Environment Simulator), along with ORCHIDEE-MICT (Organizing Carbon and Hydrology in Dynamic Ecosystems), modified to include permafrost carbon, coupled to the Integrated Model Of Global Effects of climatic aNomalies (IMOGEN), an intermediate-complexity climate and ocean carbon model. They found a difference of 0.2-12% of the maximum temperature change (Burke et al., 2017). Woodard et al. used a permafrost implementation in Hector v.2.3pf and predicted approximately 0.2 °C or 4–15% of additional warming by 2100 across all RCP scenarios (Woodard et al., 2021).

In comparison, we found between 0.13 and 0.17 °C (5.1-7.5%) temperature perturbation attributable to the permafrost at 2100. This is on the low end but within the previously found range. We found a difference at 2300 (assumed maximum temperature change) of 0.23-0.47 °C (10.1-16.7%) which is on the low range of Crichton et al. (2016) but on the high range of Burke et al. (2017).

4.3.2. Recent insights and methane priorities

Methane mitigation priorities are becoming clearer with recent research. By rapidly reducing anthropogenic methane to the greatest "economically feasible" extent, Ocko et al. saw a substantial near-term climate benefit at 2050 under RCP 8.5 (Ocko et al., 2021) and argue that because of this, rapid phaseout should be prioritized to minimize risk of overshooting climate boundaries and slow the rate of warming this century. However, by 2100 they found magnitude of mitigation was the most important factor. Although we focused on longer time scales and less extreme RCPs, we came to the same conclusions: fast mitigation does bend the temperature curve in the short term, with the largest benefit at 2050. However, by 2100, the fast mitigation and delayed mitigation pathways meet up to reach nearly the same temperature anomaly, and our inclusion of a large feedback does not change this result.

Research about methane mitigation priorities in relation to positive climate feedbacks are understudied. We find that the inclusion of the permafrost feedback alone does not indicate prioritizing rapid methane phaseout, however other feedbacks should be included in the future. Various studies indicate that CO_2 is the first priority, and that attention should not be given to CH_4 mitigation at the expense of CO_2 mitigation (McKeough, 2022; Pierrehumbert, 2014). Our research tentatively agrees with this body of literature, but we recognize the need for further study of this topic, especially in the context of other methane-climate feedbacks and methane-concentration pathway variability.

5. Conclusions

A benefit to an accelerated methane mitigation plan is that methane and CO_2 mitigation are coupled. As much of anthropogenic methane emissions are from fossil fuels (108-135 $MtCH_4$ per year), CO_2 mitigation will also mean mitigating methane (Jackson et al., 2020; Rogelj et al., 2014). As other studies have concluded, mitigating CO_2 immediately is of the utmost importance because of its long lasting climate

effects, and methane mitigation is not a substitute (Pierrehumbert, 2014; McKeough, 2022; Rogelj et al., 2014). Our simplified model using AR5 emissions scenarios found that the extent of permafrost thaw was largely dependent on CO_2 emissions and magnitude (not rate) of methane mitigation. Bringing methane emission levels down to the lowest levels possible will play an important role in avoiding the climate boundary when done *in addition* to mitigating CO_2.

Our simplified model indicates marginal long-term benefit from rapid methane phase-out in relation to permafrost thaw. However, there is still a considerable short-term benefit which may have effects on other sensitive feedbacks. Positive feedbacks, such as Amazon rainforest dieback, boreal forest loss, ice sheet melt, reduction in sea ice, increased wetland methanogenesis etc., may amplify each other and have considerable effect on outcomes (Lenton et al., 2019; Ritchie et al., 2021). Inclusion of these feedbacks would improve our understanding of methane mitigation priorities. Additionally, more work must be done to understand the relationship between the rate of methane emissions and methane concentrations, as well as emissions of other anthropogenic aerosols and gases. Future work should consider the rate of methane phaseout in light of other methane-climate dynamics, variability in the relationship between methane concentration and emissions, and possible hysteresis in the Earth System with respect to methane emissions rates.

CRediT authorship contribution statement

Hannah Bäck: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Software, Validation, Visualization, Writing – original draft, Writing – review & editing. **Riley May:** Conceptualization, Data curation, Formal analysis, Methodology, Software, Validation, Visualization, Writing – original draft, Writing – review & editing. **Divya Sree Naidu:** Conceptualization, Data curation, Investigation. **Steffen Eikenberry:** Conceptualization, Funding acquisition, Project administration, Supervision, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

All data used is referenced and publicly available. No new primary data created.

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Appendix A. Supplementary material

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.gecadv.2024.100005.

References

IPCC, 2023. Climate Change 2021 – The Physical Science Basis: Working Group I Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change, 1st edition. Cambridge University Press.

Bowerman, N.H.A., Frame, D.J., Huntingford, C., Lowe, J.A., Smith, S.M., Allen, M.R., 2013. The role of short-lived climate pollutants in meeting temperature goals. Nat. Clim. Change 3 (12), 1021–1024. https://doi.org/10.1038/nclimate2034.

Brown, R., Markewitz, D., 2018. Soil heterotrophic respiration: measuring and modeling seasonal variation and silvicultural impacts. For. Ecol. Manag. 430, 594–608. https://doi.org/10.1016/j.foreco.2018.08.018.

Burke, E.J., Ekici, A., Huang, Y., Chadburn, S.E., Huntingford, C., Ciais, P., Friedlingstein, P., Peng, S., Krinner, G., 2017. Quantifying uncertainties of permafrost carbon–climate feedbacks. Biogeosciences 14 (12), 3051–3066. https://doi.org/10.5194/bg-14-3051-2017.

Chang, K.-Y., Riley, W.J., Knox, S.H., Jackson, R.B., McNicol, G., Poulter, B., Aurela, M., Baldocchi, D., Bansal, S., Bohrer, G., Campbell, D.I., Cescatti, A., Chu, H., Delwiche, K.B., Desai, A.R., Euskirchen, E., Friborg, T., Goeckede, M., Helbig, M., Hemes, K.S., Hirano, T., Iwata, H., Kang, M., Keenan, T., Krauss, K.W., Lohila, A., Mammarella, I., Mitra, B., Miyata, A., Nilsson, M.B., Noormets, A., Oechel, W.C., Papale, D., Peichl, M., Reba, M.L., Rinne, J., Runkle, B.R.K., Ryu, Y., Sachs, T., Schäfer, K.V.R., Schmid, H.P., Shurpali, N., Sonnentag, O., Tang, A.C.I., Torn, M.S., Trotta, C., Tuittila, E.-S., Ueyama, M., Vargas, R., Vesala, T., Windham-Myers, L., Zhang, Z., Zona, D., 2021. Substantial hysteresis in emergent temperature sensitivity of global wetland CH4 emissions. Nat. Commun. 12 (1), 2266. https://doi.org/10.1038/s41467-021-22452-1.

Cheng, C.-H., Redfern, S.A.T., 2022. Impact of interannual and multidecadal trends on methane-climate feedbacks and sensitivity. Nat. Commun. 13 (1), 3592. https://doi.org/10.1038/s41467-022-31345-w.

Christensen, T.R., Arora, V.K., Gauss, M., Höglund-Isaksson, L., Parmentier, F.-J.W., 2019. Tracing the climate signal: mitigation of anthropogenic methane emissions can outweigh a large Arctic natural emission increase. Sci. Rep. 9 (1), 1146. https://doi.org/10.1038/s41598-018-37719-9.

Crichton, K.A., Bouttes, N., Roche, D.M., Chappellaz, J., Krinner, G., 2016. Permafrost carbon as a missing link to explain CO2 changes during the last deglaciation. Nat. Geosci. 9 (9), 683–686. https://doi.org/10.1038/ngeo2793.

De Vrese, P., Brovkin, V., 2021. Timescales of the permafrost carbon cycle and legacy effects of temperature overshoot scenarios. Nat. Commun. 12 (1), 2688. https://doi.org/10.1038/s41467-021-23010-5.

Dreyfus, G.B., Xu, Y., Shindell, D.T., Zaelke, D., Ramanathan, V., 2022. Mitigating climate disruption in time: a self-consistent approach for avoiding both near-term and long-term global warming. Proc. Natl. Acad. Sci. 119 (22), e2123536119. https://doi.org/10.1073/pnas.2123536119.

European Environment Agency, 2019. Trends in atmospheric concentrations of CO2 (ppm), CH4 (ppb) and N2O (ppb), between 1800 and 2017. European Environment Agency.

Feng, L., Palmer, P.I., Parker, R.J., Lunt, M.F., Bösch, H., 2023. Methane emissions are predominantly responsible for record-breaking atmospheric methane growth rates in 2020 and 2021. Atmos. Chem. Phys. 23 (8), 4863–4880. https://doi.org/10.5194/acp-23-4863-2023.

Friedlingstein, P., Jones, M.W., O'Sullivan, M., Andrew, R.M., Bakker, D.C.E., Hauck, J., Le Quéré, C., Peters, G.P., Peters, W., Pongratz, J., Sitch, S., Canadell, J.G., Ciais, P., Jackson, R.B., Alin, S.R., Anthoni, P., Bates, N.R., Becker, M., Bellouin, N., Bopp, L., Chau, T.T.T., Chevallier, F., Chini, L.P., Cronin, M., Currie, K.I., Decharme, B., Djeutchouang, L.M., Dou, X., Evans, W., Feely, R.A., Feng, L., Gasser, T., Gilfillan, D., Gkritzalis, T., Grassi, G., Gregor, L., Gruber, N., Gürses, Ö., Harris, I., Houghton, R.A., Hurtt, G.C., Iida, Y., Ilyina, T., Luijkx, I.T., Jain, A., Jones, S.D., Kato, E., Kennedy, D., Klein Goldewijk, K., Knauer, J., Korsbakken, J.I., Körtzinger, A., Landschützer, P., Lauvset, S.K., Lefèvre, N., Lienert, S., Liu, J., Marland, G., McGuire, P.C., Melton, J.R., Munro, D.R., Nabel, J.E.M.S., Nakaoka, S.-I., Niwa, Y., Ono, T., Pierrot, D., Poulter, B., Rehder, G., Resplandy, L., Robertson, E., Rödenbeck, C., Rosan, T.M., Schwinger, J., Schwingshackl, C., Séférian, R., Sutton, A.J., Sweeney, C., Tanhua, T., Tans, P.P., Tian, H., Tilbrook, B., Tubiello, F., Van Der Werf, G.R., Vuichard, N., Wada, C., Wanninkhof, R., Watson, A.J., Willis, D., Wiltshire, A.J., Yuan, W., Yue, C., Yue, X., Zaehle, S., Zeng, J., 2022. Global Carbon Budget 2021. Earth Syst. Sci. Data 14 (4), 1917–2005. https://doi.org/10.5194/essd-14-1917-2022.

Gasser, T., Kechiar, M., Ciais, P., Burke, E.J., Kleinen, T., Zhu, D., Huang, Y., Ekici, A., Obersteiner, M., 2018. Path-dependent reductions in CO2 emission budgets caused by permafrost carbon release. Nat. Geosci. 11 (11), 830–835. https://doi.org/10.1038/s41561-018-0227-0.

Global, I.P.C.C., 2022. Warming of 1.5°C: IPCC special report on impacts of global warming of 1.5°C above pre-industrial levels. In: Context of Strengthening Response to Climate Change, Sustainable Development, and Efforts to Eradicate Poverty, 1st edition. Cambridge University Press.

Glotter, M.J., Pierrehumbert, R.T., Elliott, J.W., Matteson, N.J., Moyer, E.J., 2014. A simple carbon cycle representation for economic and policy analyses. Clim. Change 126 (3–4), 319–335. https://doi.org/10.1007/s10584-014-1224-y.

Harmsen, M., Van Vuuren, D.P., Bodirsky, B.L., Chateau, J., Durand-Lasserve, O., Drouet, L., Fricko, O., Fujimori, S., Gernaat, D.E.H.J., Hanaoka, T., Hilaire, J., Keramidas, K., Luderer, G., Moura, M.C.P., Sano, F., Smith, S.J., Wada, K., 2020. The role of methane in future climate strategies: mitigation potentials and climate impacts. Clim. Change 163 (3), 1409–1425. https://doi.org/10.1007/s10584-019-02437-2.

Hartin, C.A., Patel, P., Schwarber, A., Link, R.P., Bond-Lamberty, B.P., 2015. A simple object-oriented and open-source model for scientific and policy analyses of the global climate system – Hector v1.0. Geosci. Model Dev. 8 (4), 939–955. https://doi.org/10.5194/gmd-8-939-2015.

Hartin, C.A., Bond-Lamberty, B., Patel, P., Mundra, A., 2016. Ocean acidification over the next three centuries using a simple global climate carbon-cycle model: projections and sensitivities. Biogeosciences 13 (15), 4329–4342. https://doi.org/10.5194/bg-13-4329-2016.

Hugelius, G., Strauss, J., Zubrzycki, S., Harden, J.W., Schuur, E.A.G., Ping, C.-L., Schirrmeister, L., Grosse, G., Michaelson, G.J., Koven, C.D., O'Donnell, J.A., Elberling, B., Mishra, U., Camill, P., Yu, Z., Palmtag, J., Kuhry, P., 2014. Estimated stocks of circumpolar permafrost carbon with quantified uncertainty ranges and identified data gaps. Biogeosciences 11 (23), 6573–6593. https://doi.org/10.5194/bg-11-6573-2014.

Intergovernmental Panel on Climate Change, 2023. Climate Change 2021 – The Physical Science Basis: Working Group I Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change, 1st edition. Cambridge University Press.

Jackson, R.B., Saunois, M., Bousquet, P., Canadell, J.G., Poulter, B., Stavert, A.R., Bergamaschi, P., Niwa, Y., Segers, A., Tsuruta, A., 2020. Increasing anthropogenic methane emissions arise equally from agricultural and fossil fuel sources. Environ. Res. Lett. 15 (7), 071002. https://doi.org/10.1088/1748-9326/ab9ed2.

Jeltsch-Thömmes, A., Stocker, T.F., Joos, F., 2020. Hysteresis of the Earth system under positive and negative CO_2 emissions. Environ. Res. Lett. 15 (12), 124026. https://doi.org/10.1088/1748-9326/abc4af.

Kessler, L., 2017. Estimating the economic impact of the permafrost carbon feedback. Clim. Change Econ. 08 (02), 1750008. https://doi.org/10.1142/S2010007817500087.

Lenton, T.M., Rockström, J., Gaffney, O., Rahmstorf, S., Richardson, K., Steffen, W., Schellnhuber, H.J., 2019. Climate tipping points — too risky to bet against. Nature 575 (7784), 592–595. https://doi.org/10.1038/d41586-019-03595-0.

MacDougall, A.H., Avis, C.A., Weaver, A.J., 2012. Significant contribution to climate warming from the permafrost carbon feedback. Nat. Geosci. 5 (10), 719–721. https://doi.org/10.1038/ngeo1573.

McKeough, P., 2022. A case for ensuring reductions in CO2 emissions are given priority over reductions in CH4 emissions in the near term. Clim. Change 174 (1–2), 4. https://doi.org/10.1007/s10584-022-03428-6.

Meinshausen, M., Smith, S.J., Calvin, K., Daniel, J.S., Kainuma, M.L.T., Lamarque, J.-F., Matsumoto, K., Montzka, S.A., Raper, S.C.B., Riahi, K., Thomson, A., Velders, G.J.M., Van Vuuren, D.P., 2011. The RCP greenhouse gas concentrations and their extensions from 1765 to 2300. Clim. Change 109 (1–2), 213–241. https://doi.org/10.1007/s10584-011-0156-z.

Morice, C.P., Kennedy, J.J., Rayner, N.A., Winn, J.P., Hogan, E., Killick, R.E., Dunn, R.J.H., Osborn, T.J., Jones, P.D., Simpson, I.R., 2021. An updated assessment of near-surface temperature change from 1850: the HadCRUT5 data set. J. Geophys. Res., Atmos. 126 (3). https://doi.org/10.1029/2019JD032361.

Myhre, G., Highwood, E.J., Shine, K.P., Stordal, F., 1998. New estimates of radiative forcing due to well mixed greenhouse gases. Geophys. Res. Lett. 25 (14), 2715–2718. https://doi.org/10.1029/98GL01908.

Myhre, G., Fuglestvedt, J.S., Berntsen, T.K., Lund, M.T., 2011. Mitigation of short-lived heating components may lead to unwanted long-term consequences. Atmos. Environ. 45 (33), 6103–6106. https://doi.org/10.1016/j.atmosenv.2011.08.009.

Myhre, G., Shindell, D., Bréon, F.-M., Collins, W., Fuglestvedt, J., Huang, J., Koch, D., Lamarque, J.-F., Lee, D., Mendoza, B., Nakajima, T., Robock, A., Stephens, G., Takemura, T., Zhang, H., 2014. Anthropogenic and natural radiative forcing. In: IPCC, Climate Change 2013 – The Physical Science Basis, 1st edition. Cambridge University Press, pp. 659–740.

Nisbet, E.G., Fisher, R.E., Lowry, D., France, J.L., Allen, G., Bakkaloglu, S., Broderick, T.J., Cain, M., Coleman, M., Fernandez, J., Forster, G., Griffiths, P.T., Iverach, C.P., Kelly, B.F.J., Manning, M.R., Nisbet-Jones, P.B.R., Pyle, J.A., Townsend-Small, A., al-Shalaan, A., Warwick, N., Zazzeri, G., 2020. Methane mitigation: methods to reduce emissions, on the path to the Paris Agreement. Rev. Geophys. 58 (1). https://doi.org/10.1029/2019RG000675.

Nissan, A., Alcolombri, U., Peleg, N., Galili, N., Jimenez-Martinez, J., Molnar, P., Holzner, M., 2023. Global warming accelerates soil heterotrophic respiration. Nat. Commun. 14. https://doi.org/10.1038/s41467-023-38981-w.

Ocko, I.B., Sun, T., Shindell, D., Oppenheimer, M., Hristov, A.N., Pacala, S.W., Mauzerall, D.L., Xu, Y., Hamburg, S.P., 2021. Acting rapidly to deploy readily available methane mitigation measures by sector can immediately slow global warming. Environ. Res. Lett. 16 (5), 054042. https://doi.org/10.1088/1748-9326/abf9c8.

Peng, S., Lin, X., Thompson, R.L., Xi, Y., Liu, G., Hauglustaine, D., Lan, X., Poulter, B., Ramonet, M., Saunois, M., Yin, Y., Zhang, Z., Zheng, B., Ciais, P., 2022. Wetland emission and atmospheric sink changes explain methane growth in 2020. Nature 612 (7940), 477–482. https://doi.org/10.1038/s41586-022-05447-w.

Pierrehumbert, R., 2014. Short-lived climate pollution. Annu. Rev. Earth Planet. Sci. 42 (1), 341–379. https://doi.org/10.1146/annurev-earth-060313-054843.

Qu, Z., Jacob, D.J., Zhang, Y., Shen, L., Varon, D.J., Lu, X., Scarpelli, T., Bloom, A., Worden, J., Parker, R.J., 2022. Attribution of the 2020 surge in atmospheric methane by inverse analysis of GOSAT observations. Environ. Res. Lett. 17 (9), 094003. https://doi.org/10.1088/1748-9326/ac8754.

Ritchie, P.D.L., Clarke, J.J., Cox, P.M., Huntingford, C., 2021. Overshooting tipping point thresholds in a changing climate. Nature 592 (7855), 517–523. https://doi.org/10.1038/s41586-021-03263-2.

Rogelj, J., Schaeffer, M., Meinshausen, M., Shindell, D.T., Hare, W., Klimont, Z., Velders, G.J.M., Amann, M., Schellnhuber, H.J., 2014. Disentangling the effects of CO_2 and short-lived climate forcer mitigation. Proc. Natl. Acad. Sci. 111 (46), 16325–16330. https://doi.org/10.1073/pnas.1415631111.

Rogelj, J., Forster, P.M., Kriegler, E., Smith, C.J., Séférian, R., 2019. Estimating and tracking the remaining carbon budget for stringent climate targets. Nature 571 (7765), 335–342. https://doi.org/10.1038/s41586-019-1368-z.

Schaefer, H., 2019. On the causes and consequences of recent trends in atmospheric methane. Curr. Clim. Change Rep. 5 (4), 259–274. https://doi.org/10.1007/s40641-019-00140-z.

Schneider Von Deimling, T., Meinshausen, M., Levermann, A., Huber, V., Frieler, K., Lawrence, D.M., Brovkin, V., 2012. Estimating the near-surface permafrost-carbon feedback on global warming. Biogeosciences 9 (2), 649–665. https://doi.org/10.5194/bg-9-649-2012.

Smith, S.J., Mizrahi, A., 2013. Near-term climate mitigation by short-lived forcers. Proc. Natl. Acad. Sci. 110 (35), 14202–14206. https://doi.org/10.1073/pnas.1308470110.

Stevenson, D.S., Derwent, R.G., Wild, O., Collins, W.J., 2022. Covid-19 lockdown emission reductions have the potential to explain over half of the coincident increase in global atmospheric methane. Atmos. Chem. Phys. 22, 14243–14252. https://doi.org/10.5194/acp-22-14243-2022.

Stocker, T.F., Qin, D., Plattner, G.-K., Tignor, M., Allena, S., Boschung, J., Nauels, A., Xia, Y., Bex, V., Midgle, P.M. (Eds.), in: Prather, M., Flato, G., Friedlingstein, P., Jones, C., Lamarque, J.-F., Liao, H., Rasch, P. (Eds.), IPCC, 2013: Annex II: Climate System Scenario Tables, Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 2014.

Woodard, D.L., Shiklomanov, A.N., Kravitz, B., Hartin, C., Bond-Lamberty, B., 2021. A permafrost implementation in the simple carbon–climate model Hector v. 2.3pf. Geosci. Model Dev. 14 (7), 4751–4767. https://doi.org/10.5194/gmd-14-4751-2021.

Xu, Y., Ramanathan, V., 2017. Well below 2 °C: mitigation strategies for avoiding dangerous to catastrophic climate changes. Proc. Natl. Acad. Sci. 114 (39), 10315–10323. https://doi.org/10.1073/pnas.1618481114.

Zhang, Z., Poulter, B., Feldman, A.F., Ying, Q., Ciais, P., Peng, S., Li, X., 2023. Recent intensification of wetland methane feedback. Nat. Clim. Change 13 (5), 430–433. https://doi.org/10.1038/s41558-023-01629-0.

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Review

Climate change effects on biodiversity, ecosystems, ecosystem services, and natural resource management in the United States

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HIGHLIGHTS

- Climate change is affecting ecosystems at multiple scales.
- Individual/species: changes in morphology and behavior, phenology, and range shifts observed
- Ecosystems: shifts in productivity, species interactions, and emergent properties observed
- Together, these changes are impacting ecosystem services and human well-being.
- Natural resource managers need proactive, flexible approaches to deal with changes.

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ABSTRACT

Climate change is a pervasive and growing global threat to biodiversity and ecosystems. Here, we present the most up-to-date assessment of climate change impacts on biodiversity, ecosystems, and ecosystem services in the U.S. and implications for natural resource management. We draw from the 4th National Climate Assessment to summarize observed and projected changes to ecosystems and biodiversity, explore linkages to important ecosystem services, and discuss associated challenges and opportunities for natural resource management. We find that species are responding to climate change through changes in morphology and behavior, phenology, and geographic range shifts, and these changes are mediated by plastic and evolutionary responses. Responses by species and populations, combined with direct effects of climate change on ecosystems (including more extreme events), are resulting in widespread changes in productivity, species interactions, vulnerability to biological invasions, and other emergent properties. Collectively, these impacts alter the benefits and services that natural ecosystems can provide to society. Although not all impacts are negative, even positive changes can require costly societal adjustments. Natural resource managers need proactive, flexible adaptation strategies that consider historical and future outlooks to minimize costs over the long term. Many organizations are beginning to explore these approaches, but implementation is not yet prevalent or systematic across the nation.

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1. Introduction

Climate change is a pervasive and growing global threat to biodiversity and ecosystems (Díaz et al., 2019). Climate change affects individual species and the way they interact with other organisms and their habitats, which alters the structure and function of ecosystems and the goods and services that natural systems provide to society (Díaz et al., 2019). Understanding the direction and magnitude of ecological responses allows human communities to better anticipate these changes and adapt as necessary.

Periodic assessments of current and future climate change impacts on ecosystems are important for developing and updating natural resource management plans and evaluating adaptation actions (West et al., 2009). The National Climate Assessment (NCA) is a key assessment in the United States, required by the Global Change Research Act to summarize current and projected impacts of climate change on a variety of sectors and regions in the U.S. every four years (USGCRP, 2018). Here, we draw upon the recently published Fourth NCA (NCA4) Volume II to present the most up-to-date assessment of climate change impacts on biodiversity, ecosystems, and ecosystem services in the U.S. (USGCRP, 2018). We synthesize, extend, and integrate the NCA4 chapters focused on natural resources: "Ecosystems, Ecosystem Services, and Biodiversity" (Ch. 7); "Forests" (Ch.6); "Oceans and Marine Resources" (Ch. 9); "Coastal Effects" (Ch. 8); and "Tribes & Indigenous Peoples" (Ch.15) (USGCRP, 2018).

We provide a more in-depth, technical analysis of topics of interest to scientists and practitioners, and review climate change impacts at multiple scales, including: 1) the individual organisms, populations, and species of biodiversity which comprise ecosystems; 2) the properties and processes that characterize ecosystems; and 3) the goods and services that ecosystems provide which support human economies and well-being (Fig. 1). Further, we explore natural resource management challenges posed by climate change and present examples of on-the-ground adaptation actions. Many topics covered in this review are complex and deserve a review of their own. However, by covering multiple scales in one place, we provide a holistic overview of how climate change is affecting different ecosystems and how these changes may in turn affect human well-being, including impacts to vulnerable communities, tribes, and Indigenous peoples.

2. Individuals, populations, and species

Although climate change impacts are widespread, they are not uniform, and accumulating evidence indicates that climate change responses vary as a function of relative vulnerability due to differences in exposure, sensitivity, and adaptive capacity (Beever et al., 2016; Foden and Young, 2016; Glick et al., 2011; Kovach et al., 2019). Below, we discuss major impacts observed at the scale of individuals, populations, and species, and review the mechanisms driving changes.

2.1. Behavior and morphology

One way that organisms cope with changes in their environment is by altering their behavior or morphology. Behavioral responses to climate change can result from changes in temperature and manifest before changes at the population and species level, such as distribution changes or population declines (Beever et al., 2017). Behavioral responses include seeking shade or refuge, altering feeding times, changing site use, and shifting circadian or circannual rhythms (e.g., hibernation, migration; Beever et al., 2017; Bradshaw and Holzapfel, 2007; McCann et al., 2017).

Morphological changes commonly entail changes in body size (Cheung et al., 2013; Eastman et al., 2012; Ozgul et al., 2010). For example, increasing summer temperatures have been associated with reduced body size and increased wing length in North American migratory birds (Weeks et al., 2019). In ectotherms, where metabolic rate is sensitive to temperature (Gardner et al., 2011), warmer temperatures can lead to faster growth rates but can ultimately lead to smaller body size (Atkinson, 1994). This direct impact of temperature on growth has been observed, for example, in American lobster (*Homarus americanus*; Le Bris et al., 2017) and Atlantic cod (*Gadus morhua*; Pershing et al., 2016) during recent warming in the northwest Atlantic. Morphological responses, however, are complex and highly variable: changes in phenotype may not be observed if genetic change is counteracted by environmental effects (Conover et al., 2009). Moreover, short term benefits may not be adaptive in the long term (Section 2.4).

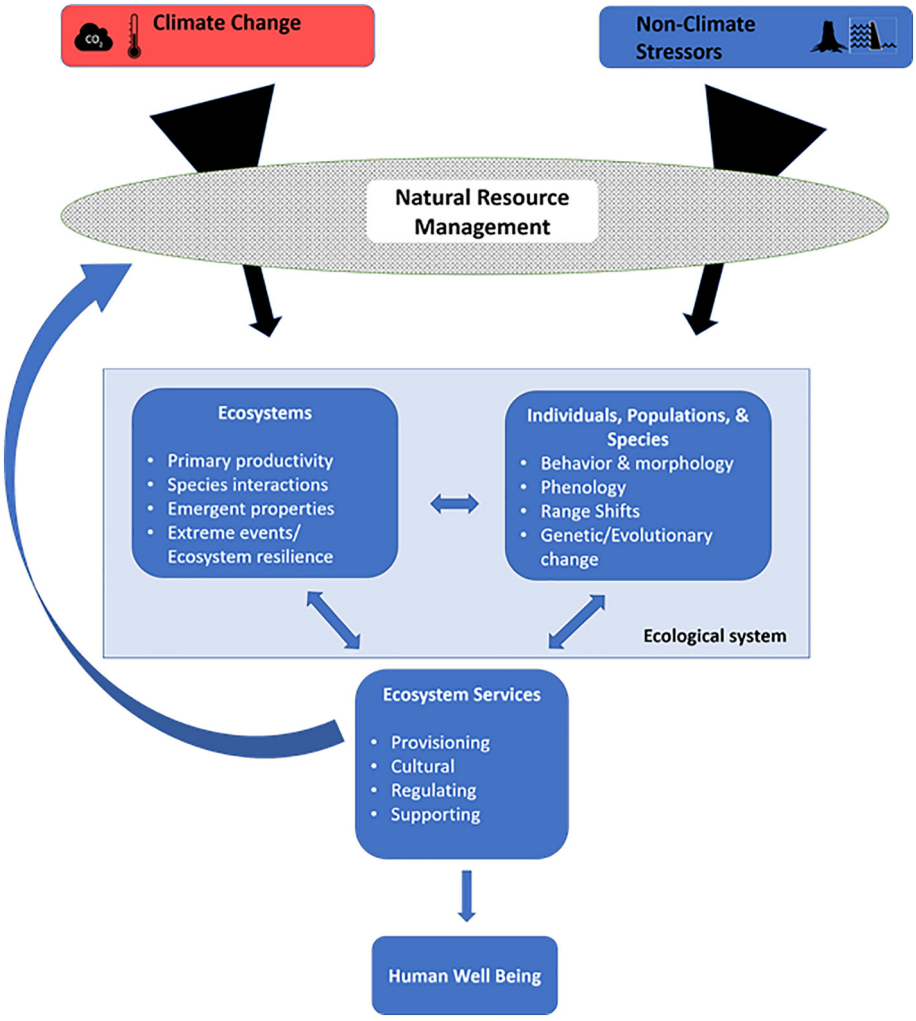


Fig. 1. Climate change and non-climate stressors interact and affect ecological systems at multiple scales. These combined stressors affect individuals, populations, and species, as well as ecosystem processes and properties. The relative impact of climate change versus other stressors varies depending on the species or ecosystem. Diverse biological communities and functioning ecosystems are critical to maintaining the ecosystem services (Millennium Ecosystem Assessment, 2005) that support human well-being (Díaz et al., 2019). Natural resource management affects biodiversity, ecosystems and their services and can moderate or exacerbate climate change and non-climate stressors.

2.2. Phenology

Phenology, or the seasonal timing of recurring biological events, is a critical part of ecological relationships (Rudolf, 2019), and a primary indicator of species responses to climate change (Staudinger et al., 2019). Across much of the terrestrial U.S., broad changes in seasonality are evidenced by an earlier start to spring compared to 20th-century averages (Ault et al., 2015; Monahan et al., 2016). Although changes in phenology are well documented, trends are far from homogenous (Cohen et al., 2018), a result of high variability in climate drivers and phenological responses across habitat types (Chmura et al., 2019; Fu et al., 2015; Pearson, 2019). Migratory birds provide clear examples of phenological shifts, with extensive documentation of earlier migration (Lehikoinen et al., 2019) and earlier breeding (Lany et al., 2016) in response to rising temperatures and altered precipitation patterns.

Phenological shifts in marine and aquatic habitats are less well documented in comparison to terrestrial systems, largely due to difficulty detecting and tracking aquatic organisms (Staudinger et al., 2019). Nonetheless, there have been clear, directional shifts in the timing of seasonal aquatic and marine abiotic drivers, including earlier transitions from winter to spring temperatures (Thomas et al., 2017) and earlier ice melting and runoff (Post, 2017; Staudinger et al., 2019). Marine phytoplankton can respond rapidly to such abiotic changes, resulting in altered timing of phytoplankton blooms (Wasmund et al., 2019), which in turn can create a mismatch with secondary consumers and change the food web structure (Post, 2017; Sundby et al., 2016). Phenological changes have also been observed in freshwater and riparian systems, including advances in the winter spawning phenology of coho (*Oncorhynchus kisutch*) and chum salmon (*O. keta*) in the Pacific Northwest, which has driven phenological changes in bald eagle (*Haliaeetus leucocephalus*) populations (Rubenstein et al., 2019).

Differential shifts in phenology among interacting organisms could drive population declines through reduced reproductive success and/or increased predation or competition (Visser and Gienapp, 2019; Wann et al., 2019; Zimova et al., 2016). Additionally, phenology changes in species with multiple life stages are complex and shifts that are beneficial for one life stage may be detrimental to another (Campbell et al., 2019; Schluter et al., 1991). However, few species have had documented population-level consequences of mistimed reproduction, perhaps due to mitigating effects of density-dependence and greater ability to alter prey or behavior (Dunn and Møller, 2014; Staudinger et al., 2019). Asynchronous phenological shifts have the potential to disrupt the functioning, persistence, and resilience of population dynamics, ecosystems, and ecosystem services (Asch et al., 2019; Mayor et al., 2017; Staudinger et al., 2019; Visser and Gienapp, 2019).

2.3. Geographic range shifts

Climate change is driving large-scale shifts in species distribution, abundance, and reorganization of terrestrial and aquatic ecosystems (Lenoir and Svenning, 2015; Pacifici et al., 2017; Staudinger et al., 2012). Geographic range shifts are widespread across taxa and ecosystems: a recent review of plant and animal species in temperate North America found 55% have either contracted the warm edge or expanded the cool edge of their range (Wiens, 2016). Documented shifts poleward, upslope, and deeper average tens of kilometers per decade (Burrows et al., 2011; Chen et al., 2011). Northern Hemisphere birds, for example, are decreasing in abundance along species' southern and lower elevational range edges (Ralston et al., 2017; Tayleur et al., 2015).

Marine organisms have also demonstrated range shifts, in some cases at faster rates than observed in terrestrial systems and at pace with climate velocities (García Molinos et al., 2015; Poloczanska et al., 2013). The majority of marine taxa surveyed in a 2013 review, for example, shifted in directions consistent with climate velocity (Pinsky et al., 2013). This response, however, is not uniform, with some fish demonstrating a lag effect, potentially due to species-specific sensitivities (Alabia et al., 2018). Arctic marine environments are experiencing changes to sea ice cover, increasing temperatures, and ocean acidification, resulting in range shifts for marine fish, arthropods, and marine mammals (Mecklenburg et al., 2016; Taylor et al., 2017; U.S. Environmental Protection Agency, 2016). Some temperate marine ecosystems are 'tropicalizing', with herbivorous tropical fish expanding poleward, causing decreases in macroalgal plant communities (Vergés et al., 2014).

Despite evidence for widespread range shifts, fewer shifts have been documented than expected from projections, and some shifts are counterintuitive to expectations from projections based solely on temperature changes (Crimmins et al., 2011; Foster and D'Amato, 2015; Morley et al., 2017; Rowe et al., 2015). Indirect effects of climate change and interactive ecological and evolutionary processes can complicate predictions (Estrada et al., 2016; MacLean and Beissinger, 2017; Pacifici et al., 2017). Microclimates, complex topography, and factors such as land use change also need to be considered to accurately predict shifts (Elsen and Tingley, 2015; Guo et al., 2018; Hannah et al., 2014; Kleisner et al., 2016, 2017; Sirami et al., 2017). Moreover, documenting range shifts is challenging, requiring baseline information on historical ranges that is missing for many species, ecosystems, and geographic areas. Additionally, life stages that are most responsive to climate may not be the focus of monitoring or might show lag effects (Alexander et al., 2018). Limited and occasionally conflicting evidence could actually indicate that some species are able to adapt in place, at least for now (Beever et al., 2015; Berg et al., 2010; Jurgens and Gaylord, 2018). Although range shifts are generally regarded as a primary mechanism by which species can effectively adapt to climate change, shifts should be considered in the context of entire ecosystems: an adaptive shift for one species may negatively impact recipient communities (Wallingford et al., in review) (Box 1).

2.4. Mechanisms and rate of change

An organism's response to climate change can be driven by genetic (evolutionary) or non-genetic (plastic) processes (e.g., Franks et al., 2014; Kingsolver and Buckley, 2017). This distinction is important because the mechanism determines the rate of response and whether individuals, populations, and species will be able to keep pace with rapidly changing conditions (Boutin and Lane, 2014). Plastic responses occur within an individual's lifetime and are almost immediate, whereas evolutionary change requires multiple generations (Harrisson et al., 2014; Hendry et al., 2011). Current research is starting to explore the role of epigenetic responses, wherein environmental drivers alter gene expression and can be passed to future generations, occur between generations, and are considered intermediate responses (Jeremias et al., 2018). The distinction between plastic/epigenetic responses and evolutionary change is not always clear, as an organism's ability to respond through these mechanisms can be heritable and subject to evolutionary pressure (Banta and Richards, 2018; Grenier et al., 2016).

Some rapid responses reflect a long history of genetic adaptation to natural variability in climate, and may facilitate persistence during directional climate change by allowing populations to persist long enough for genetic adaptation to occur (Fox et al., 2019; Snell-Rood et al., 2018). While often effective at increasing survival in the short term, some plastic responses are not beneficial over the long term (Ghalambor et al., 2007): they may entail tradeoffs with fecundity (e.g., smaller body sizes typically produce fewer eggs and more boom/bust population dynamics; Waples and Audzijonyte, 2016), or they may lead to interactions with other species or habitats that ultimately lower survival (Bonamour et al., 2019; Schlaepfer et al., 2002). Negative effects of plastic responses are often delayed and difficult to measure, so tracking long-term demographic responses to ensure populations of concern are truly coping with climate change is important.

The pace of climate change often exceeds average rates of evolutionary change (De Meester et al., 2018). However, evolution can happen in very few generations if populations survive strong selection and favorable genetic variation is already present (Hendry, 2017).Strong selection typically involves high mortality, so populations face extirpation before they can effectively adapt via evolution (Bay et al., 2018). Indeed, recent meta-analyses demonstrate that even species demonstrating adaptive phenotypic responses may be adapting too slowly to keep pace with climate change (Radchuk et al., 2019).

Substantial theoretical and empirical work has focused on predicting and measuring rates of response to climate change in recent years (Bell, 2013; Carlson et al., 2014; Gomulkiewicz et al., 2018; Kopp and Matuszewski, 2014; Pelletier and Coltman, 2018). Rapid trait changes are common and well documented, but most cases are consistent with plastic rather than evolutionary mechanisms (Eastman et al., 2012; Merilä and Hendry, 2014). Although examples do exist of evolutionary responses across multiple taxa (Boutin and Lane, 2014; Charmantier and Gienapp, 2014; Crozier and Hutchings, 2013; Franks et al., 2014), the comparative lack of evidence may be due to complex selection and genetic landscapes, methodological constraints that hinder measurement of genetic change (Merilä, 2012), and altered species interactions which may outpace evolutionary responses (Section 3.2). Evolutionary rates are complicated to predict because selection acts on many traits simultaneously, possibly with opposing costs and benefits in different life stages or habitats (Crozier et al., 2008). However, because responses vary in the extent to which they reduce extinction risk, tracking multiple responses and understanding their limitations is critical for successful resource management.

3. Ecosystems

Observed ecosystem-level changes in response to climate change are due to direct impacts from changing climate drivers and interacting effects of species- and population-level responses. Here, we focus on several key ecosystem-level characteristics and properties affected by climate change: primary production; species interactions and emergent properties, including biological invasions; and the impact of extreme events on ecosystem resilience.

3.1. Primary productivity

Almost all life on Earth relies on primary producers, photosynthetic organisms that are the foundation of most food webs and are responsible for producing Earth's oxygen and regulating important components of carbon cycling and sequestration. Climate change has had varying effects on primary production across spatial and temporal scales (Lipton et al., 2018). Changes in primary production are likely to be amplified at higher trophic levels (Chust et al., 2014; Lefort et al., 2015; Stock

Box 1
Examples of climate-driven changes to ecosystems.

Terrestrial



Photo: U.S. Geological Survey



Photo: U.S. Forest Service

The 2012–2017 drought across California resulted in direct physiological stress to trees and facilitated bark beetle outbreaks, causing an unprecedented mortality of 129 million trees in Sierra Nevada forests (Asner et al., 2016; Cal Fire, 2018; Stephens et al., 2018). High levels of mortality among ponderosa pine led to increases in the relative proportion of incense cedar (*Calocedrus decurrens*), which has increased the likelihood of high-intensity surface fires and large wildfires (Stephens et al., 2018). The combined effects of drought, insects, and altered community composition has drastically changed this ecosystem.

Marine



Photo: NOAA



Photo: New York State Department of Environmental Conservation

Non-native invasive species such as European green crab (*Carcinus maenas*) are now present off the California coast, alongside recent "invasions" (due to climate-driven range expansion) of the Humboldt squid (*Dosidicus gigas*) (Epstein and Smale, 2017; Grosholz et al., 2000; Zeidberg and Robison, 2007). Both Humboldt squid and green crab are voracious predators that feed on a variety of native prey (Field et al., 2013; Grosholz et al., 2000). Although ultimate synergistic impact on California marine communities is not yet known, impacts from these species that have already been observed separately include prey population reductions, alteration of the resource base available to migratory shorebirds, and potential fundamental modification of ecosystem structure.

et al., 2014), resulting in further changes to ecosystem function and potentially substantial changes to entire ecosystems.

Globally, terrestrial primary production increased during the late 20th and early 21st centuries due to the fertilizing effect of increasing atmospheric CO_2, nutrient additions from human activities, longer growing seasons, and forest regrowth (Campbell et al., 2017; Domke et al., 2018; Graven et al., 2013; Wenzel et al., 2016; Zhu et al., 2016). However, regional trends vary, and different components of climate change may have opposing impacts on production; while increased atmospheric CO_2 can increase vegetation growth (e.g., Norby et al., 2002), excess or lack of nutrients, water deficits, and air pollution can limit growth (Norby et al., 2010; Oren et al., 2001; Pan et al., 2009). Warming and increased atmospheric CO_2 may also affect belowground biogeochemical processes, such as carbon and nitrogen cycling (Melillo et al., 2017), which can affect terrestrial production (Campbell et al., 2009).

Climate-driven changes to forest primary productivity vary by forest type and elevation. Primary production will likely decrease in forests where soil water availability is limited during the growing season (Latta et al., 2010), but will likely increase in energy-limited forests where snow and cold temperatures restrict the growing season (Latta et al., 2010; Marcinkowski et al., 2015; Wang et al., 2017). However, even in energy-limited forests, drought and extreme temperatures could limit growth increases (Anderegg et al., 2015; Hember et al., 2017). It is also unclear if fertilization effects will continue as forests age (Norby et al., 2010).

In marine and aquatic systems, phytoplankton is responsible for nearly all primary production and generates almost half of the total global primary production. Phytoplankton growth rates affect CO_2 uptake from seawater and organic carbon export to the deep ocean, and also impact fisheries productivity (Tyrrell, 2019). Like terrestrial systems, climate change impacts to marine primary production vary regionally; warming in temperate and tropical oceans can increase stratification, limiting upwelling of deep nutrients that stimulate new production (IPCC, 2013). In contrast, reduced ice cover at higher latitudes increases sunlight availability to the ocean surface, increasing phytoplankton growing seasons and annual primary production (Wasmund et al., 2019). Understanding how these changes impact the food web is crucial for maintaining sustainable fisheries.

3.2. Species interactions, emergent properties, and biological invasions

Variability in species' exposure and responses to climate change are primary drivers of altered species interactions. Emergent properties of ecosystems, including community characteristics such as food-web

structure and function that are mediated by species interactions, are changing as species shift their distributions (Section 2.3) and phenologies (Section 2.2) in response to climate impacts (Breeggemann et al., 2016). Higher trophic levels, for example, are expected to be more sensitive to climate change because of changes in predatory demand and search and encounter rates (Abbott et al., 2014; Daly and Brodeur, 2015; Dell et al., 2014). However, functional responses vary and depend on species composition, abiotic conditions (Davis et al., 2017; McCluney and Sabo, 2016; Verdeny-Vilalta and Moya-Laraño, 2014), body size (Ewald et al., 2013), and predator-prey interactions (Peers et al., 2014; Van Zuiden et al., 2016). Collectively, these changes are resulting in novel (i.e., species composition or function is completely transformed) or hybrid (i.e., some historical characteristics persist but structure and composition lie outside the historical range of variability) ecosystems and altered interspecific relationships with no historical analog (Hobbs et al., 2009).

Emergent ecosystem properties are more difficult to predict than direct impacts to individual species because they develop from interactions radiating throughout the system. Modeling is commonly used to evaluate changes in species interactions, but high uncertainty remains for many species and ecosystems due to lack of baseline research on biotic interactions, community structure and function, adaptive capacity, and interactions of climate and non-climate stressors (Beever et al., 2016; Blois et al., 2013; Rosenblatt and Schmitz, 2014). A growing number of studies are assessing how direct and indirect climate impacts may alter ecosystem properties. For example, fossil records have shown that ecosystems respond similarly to past climate change events by becoming dominated with generalist species (Blois et al., 2013) which may be an indicator of what could be expected under contemporary climate change. Research is also providing more nuanced evaluations of behavioral changes, including phenological, reproductive, and foraging changes (Beever et al., 2016), such as how increasing temperatures are increasing ratsnake predation on birds in the southeastern U.S. (DeGregorio et al., 2015). Finally, studies are suggesting that possessing population-specific traits (Dell et al., 2014; Rasmann et al., 2014) or local adaptations (Davis et al., 2017; Herstoff and Urban, 2014) may allow species to transition and persist in novel environments (Cannizzo and Griffen, 2016). More sophisticated models that account for multi-species interactions, community structure, dispersal, and evolution are needed to make robust predictions, although complex models may not always increase predictive capability (Alexander et al., 2016; Herstoff and Urban, 2014; Novak et al., 2011; Young, 2014).

Of additional concern is that climate change is facilitating the introduction and spread of non-native invasive species. Global economic costs of invasive species are currently estimated to be over $1.4 trillion annually and climate change has the potential to intensify these impacts (Burgiel et al., 2014). Many non-native invasive species are opportunistic generalists that can take advantage of changing conditions, colonize disturbed areas, and out-compete species, thereby altering community composition, dominance, production, and increasing extinction risk in some cases (e.g., Schmitt et al., 2019; Yeruham et al., 2020). For example, disturbance along with warming temperatures, was found to be important for plant invasions at cold, high-altitude regions in South America and Scandinavia (Lembrechts et al., 2016). Moreover, many non-native invasive plants respond more positively than native plants to increasing CO_2, nitrogen deposition, and temperature, likely increasing their competitiveness under increasing climate change (Liu et al., 2017). Stronger competitive abilities will likely lead to higher non-native invasive plant abundance and declines of native species abundances and community diversity (Bradley et al., 2019). Infiltration of non-native species into natural communities has already negatively impacted biodiversity (Bradley et al., 2019). Although new interactions resulting from invasive and native range-shifting species often negatively impact ecosystems (Carey et al., 2012; Valéry et al., 2009; Vergés et al., 2016; Wallingford et al., in review) and related services (Blois et al., 2013), species responses can have counter-intuitive outcomes. For example, the introduction of a non-native invasive bryozoan in the Gulf of Maine is thought to have resulted in substantial expansion of a native nudibranch species due to increased availability of a novel food source (Dijkstra et al., 2013). In some cases, climate change could also indirectly benefit native species by reducing populations of invasive species (Wenger et al., 2011).

3.3. Extreme events and ecosystem resilience

Climate change has altered the duration, magnitude, and frequency of extreme events, including droughts, forest fires, and heatwaves (Jay et al., 2018). Many of these events have significant impacts on ecosystems and interact with other climate-driven changes, reducing ecological resilience.

More extreme droughts and wildfires, driven by rising temperatures and altered precipitation patterns, affect ecosystem structure and function, particularly in forested ecosystems. Over the last two decades, warming and more variable precipitation have increased forest drought severity in the West, Southeast, and the Lake States (Clark et al., 2016), reducing tree growth and increasing mortality (Peters et al., 2015). However, responses vary (Choat et al., 2012) and can be lagged in long-lived species (Walter et al. 2013). Drought weakens tree defenses, increasing susceptibility to other disturbances, including insects, pathogens, invasive species (Trottier et al., 2017), and wildfires (Littell et al., 2016; Logan and Powell, 2009; Weed et al., 2013; see Box 1). While drought impacts have direct long-term consequences, drought-facilitated disturbances can result in more immediate changes to forest ecosystem structure and function (Loehman et al., 2017).

Earlier spring warming (Westerling et al., 2006), increased vapor pressure deficit (Abatzoglou and Williams, 2016), and reduced summer precipitation (Dennison et al., 2014; Holden et al., 2018) have increased fire season length and area burned across the western U.S. (Abatzoglou and Kolden, 2013; Gergel et al., 2017; Luce et al., 2014; McKenzie and Littell, 2017; Westerling, 2016). Climate changes have interacted with forest management practices to create large, dense forest with high fuel loads, especially in lower-elevation ponderosa pine (*Pinus ponderosa*) and dry mixed-conifer forests in the West (Keane et al., 2002). Fire frequency and area burned will likely increase in fire-prone forests (Barbero et al., 2015; Liu et al., 2015); by the 2050s, annual area burned in the U.S. might increase by 2–6 times compared to present (Kitzberger et al., 2017; Litschert et al., 2012; Ojima et al., 2014), However, frequency and severity will depend on topography, fuel levels, and fire suppression efforts (Abt et al., 2015; Butry et al., 2010).

In the North Atlantic, storms are getting stronger due to rising ocean temperatures and sea level rise (Elsner et al., 2008; Malmstadt et al., 2010). There is also evidence that tropical cyclones are bringing more extreme rainfall, even if wind speeds have not increased (Patricola and Wehner, 2018). Increased storm intensity can impact ecosystems and human communities through extreme flooding, erosive waves, and higher storm surge, making recovery from extreme events more challenging. Rising ocean temperatures have also led to periods of extraordinarily warm conditions across the globe, known as marine heatwaves (Hobday et al., 2016, 2018). The U.S. experienced significant heatwaves in the northwest Atlantic in 2012 (Mills et al., 2013) and 2016 (Pershing et al., 2018) and the northeast Pacific in 2014–2015 (Bond et al., 2015). Rising ocean temperatures are driving widespread coral bleaching, contributing to coral cover loss, impacting fish communities, and increasing exposure of nearby shores to waves (Eakin et al., 2019).

4. Ecosystem services

Diverse biological communities and functioning ecosystems are critical to maintaining ecosystem services that support human well-being (Díaz et al., 2019). Therefore, climate change impacts to species, populations, and ecosystems affect the availability and delivery of ecosystem

services, including changes to provisioning, regulating, supporting, and cultural services.

4.1. Provisioning services

Climate-induced changes in provisioning services, the material goods that people obtain from ecosystems and biodiversity, can have profound impacts on human economies and well-being. For example, climate impacts to forested watersheds, including increased temperatures, changes to precipitation and snowfall, and disturbances such as wildfires, are altering freshwater supply for municipalities, agriculture, and power generation (Barnett et al., 2008; Stewart et al., 2005). Surface water shortages are likely in dry years in some locations (Li et al., 2017). Rising stream temperatures also affect water quality (Warziniack et al., 2018). Similarly, wildfires can increase sediment deposition and debris in streams, lakes, and reservoirs (Luce et al., 2012). These changes will stress water supplies, potentially increasing water treatment costs (Warziniack et al., 2018).

Changes in water supply, along with other climate change impacts, can alter agricultural production. Droughts and other extreme events can decrease crop yield and quality (Gowda et al., 2018), with production declines projected for several important crop species as temperatures rise (Zhao et al., 2017). In contrast, changes to growing season length can have both positive and negative effects on crop yield and prices (U.S. Environmental Protection Agency, 2016),

In marine systems, fish and invertebrate harvesting contributes $212 billion in sales annually to the US economy (National Marine Fisheries Service, 2018), and climate change is affecting the availability, distribution (section 2.3), and quality of commercially important species (Kleisner et al., 2016; Peer and Miller, 2014; Pershing et al., 2015; Walsh et al., 2015). Rising ocean temperatures also decrease oxygen levels, which may reduce average fish body size by 14–24% by 2050 (Cheung et al., 2013). In freshwater systems, rising stream temperatures will negatively affect some harvested species (Crozier et al., 2019; Isaak et al., 2012). Future warming is expected to reduce the catch potential of all U.S. regions except the Arctic (Lam et al., 2016).

4.2. Regulating services

Biodiversity and ecosystems provide important regulation services, such as sequestering carbon, moderating the impacts of extreme events (section 3.3), maintaining soil and air quality, and controlling disease spread.

Carbon storage is an important service that will become increasingly important as climate change accelerates. Although forest area has increased nationally since 2000 (EPA, 2017; Oswalt et al., 2014), it is unclear whether carbon storage from afforestation will continue to outweigh emissions from deforestation (Coulston et al., 2015). Moreover, carbon storage in many forests will likely decrease due to higher temperatures, increased water stress and disturbances (section 3.1), and lower rates of CO_2 uptake in aging forests when compared to regrowth forests after past disturbances (Oswalt et al., 2014; Pugh et al., 2019; USDA, 2016; Wear and Coulston, 2015). Coastal wetlands are highly productive ecosystems that store carbon (Davis et al., 2015; Howard et al., 2017), and also provide natural defenses against erosion, waves, flooding, and storm surge (Arkema et al., 2013). As human development or sea level rise degrade coastal wetlands, their capacity to provide these services diminishes.

Ecosystems also regulate the distribution, abundance, and life cycles of disease carrying organisms (Corvalan et al., 2005). Climate change is affecting the ability of ecosystems to provide this service as species ranges (section 2.3), abundances, and habitat conditions shift. For example, Aedes mosquitoes, which transmit diseases such as dengue, are expanding their geographic distribution in the southern U.S., increasing disease risk (Ebi and Nealon, 2016).

4.3. Supporting services

Supporting ecosystem services facilitate basic ecosystem function, such as primary productivity (see section 3.1), nutrient cycling, and maintenance of genetic diversity. As temperatures rise, decomposition of soil organic matter generally increases, potentially increasing soil carbon losses and altering C:N balances (Davidson and Janssens, 2006). These changes are impacted by biotic interactions, including indirect changes to soil microbial community composition (Crowther et al., 2011).

The same activities responsible for climate change (e.g., fossil fuel combustion) result in increased nitrogen deposition, which has significant impacts on terrestrial and aquatic ecosystems, including through eutrophication (Galloway et al., 2008). The combination of higher nutrient loading and rising temperatures is increasing the frequency, duration, and extent of cyanobacteria responsible for harmful algal blooms, which can negatively impact human and animal health (Hilborn and Beasley, 2015). Estimates suggest that by the end of this century, conditions may allow blooms of the toxic alga *Alexandrium catanella* to be up to two months earlier and persist for up to an additional month (Moore et al., 2008; Sandifer and Sutton-Grier, 2014), with resulting impacts on aquaculture, recreation, and other activities.

4.4. Cultural services

Cultural services are the non-material benefits that people gain from biodiversity and ecosystems, such as cultural identity, recreation, and mental and physical health. Despite their importance to human well-being, cultural services have been understudied compared to other ecosystem services (Runting et al., 2017). Indigenous peoples were among the earliest voices connecting culture and environmental change through science, scholarship, and other forms of expression (ACIA, 2004; Maynard, 1998).

There is growing evidence that human health benefits from exposure to natural ecosystems (Donatuto et al., 2014; Sandifer et al., 2015); conversely, climate-driven extremes such as increased temperatures and storms can decrease mental and physical health (Bell et al., 2016; Obradovich et al., 2018). Indirect economic costs (such as lost livelihoods) can also cause adverse socio-psychological impacts (Becker et al., 2015; Morris and Deterding, 2016; Shen and Aydin, 2014).

Although quantifying the value of ecosystems to cultural services is difficult, studies suggest that Americans place a high cultural value on natural systems: for example, a recent survey found that nearly 49 million adults nationwide participated in ocean and coastal recreation, spending more than 1.2 billion days along the coasts and over $141 billion in ocean recreation-related goods and services (National Marine Fisheries Service, 2018). As climate change alters the ability of ecosystems to provide jobs, recreational opportunities, and restorative experiences, communities will experience declines in mental and physical health and potential losses of nature-based tourism dollars (Sandifer and Sutton-Grier, 2014).

5. Vulnerability of human communities

The adaptive capacity of human communities to deal with changes in ecosystem services will partly determine the magnitude of impacts on well-being. While some human communities have been proactive in identifying and planning for changes, others are more vulnerable due to a reduced ability to adapt.

Tribes and Indigenous peoples in the U.S. (groups whose exercise of self-determination as governing entities pre-dates the establishment of the U.S.; Jantarasami et al., 2018) have over 800 climate change initiatives and have led or participated in numerous climate change studies; many have developed their own climate change plans (Jantarasami et al., 2018). Since 1998, tribes and Indigenous peoples

Table 1
Example management responses to changing biodiversity, ecosystems, and ecosystem services that can increase resilience, use updated technology or infrastructure, or be incorporated into governance approaches.

	Increasing ecosystem resilience	Utilizing technology and infrastructure	Improved governance
Individuals, populations, species	Maintaining population sizes, connectivity, and gene flow to allow for shifting ranges and increases in evolutionary resilience of populations and species	Matching individual genotypes with future environments under projected climate change increases adaptability of species	Considering climate change impacts on threatened and endangered species in listing decisions can improve overall understanding of vulnerability
Ecosystems	Reduction of non-climate stressors, such as pollution and invasive species to minimize climate change impacts	Adopting use of natural and nature-based infrastructure to improve resilience of natural communities, leveraging programs in place addressing other stressors	Implementing use of boundary organizations (e.g., North American Marine Protected Areas Network) can promote dialogue of diverse stakeholders in ecosystems that cross multiple jurisdictional boundaries and look for efficiencies in addressing multiple stressors
Ecosystem services	Maintain biodiversity and ecological redundancy to minimize losses in valuable services	Forecasting environmental conditions to prepare for economic changes in a particular industry (e.g., fishery)	Promoting consideration of ecosystem services and related climate impacts within federal planning and decision frameworks

have collaborated on the NCA, focusing on Indigenous concerns, knowledge of vulnerability, and goals for adaptation and mitigation.

Although tribes and Indigenous peoples continue to exercise self-governance, federal policies provide uneven levels of political engagement and support. Indigenous leadership is critical to addressing climate change; however, federal, state, and local governments pose barriers to tribal and Indigenous mitigation and adaptation efforts (Jantarasami et al., 2018). Historical and contemporary land-reduction, land-use restrictions, and poorly implemented treaty rights and consultation requirements exacerbate economic and health risks, which in many cases are associated with threats to Indigenous cultural maintenance. For example, climate-driven range shifts in culturally important species pose challenges to tribes and Indigenous peoples when tribal land areas are small and have limited connectivity (Rapp et al., 2019). Indigenous peoples face risks related to resettlement due to the impacts of climate change, such as coastal erosion and sea ice loss in Alaska. Despite a history of forced relocations, there are structural barriers for Indigenous peoples to participate in current policy processes trying to plan for climate-driven resettlement (Jantarasami et al., 2018).

Across the U.S., coastal communities are also particularly vulnerable to climate change impacts from rising sea levels and more intense storms, which are exacerbating high tide and storm surges, erosion, and saltwater intrusion. High tide flooding is already forcing some cities to install costly pump stations to clear floodwaters and mobilize emergency responders to routinely close flooded streets.

Society's most vulnerable populations, including children, the elderly, economically disadvantaged, homeless, and those with preexisting mental illness tend to be the most heavily impacted by climate changes and resulting impacts to ecosystem services (Dodgen et al., 2016).

6. Implications for natural resource management

Natural resource management traditionally focuses on maintaining or restoring to historical conditions (e.g., National Park System Advisory Board, 2012). While historical context may still motivate management decisions, restoring to historical baselines may not be realistic as the climate changes (Stein et al., 2014). In some cases, management practices to resist change may be effective; in others, managers may choose to accept ecosystem changes or to alter management practices to direct changes in order to minimize loss of valued species and services as ecosystems transform (Aplet and Mckinley, 2017; Millar and Stephenson, 2015; Stein et al., 2013).

Adaptive and proactive approaches that are continually updated to reflect emerging and anticipated climate change impacts will be needed (Bradford et al., 2018; Holsman et al., 2019; Stein et al., 2014; Table 1). For example, the U.S. has a rigorous, science-based system for detecting changes in fish abundance, productivity, and catch, which informs fishery management decisions such as seasonal and spatial closures, annual quotas, and stock rebuilding plans (Pinsky and Mantua, 2014). Collection of this type of information is important for future assessment and updating of management objectives (Stein et al., 2014). NOAA Fisheries has developed adaptation strategies that incorporate climate and ecosystem-related factors into fishery decision-making (Busch et al., 2016; Hare et al., 2016a; Link et al., 2015). Decision support tools, including scenario planning (Cobb and Thompson, 2012; Mahmoud et al., 2009; Peterson et al., 2003) and structured decision-making (Gregory et al., 2012) can help decision-makers explore broad scenarios of risk and develop and prioritize actions that account for uncertainty, optimize tradeoffs, and reflect institutional capacity. Below, we discuss strategies for increasing resilience of ecosystems and human communities.

6.1. Increasing ecosystem resilience

To create effective adaptation strategies, managers need to understand which species are most at risk and why. One way to determine relative risk is through climate change vulnerability assessments that examine species exposure, sensitivity, and adaptive capacity to climate change, and exposure to non-climate stressors (Glick et al., 2011; Hare et al., 2016b; Spencer et al., 2019; Staudinger et al., 2015). Managers can then take proactive steps to increase resilience (Table 1).

Systems that are already degraded from non-climate stressors have lower resilience; therefore, restoring and conserving areas that support valued resources are important. Many strategies for reducing other stressors are things that managers already know, such as restoring populations and habitats, increasing connectivity, and reducing stress from disease, pollution and invasive species (Box 2). For example, prescribed burning and reducing forest stand density can lower wildfire risk in some forest types and can increase resistance and resilience to drought and insect outbreaks (Bottero et al., 2017; Sohn et al., 2016; Vernon et al., 2018). Similarly, in aquatic systems, effective strategies include reconnecting floodplains and side channels, ensuring effective passage for aquatic organisms, and maintaining large trees in forested riparian areas for shade and recruitment to streams (Peterson and Halofsky, 2018; Pollock et al., 2014).

Limiting invasive species spread can help maintain biodiversity, ecosystem function, and resilience (Fischer et al., 2006; Katsanevakis et al., 2014; Oliver et al., 2015). Dialogue between managers, scientists, and policymakers can help ensure that climate change mitigation does not exacerbate invasive species spread (Beaury et al., 2019). Similarly, invasive species policies that explicitly address climate change will enable proactive management (Pyke et al., 2008). Managers may also benefit from considering potential negative effects from native species range expansions (Burgiel et al., 2014; Carey et al., 2012; Giakoumi et al., 2019; Wallingford et al., in review).

Restoring habitat and increasing connectivity to enable species to disperse across the landscape and follow physiological niches is another

Box 2
Examples of on-the-ground adaptation.

Restoring meadows in the Sierra Nevada



Photo: Toni Lyn Morelli

The Sierra Nevada region is critical to the California water supply. Snow in the mountains melts slowly during spring and summer, providing water for ecosystems and people. Climate change is projected to cause more winter precipitation to fall as rain and earlier snowmelt, leading to decreased summer water flows (Viers et al., 2013). Increased frequency and severity of floods is also anticipated. Well-functioning mountain meadows can attenuate floods and increase groundwater storage (National Wildlife Federation, 2010), and some have been identified as climate change refugia for wildlife (Morelli et al., 2017). However, historic land use changes have degraded approximately 40–60% of Sierra meadows. In 2015, Federal, state, and NGO partners restored four meadows with high ecological value located in areas projected to experience the most significant changes in hydrology (Fair and Hunt, 2015; National Wildlife Federation, 2010).

Nature-based infrastructure



Photo: Linda Walters

The use of nature-based designs for coastal resilience structures like living shorelines tends to be more effective at withstanding extreme events (Powell et al., 2019). For example, during Tropical Storm Irene in 2011, stream-designed road crossings survived a category 3 hurricane while nearly 1000 traditional culverts were damaged or destroyed (Sutton-Grier et al., 2018). In another example, living shorelines fared much better under a category 1 hurricane in North Carolina than traditional bulk heads (Gittman et al., 2014).

key climate adaptation action (Anderson et al., 2015; Mcguire et al., 2016; Timpane-Padgham et al., 2017). For example, the recent recovery plan for Atlantic salmon (*Salmo salar*) included identifying vacant habitats, creating redundant populations, and revisiting critical habitat designations to ensure sufficient climate resilient habitats under future conditions (USFWS and NMFS, 2019). Additionally, conserving climate change refugia (areas relatively buffered from contemporary climate change that enable persistence of valued resources), has become a focus of conservation efforts for highly valued vulnerable ecosystems and species (Keppel et al., 2015; Morelli et al., 2016).

Restoring populations can be an effective way to increase genetic diversity and potential for species to evolve and adapt to changing climatic conditions (Sgrò et al., 2011). More active approaches such as diverse seed sourcing, translocation of genes or individuals to accelerate evolution, and assisted migration may be warranted for species with limited dispersal ability or that face movement barriers (Anderson et al., 2014; Isaac-Renton et al., 2014; Whiteley et al., 2015). Unforeseen and unwanted consequences are possible for any assisted migration, but developing policies to analyze and manage potential consequences could minimize unintended outcomes (Invasive Species Advisory Committee, 2017; Schwartz et al., 2012).

6.2. Leveraging technology and infrastructure

Human communities may need to adapt by updating technology and infrastructure (Table 1). Extreme events often motivate adaptation. For example, the inability of the lobster supply chain to handle the sudden influx of soft-shell lobster during the 2012 heatwave (Mills et al., 2013) led to increased domestic processing capacity and expanded marketing. These adaptations allowed the fishery to achieve record value during a subsequent heatwave in 2016 (Pershing et al., 2018). To-date, most documented cases of adaptation to climate impacts on the ocean have been reactive. However, it is now possible to forecast temperature, pH, and oxygen conditions several months in advance (Jacox et al., 2017; Siedlecki et al., 2016; Tommasi et al., 2017). Ensuring that these data products are distributed and used effectively will require considerable engagement with the user community (Hobday et al., 2019; Siedlecki et al., 2016).

In coastal ecosystems, there is growing interest in natural and nature-based infrastructure (NNBI) to increase coastal community resilience (Powell et al., 2019; Spalding et al., 2014; Sutton-Grier et al., 2015). NNBI strategies include restoring or creating coastal ecosystems like salt marsh, mangroves, oyster or coral reefs, beaches, and dunes to mitigate waves and erosion (Ferrario et al., 2014; Möller et al., 2014; Powell et al., 2019; Rodriguez et al., 2014; Zhang et al., 2012), but also include hybrid combinations of natural and built infrastructure such as living shorelines or using combinations of habitat restoration and flood walls (Box 2) (Gittman et al., 2014; Sutton-Grier et al., 2015). NNBI approaches provide co-benefits in terms of habitat, water quality, and recreation, and can be cheaper and survive extreme events better than traditional infrastructure (Gittman et al., 2014; Powell et al., 2019; Sutton-Grier et al., 2018). Although long-term planning may require some coastal communities to relocate due to prohibitively high cost or infeasibility of sea level rise protection, NNBI approaches can at least mitigate some short-term impacts and allow communities more time to consider options. NNBI approaches are often not as well known or trusted in comparison to traditional grey (e.g., seawall) approaches; therefore it is important to increase information on the performance of these techniques, communicate their ecosystem service benefits, and increase coordination and planning around shared socio-ecological goals (Powell et al., 2019).

6.3. Strengthening governance

Federal agencies that manage natural resources are increasingly considering climate change impacts in their management plans (e.g.

Busch et al., 2016; Link, 2016; National Fish Wildlife and Plants Climate Adaptation Partnership, 2012; National Park Service, 2013; Swanston and Janowiak, 2012; Table 1). For example, the National Marine Fisheries Service has developed guidance on how climate change information should be considered in Endangered Species Act (ESA) decisions (National Marine Fisheries Service, 2016). The U.S. Fish and Wildlife Service has also considered climate change in listing decisions, biological opinions, and proposed alternative actions under the ESA (e.g., U.S. Fish and Wildlife Service, 2008, 2010), although climate change is still not included for many species. Even when climate change has been listed as a threat, specific management actions are often lacking (Delach et al., 2019). Federal agencies have also been directed to promote consideration of ecosystem services and related climate impacts within existing planning and decision frameworks (Executive Office of the President of the United States, 2015).

Despite progress, institutional barriers such as a focus on near-term planning, fixed policies and protocols, jurisdictional restrictions, and an established practice of managing based on historical conditions remain

Box 3

An integrated case study: climate change impacts on salmon across the U.S.

Individual, population, and species level responses



Bureau of Land Management



Photo: National Park Service

- In the Northwest, abnormally warm temperatures have led to losses of migrating and spawning salmon in the Columbia River (NOAA Fisheries, 2016).
- In Alaska, some salmon populations have benefited from warmer temperatures, earlier spring, and increased density of zooplankton prey (Schindler et al., 2005).
- Coho salmon on the west coast of the U.S. are expected to shift their range north by 2050 (Cheung et al., 2015). Under a high greenhouse gas emissions scenario, projected stream temperature increases could lead to a 22% reduction in salmon habitat in Washington by late century (Niemi et al., 2009).
- Sockeye salmon (*Oncorhynchus nerka*) in the Columbia River have been migrating earlier. Nearly two--thirds of this response was explained by evolutionary rather than plastic responses (Crozier et al., 2011).
- In the Penobscot River in the Gulf of Maine, adult Atlantic salmon (*Salmo salar*) have arrived as much as 2–3 weeks earlier to their freshwater spawning grounds between the late 1970s and early 2000s (Huntington et al., 2003; Juanes et al., 2004).

Ecosystem level responses



- Kodiak brown bears (*Ursus arctos middendorffi*) have responded to phenological shifts in sockeye salmon and red elderberry (*Sambucus racemosa*). During years with warmer springs, elderberry fruited earlier and overlapped with the salmon spawning run, causing bears to eat less salmon and more berries (Deacy et al., 2017).
- In the Pacific Northwest, warming stream temperatures are likely to reduce the amount of rearing habitat for Chinook salmon (*Oncorhynchus tshawytscha*), but will likely increase the range of invasive smallmouth bass (*Micropterus dolomieu*) (Lawrence et al., 2014).

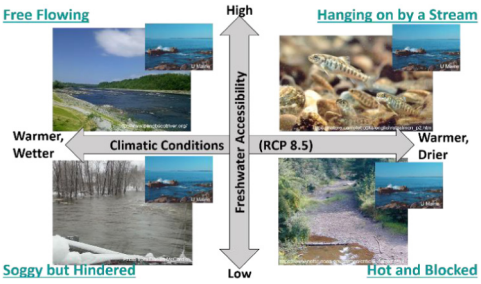
Impacts to ecosystem services



Matt Nagle, Puyallup Tribal News

- As Kodiak brown bear diet shifted away from salmon (see panel 2), this reduced the distribution of marine derived nutrients being distributed into the surrounding terrestrial landscape, with implications for ecological function (Deacy et al., 2017).
- Shifts in availability and declines of salmon and other cold-water fishes impact cherished cultural resources, particularly in the Pacific Northwest where they are important to tribal nations such as the Nez Perce Tribe as cultural, subsistence, and economic resources. Tribes view salmon as an extension of life and an indicator of environmental health, and loss of salmon is equated with loss of tribal identity and culture (Colombi, 2012).

Implications for management



(Pictorial representation of scenarios used in Borggaard et al., 2019)

- Atlantic salmon and many distinct Pacific salmon population groups are federally protected species. Climate change is expected to exacerbate pre-existing anthropogenic stressors, which have reduced adaptive capacity (Crozier et al., 2019; Hare et al., 2016b). The Pacific Salmon Climate Vulnerability Assessment identified life stages that are most vulnerable to climate change and established a methodology for future status reviews to monitor and update recovery needs and prioritize recovery actions (Crozier et al., 2019).
- In the Yakima Basin, water resource managers, conservation groups, and state and federal agencies are enhancing reservoir storage capacity to ensure minimum flows for fish, allow passage above dams for access to cool, historical habitat, restore a more natural hydrograph, and improve riparian conditions for natural temperature and flow stabilization to bolster salmon runs and riparian habitat during droughts. Actions to redistribute water also impacted farmers, but agreements were made to sustain conditions needed to support salmon (NOAA Fisheries, 2015).
- NOAA used Atlantic salmon as a pilot case study for Scenario Planning - a structured process that embraces uncertainty and explores plausible alternative future conditions to help manage risk and prioritize actions - to explore actions to increase resilience to changing conditions in riverine and marine environments in response to declining population trends (Borggaard et al., 2019). Some outcomes from this effort have already been incorporated into the most recent revision of the Atlantic Salmon Recovery Plan (USFWS and NMFS, 2019).

a challenge (Kemp et al., 2015; Stein et al., 2014). Even with agency-level directives for climate adaptation, implementing actions on the ground can be difficult due to lack of funding and time, negative public perceptions, and difficulty transferring science between researchers and managers (Kemp et al., 2015). Boundary organizations that work at the interface of research and management, such as the U.S. Geological Survey Climate Adaptation Science Centers and the NOAA Regional Integrated Sciences and Assessment Programs, can help address some of these issues by bringing together multiple stakeholders and working with managers to develop adaptation plans.

Promoting local climate adaptation initiatives can also be an effective management strategy. Self-determination and self-governance of tribes and Indigenous peoples, as well as involvement of communities of color or natural resource users such as anglers in particular localities, supports the use of local knowledge and cultural practices that can track, adapt to and mitigate environmental change (Maldonado et al., 2013; Norton-Smith et al., 2016; Vinyeta et al., 2015). For many tribes and Indigenous peoples, their political rights are connected to cultural responsibilities to live sustainably (Borrows, 1997; De Chavez and Tauli-Corpuz, 2009). These cultural responsibilities often involve rich scientific traditions of observation and ecosystem stewardship (Shilling and Nelson, 2018; Trosper, 2009). Tribal and Indigenous governments have emphasized the importance of Indigenous scientists and knowledge keepers working collaboratively to observe changes and create adaptation strategies (Grossman and Parker, 2012; Houser et al., 2001). These governments are in unique positions to cooperate with local, state, and federal government to coordinate regional conservation and adaptation efforts that emphasize strategic foresight and sustainability (Krakoff, 2008; Morishima, 2014; Whyte et al., 2014).

7. Conclusion

Climate change is a pervasive and growing threat to biodiversity, ecosystems, and ecosystem services in the U.S. Climate impacts have been and will continue to be observed at the level of individuals, populations, and species through changes in behavior and morphology, phenology, and range shifts, and at the ecosystem level through changes in primary production, species interactions and emergent properties, and extreme events. Ecosystems and biodiversity underpin important services to people, thus these changes impact provisioning, regulating, supporting, and cultural services, with implications for human well-being. Effective management will require flexible, proactive approaches that account for potential climate change impacts (Box 3). Managers are beginning to implement these strategies, but face challenges due to lack of information and institutional barriers. Widespread incorporation of climate change into natural resource management is yet to be achieved, but examples are emerging that help increase awareness and provide case studies in different sectors. Moving forward, evaluations of effectiveness and demonstrative case studies of adaptation success stories are needed to promote and guide climate-smart management.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References

Abatzoglou, J.T., Kolden, C.A., 2013. Relationships between climate and macroscale area burned in the western United States. Int. J. Wildl. Fire 22, 1003–1020. https://doi.org/10.1071/WF13019.

Abatzoglou, J.T., Williams, A.P., 2016. Impact of anthropogenic climate change on wildfire across western US forests. Proc. Natl. Acad. Sci. 113, 11770–11775. https://doi.org/10.1073/pnas.1607171113.

Abbott, K.C., Harmon, J.P., Fabina, N.S., 2014. The challenge of predicting temperature effects on short-term predator–prey dynamics. Popul. Ecol. 56, 375–392.

Abt, K.L., Butry, D.T., Prestemon, J.P., Scranton, S., 2015. Effect of fire prevention programs on accidental and incendiary wildfires on tribal lands in the United States. Int. J. Wildl. Fire 24, 749–762. https://doi.org/10.1071/WF14168.

ACIA, 2004. Impacts of a Warming Arctic-Arctic Climate Impact Assessment. Cambridge University Press.

Alabia, I.D., García Molinos, J., Saitoh, S.I., Hirawake, T., Hirata, T., Mueter, F.J., 2018. Distribution shifts of marine taxa in the Pacific Arctic under contemporary climate changes. Divers. Distrib. 24, 1583–1597. https://doi.org/10.1111/ddi.12788.

Alexander, J.M., Diez, J.M., Hart, S.P., Levine, J.M., 2016. When climate reshuffles competitors: a call for experimental macroecology. Trends Ecol. Evol. 31, 831–841. https://doi.org/10.1016/j.tree.2016.08.003.

Alexander, J.M., Chalmandrier, L., Lenoir, J., Burgess, T.I., Essl, F., Haider, S., Kueffer, C., McDougall, K., Milbau, A., Nuñez, M.A., Pauchard, A., Rabitsch, W., Rew, L.J., Sanders, N.J., Pellissier, L., 2018. Lags in the response of mountain plant communities to climate change. Glob. Chang. Biol. 24, 563–579. https://doi.org/10.1111/gcb.13976.

Anderegg, W.R.L., Hicke, J.A., Fisher, R.A., Allen, C.D., Aukema, J., Bentz, B.J., Hood, S., Lichstein, J.W., Macalady, A.K., McDowell, N.G., Pan, Y., Raffa, K., Sala, A., Shaw, J.D., Stephenson, N.L., Tague, C., Zeppel, M., 2015. Tree mortality from drought, insects, and their interactions in a changing climate. New Phytol. 208, 674–683. https://doi.org/10.1111/nph.13477.

Anderson, J.H., Pess, G.R., Carmichael, R.W., Ford, M.J., Cooney, T.D., Baldwin, C.M., Mcclure, M.M., 2014. Planning Pacific salmon and steelhead reintroductions aimed at long-term viability and recovery. North Am. J. Fish. Manag. 34, 72–93. https://doi.org/10.1080/02755947.2013.847875.

Anderson, M.G., Clark, M., Mcrae, B.H., 2015. Permeable Landscapes for Climate Change the Nature Conservancy. Eastern Conservation Science, Boston, Massachussetts.

Aplet, G.H., Mckinley, P.S., 2017. A portfolio approach to managing ecological risks of global change. Ecosyst. Heal. Sustain. 3, 1–15. https://doi.org/10.1002/ehs2.1261.

Arkema, K.K., Guannel, G., Verutes, G., Wood, S.A., Guerry, A., Ruckelshaus, M., Kareiva, P., Lacayo, M., Silver, J.M., 2013. Coastal habitats shield people and property from sea-level rise and storms. Nat. Clim. Chang. 3, 913–918. https://doi.org/10.1038/nclimate1944.

Asch, R.G., Stock, C.A., Sarmiento, J.L., 2019. Climate change impacts on mismatches between phytoplankton blooms and fish spawning phenology. Glob. Chang. Biol. 25, 2544–2559. https://doi.org/10.1111/gcb.14650.

Asner, G.P., Brodrick, P.G., Anderson, C.B., Vaughn, N., Knapp, D.E., Martin, R.E., 2016. Progressive forest canopy water loss during the 2012-2015 California drought. Proc. Natl. Acad. Sci. U. S. A. 113, E249–E255. https://doi.org/10.1073/pnas.1523397113.

Atkinson, D., 1994. Temperature and organism size - a biological law for ectotherms. Adv. Ecol. Res. 25, 1–58.

Ault, T.R., Schwartz, M.D., Zurita-Milla, R., Weltzin, J.F., Betancourt, J.L., 2015. Trends and natural variability of spring onset in the coterminous United States as evaluated by a new gridded dataset of spring indices. J. Clim. 28, 8363–8378. https://doi.org/10.1175/JCLI-D-14-00736.1.

Banta, J.A., Richards, C.L., 2018. Quantitative epigenetics and evolution. Heredity (Edinb) 121, 210–224. https://doi.org/10.1038/s41437-018-0114-x.

Barbero, R., Abatzoglou, J.T., Larkin, N.K., Kolden, C.A., Stocks, B., 2015. Climate change presents increased potential for very large fires in the contiguous United States. Int. J. Wildl. Fire 24, 892–899. https://doi.org/10.1071/WF15083.

Barnett, T.P., Pierce, D.W., Hidalgo, H.G., Bonfils, C., Santer, B.D., Das, T., Bala, G., Wood, A.W., Nozawa, T., Mirin, A. a, Cayan, D.R., Dettinger, M.D., 2008. Human-induced changes United States. Science (80-.) 319, 1080–1083. https://doi.org/10.1126/science.1152538.

Bay, R.A., Harrigan, R.J., Buermann, W., Le Underwood, V., Gibbs, H.L., Smith, T.B., Ruegg, K., 2018. Response to comment on "Genomic signals of selection predict climate-driven population declines in a migratory bird.". Science (80-.) 361, 83–86. https://doi.org/10.1126/science.aat7956.

Beaury, E.M., Fusco, E.J., Jackson, M.R., Laginhas, B.B., Morelli, T.L., Allen, J.M., Pasquarella, V.J., Bradley, B.A., 2019. Incorporating climate change into invasive species management: insights from managers. Biol. Invasions 6. https://doi.org/10.1007/s10530-019-02087-6.

Becker, A.H., Matson, P., Fischer, M., Mastrandreade, M., 2015. Towards seaport resilience for climate change adaptation: stakeholder perceptions of hurricane impacts in Gulfport (MS) and Providence (RI). Prog. Plann. 99, 1–49.

Beever, E.A., Leary, J.O., Mengelt, C., West, J.M., Julius, S., Green, N., Magness, D., Petes, L., Stein, B., Nicotra, A.B., Hellmann, J.J., 2015. Improving Conservation Outcomes with a New Paradigm for Understanding Species ' Fundamental and Realized Adaptive Capacity 00. , pp. 1–7. https://doi.org/10.1111/conl.12190.

Beever, E.A., O'Leary, J., Mengelt, C., West, J.M., Julius, S., Green, N., Magness, D., Petes, L., Stein, B., Nicotra, A.B., Hellmann, J.J., Robertson, A.L., Staudinger, M.D., Rosenberg, A.A., Babij, E., Brennan, J., Schuurman, G.W., Hofmann, G.E., 2016. Improving conservation outcomes with a new paradigm for understanding species' fundamental and realized adaptive capacity. Conserv. Lett. 9, 131–137. https://doi.org/10.1111/conl.12190.

Beever, E.A., Hall, L.E., Varner, J., Loosen, A.E., Dunham, J.B., Gahl, M.K., Smith, F.A., Lawler, J.J., 2017. Behavioral flexibility as a mechanism for coping with climate change. Front. Ecol. Environ. 15, 299–308. https://doi.org/10.1002/fee.1502.

Bell, G., 2013. Evolutionary rescue and the limits of adaptation. Philos. Trans. R. Soc. B Biol. Sci. 368, 1–6. https://doi.org/10.1098/rstb.2012.0080.

Bell, J.E., Herring, S.C., Jantarasami, L., Adrianopoli, C., Benedict, K., Conlon, K., Escobar, V., Hess, J., Luvall, J., Garcia-Pando, C.P., Quattrochi, D., Runkle, J., II Schreck, C.J., 2016. Ch. 4: impacts of extreme events on human health. The Impacts of Climate Change on Human Health in the United States: A Scientific Assessment. U.S. Global Change Research Program, Washington, D.C., USA.

Berg, M.P., Toby Kiers, E., Driessen, G., van der Heijden, M., Kooi, B.W., Kuenen, F., Liefting, M., Verhoef, H.A., Ellers, J., 2010. Adapt or disperse: understanding species persistence in a changing world. Glob. Chang. Biol. 16, 587–598. https://doi.org/10.1111/j.1365-2486.2009.02014.x.

Blois, J.L., Zarnetske, P.L., Fitzpatrick, M.C., Finnegan, S., 2013. Climate change and the past, present, and future of biotic interactions. Science (80-.) 341, 499–504. https://doi.org/10.1126/science.1237184.

Bonamour, S., Chevin, L.M., Charmantier, A., Teplitsky, C., 2019. Phenotypic plasticity in response to climate change: the importance of cue variation. Philos. Trans. R. Soc. B Biol. Sci. 374. https://doi.org/10.1098/rstb.2018.0178.

Bond, N.A., Cronin, M.F., Freeland, H., Mantua, N., 2015. Causes and impacts of the 2014 warm anomaly in the NE Pacific. Geophys. Res. Lett. 42, 3414–3420. https://doi.org/10.1002/2015GL063306.

Borggaard, D., Dick, D., Star, J., Alexander, M., Bernier, M., Collins, M., Damon-Randall, K., Dudley, R., Griffis, R., Hayes, S., Johnson, M., Kircheis, D., Kocik, J., Letcher, B., Mantua, N., Morrison, W., Nislow, K., Saba, V., Saunders, R., Sheehan, T., Staudinger, M., 2019. Atlantic salmon (Salmo salar) climate scenario planning pilot report. Greater Atlantic Region Policy Series [19-05].

Borrows, J., 1997. Living between water and rocks: first nations, environmental planning and democracy. Univ. Tor. Law J. 47, 417–468.

Bottero, A., D'Amato, A.W., Palik, B.J., Bradford, J.B., Fraver, S., Battaglia, M.A., Asherin, L.A., 2017. Density-dependent vulnerability of forest ecosystems to drought. J. Appl. Ecol. 54, 1605–1614. https://doi.org/10.1111/1365-2664.12847.

Boutin, S., Lane, J.E., 2014. Climate change and mammals: evolutionary versus plastic responses. Evol. Appl. 7, 29–41. https://doi.org/10.1111/eva.12121.

Bradford, J.B., Betancourt, J.L., Butterfield, B.J., Munson, S.M., Wood, T.E., 2018. Anticipatory natural resource science and management for a changing future. Front. Ecol. Environ. 16, 295–303. https://doi.org/10.1002/fee.1806.

Bradley, B.A., Laginhas, B.B., Whitlock, R., Allen, J.M., Bates, A.E., Bernatchez, G., Diez, J.M., Early, R., Lenoir, J., Vilà, M., Sorte, C.J.B., 2019. Disentangling the abundance–impact relationship for invasive species. Proc. Natl. Acad. Sci. U. S. A. 116, 9919–9924. https://doi.org/10.1073/pnas.1818081116.

Bradshaw, W.E., Holzapfel, C.M., 2007. Evolution of animal photoperiodism. Annu. Rev. Ecol. Evol. Syst. 38, 1–25. https://doi.org/10.1146/annurev.ecolsys.37.091305.110115.

Breeggemann, J.J., Kaemingk, M.A., DeBates, T.J., Paukert, C.P., Krause, J.R., Letvin, A.P., Stevens, T.M., Willis, D.W., Chipps, S.R., 2016. Potential direct and indirect effects of climate change on a shallow natural lake fish assemblage. Ecol. Freshw. Fish 25, 487–499. https://doi.org/10.1111/eff.12248.

Burgiel, S.W., Hall, T., Adams, N., Anderson, K., Bella, E., Bierwagen, B., Boroja, M., Brusati, E., Burgett, J., Carlisle, L., Cleary, R., Cleland, D., Darling, J., Draheim, R., Forest, D., Grise-Stahlman, S., Hart, S., Hatch, K., Heimowitz, P., Hoffman, J., Holcombe, T., Johnson, D., Lassuy, D., McMartin, L., Moy, P., Muir, A., Nelson, R., Pederson, J., Plumb, G., Quinn, J., Resnick, J., Savignano, D., Schmal, N., Shaw, L., Stein, B., Winter, G., Woodson, D., Wooten, D., Wullschleger, J., 2014. Bioinvasions in a Changing World : A Resource on Invasive Species-climate Change Interactions for Conservation and Natural Resource Management. The Aquatic Nuisance Species Task Force (ANSTF) and The National Invasive Species Council (NISC).

Burrows, M.T., Schoeman, D.S., Buckley, L.B., Moore, P., Poloczanska, E.S., Brander, K.M., Brown, C., Bruno, J.F., Duarte, C.M., Halpern, B.S., Holding, J., Kappel, C.V., Kiessling, W., O'Connor, M.I., Pandolfi, J.M., Parmesan, C., Schwing, F.B., Sydeman, W.J., Richardson, A.J., 2011. The pace of shifting climate in marine and terrestrial ecosystems. Science (80-.) 334, 652–655. https://doi.org/10.1126/science.1210288.

Busch, D.S., Griffis, R., Link, J., Abrams, K., Baker, J., Brainard, R.E., Ford, M., Hare, J.A., Himes-Cornell, A., Hollowed, A., Mantua, N.J., McClatchie, S., McClure, M., Nelson, M.W., Osgood, K., Peterson, J.O., Rust, M., Saba, V., Sigler, M.F., Sykora-Bodie, S., Toole, C., Thunberg, E., Waples, R.S., Merrick, R., 2016. Climate science strategy of the US National Marine Fisheries Service. Mar. Policy 74, 58–67. https://doi.org/10.1016/j.marpol.2016.09.001.

Butry, D.T., Prestemon, J.P., Abt, K.L., Sutphen, R., 2010. Economic optimisation of wildfire intervention activities. Int. J. Wildl. Fire 19, 659–672. https://doi.org/10.1071/WF09090.

Cal Fire, 2018. Over 129 Million Dead Trees in California Between 2010–2017 [Story Map] [WWW Document].

Campbell, E.Y., Dunham, J.B., Reeves, G.H., Wondzell, S.M., 2019. Phenology of hatching, emergence, and end-of-season body size in young-of-year coho salmon in thermally contrasting streams draining the Copper River Delta, Alaska. Can. J. Fish. Aquat. Sci. 76, 185–191. https://doi.org/10.1139/cjfas-2018-0003.

Campbell, J.E., Berry, J.A., Seibt, U., Smith, S.J., Montzka, S.A., Launois, T., Belviso, S., Bopp, L., Laine, M., 2017. Large historical growth in global terrestrial gross primary production. Nature 544, 84–87. https://doi.org/10.1038/nature22030.

Campbell, J.L., Rustad, L.E., Boyer, E.W., Christopher, S.F., Driscoll, C.T., Fernandez, I.J., Groffman, P.M., Houle, D., Kiekbusch, J., Magill, A.H., Mitchell, M.J., Ollinger, S.V., 2009. Consequences of climate change for biogeochemical cycling in forests of northeastern North America. Can. J. For. Res. 39, 264–284. https://doi.org/10.1139/X08-104.

Cannizzo, Z.J., Griffen, B.D., 2016. Changes in spatial behaviour patterns by mangrove tree crabs following climate-induced range shift into novel habitat. Anim. Behav. 121, 79–86. https://doi.org/10.1016/j.anbehav.2016.08.025.

Carey, M.P., Sanderson, B.L., Barnas, K.A., Olden, J.D., 2012. Native invaders - challenges for science, management, policy, and society. Front. Ecol. Environ. 10, 373–381. https://doi.org/10.1890/110060.

Carlson, S.M., Cunningham, C.J., Westley, P.A.H., 2014. Evolutionary rescue in a changing world. Trends Ecol. Evol. 29, 521–530. https://doi.org/10.1016/j.tree.2014.06.005.

Charmantier, A., Gienapp, P., 2014. Climate change and timing of avian breeding and migration: evolutionary versus plastic changes. Evol. Appl. 7, 15–28. https://doi.org/10.1111/eva.12126.

Chen, I.-C., Hill, J.K., Ohlemüller, R., Roy, D.B., Thomas, C.D., 2011. Rapid range shifts of species of climate warming. Science (80-.). 333, 1024–1026.

Cheung, W.W.L., Sarmiento, J.L., Dunne, J., Frölicher, T.L., Lam, V.W.Y., Palomares, M.L.D., Watson, R., Pauly, D., 2013. Shrinking of fishes exacerbates impacts of global ocean changes on marine ecosystems. Nat. Clim. Chang. 3, 254–258. https://doi.org/10.1038/nclimate1691.

Cheung, W.W.L., Brodeur, R.D., Okey, T.A., Pauly, D., 2015. Projecting future changes in distributions of pelagic fish species of Northeast Pacific shelf seas. Prog. Oceanogr. 130, 19–31. https://doi.org/10.1016/j.pocean.2014.09.003.

Chmura, H.E., Kharouba, H.M., Ashander, J., Ehlman, S.M., Rivest, E.B., Yang, L.H., 2019. The mechanisms of phenology: the patterns and processes of phenological shifts. Ecol. Monogr. 89, 1–22. https://doi.org/10.1002/ecm.1337.

Choat, B., Jansen, S., Brodribb, T.J., Cochard, H., Delzon, S., Bhaskar, R., Bucci, S.J., Feild, T.S., Gleason, S.M., Hacke, U.G., Jacobsen, A.L., Lens, F., Maherali, H., Martínez-Vilalta, J., Mayr, S., Mencuccini, M., Mitchell, P.J., Nardini, A., Pittermann, J., Pratt, R.B., Sperry, J.S., Westoby, M., Wright, I.J., Zanne, A.E., 2012. Global convergence in the vulnerability of forests to drought. Nature 491, 752–755. https://doi.org/10.1038/nature11688.

Chust, G., Allen, J.I., Bopp, L., Schrum, C., Holt, J., Tsiaras, K., Zavatarelli, M., Chifflet, M., Cannaby, H., Dadou, I., Daewel, U., Wakelin, S.L., Machu, E., Pushpadas, D., Butenschon, M., Artioli, Y., Petihakis, G., Smith, C., Garçon, V., Goubanova, K., Le Vu, B., Fach, B.A., Salihoglu, B., Clementi, E., Irigoien, X., 2014. Biomass changes and trophic amplification of plankton in a warmer ocean. Glob. Chang. Biol. 20, 2124–2139. https://doi.org/10.1111/gcb.12562.

Clark, J.S., Iverson, L., Woodall, C.W., Allen, C.D., Bell, D.M., Bragg, D.C., D'Amato, A.W., Davis, F.W., Hersh, M.H., Ibanez, I., Jackson, S.T., Matthews, S., Pederson, N., Peters, M., Schwartz, M.W., Waring, K.M., Zimmermann, N.E., 2016. The impacts of increasing drought on forest dynamics, structure, and biodiversity in the United States. Glob. Chang. Biol. 22, 2329–2352. https://doi.org/10.1111/gcb.13160.

Cobb, A.N., Thompson, J.L., 2012. Climate change scenario planning: a model for the integration of science and management in environmental decision-making. Environ. Model. Softw. 38, 296–305. https://doi.org/10.1016/j.envsoft.2012.06.012.

Cohen, J.M., Lajeunesse, M.J., Rohr, J.R., 2018. A global synthesis of animal phenological responses to climate change. Nat. Clim. Chang. 8, 224–228. https://doi.org/10.1038/s41558-018-0067-3.

Colombi, B.J., 2012. Salmon and the adaptive capacity of Nimiipuu (Nez Perce) culture to cope with change. Am. Indian Q. 36, 75. https://doi.org/10.5250/amerindiquar.36.1.0075.

Conover, D.O., Duffy, T.A., Hice, L.A., 2009. The covariance between genetic and environmental influences across ecological gradients: reassessing the evolutionary significance of countergradient and cogradient variation. Ann. N. Y. Acad. Sci. https://doi.org/10.1111/j.1749-6632.2009.04575.x.

Corvalan, C., Hales, S., McMichael, A., Butler, C., Campbell-Lendrum, D., Confalonieri, U., Leitner, K., Lewis, N., Patz, J., Polson, K., Scheraga, J., Woodward, A., Younes, Maged, 2005. Ecosystems and Human Well-being: Health Synthesis, a Report of the Millennium Ecosystem Assessment.

Coulston, J.W., Wear, D.N., Vose, J.M., 2015. Complex forest dynamics indicate potential for slowing carbon accumulation in the southeastern United States. Sci. Rep. 5, 1–6. https://doi.org/10.1038/srep08002.

Crimmins, S.M., Dobrowski, S.Z., Greenberg, J. a, Abatzoglou, J.T., Mynsberge, A.R., 2011. Changes in climatic water balance drive downhill shifts in plant species' optimum elevations. Science 331, 324–327. https://doi.org/10.1126/science.1199040.

Crowther, T.W., Boddy, L., Jones, T.H., 2011. Outcomes of fungal interactions are determined by soil invertebrate grazers. Ecol. Lett. 14, 1134–1142. https://doi.org/10.1111/j.1461-0248.2011.01682.x.

Crozier, L.G., Hutchings, J.A., 2013. Plastic and Evolutionary Responses to Climate Change in Fish. https://doi.org/10.1111/eva.12135.

Crozier, L.G., Hendry, A.P., Lawson, P.W., Quinn, T.P., Mantua, N.J., Battin, J., Shaw, R.G., Huey, R.B., 2008. Potential responses to climate change in organisms with complex life histories: evolution and plasticity in Pacific salmon. Evol. Appl. 1, 252–270. https://doi.org/10.1111/j.1752-4571.2008.00033.x.

Crozier, L.G., Scheuerell, M.D., Zabel, R.W., 2011. Using time series analysis to characterize evolutionary and plastic responses to environmental change: a case study of a shift toward earlier migration date in sockeye salmon. Am. Nat. 178, 755–773. https://doi.org/10.1086/662669.

Crozier, L.G., McClure, M.M., Beechie, T., Bograd, S.J., Boughton, D.A., Carr, M., Cooney, T.D., Dunham, J.B., Greene, C.M., Haltuch, M.A., Hazen, E.L., Holzer, D.M., Huff, D.D., Johnson, R.C., Jordan, C.E., Kaplan, I.C., Lindley, S.T., Mantua, N.J., Moyle, P.B., Myers, J.M., Nelson, M.W., Spence, B.C., Weitkamp, L.A., Williams, T.H., Willis-Norton, E., 2019. Climate vulnerability assessment for Pacific salmon and steelhead in the California Current Large Marine Ecosystem. PLoS One https://doi.org/10.1371/journal.pone.0217711.

Daly, E.A., Brodeur, R.D., 2015. Warming ocean conditions relate to increased trophic requirements of threatened and endangered salmon. PLoS One 10, 1–23. https://doi.org/10.1371/journal.pone.0144066.

Davidson, E.A., Janssens, I.A., 2006. Temperature sensitivity of soil carbon decomposition and feedbacks to climate change. Nature 440, 165–173. https://doi.org/10.1038/nature04514.

Davis, C.L., Miller, D.A.W., Walls, S.C., Barichivich, W.J., Riley, J.W., Brown, M.E., 2017. Species interactions and the effects of climate variability on a wetland amphibian metacommunity. Ecol. Appl. 27, 285–296. https://doi.org/10.1002/eap.1442.

Davis, J.L., Currin, C.A., O'Brien, C., Raffenburg, C., Davis, A., 2015. Living shorelines: coastal resilience with a blue carbon benefit. PLoS One 10, 1–18. https://doi.org/10.1371/journal.pone.0142595.

De Chavez, R., Tauli-Corpuz, V., 2009. Guide on Climate Change and Indigenous Peoples. Tebtebba Foundation, Baguio City, Philippines.

De Meester, L., Stoks, R., Brans, K.I., 2018. Genetic adaptation as a biological buffer against climate change: potential and limitations. Integr. Zool. 13, 372–391. https://doi.org/10.1111/1749-4877.12298.

Deacy, W.W., Armstrong, J.B., Leacock, W.B., Robbins, C.T., Gustine, D.D., Ward, E.J., Erlenbach, J.A., Stanford, J.A., 2017. Phenological synchronization disrupts trophic interactions between Kodiak brown bears and salmon. Proc. Natl. Acad. Sci. 114, 10432–10437.

DeGregorio, B.A., Westervelt, J.D., Weatherhead, P.J., Sperry, J.H., 2015. Indirect effect of climate change: shifts in ratsnake behavior alter intensity and timing of avian nest predation. Ecol. Model. 312, 239–246. https://doi.org/10.1016/j.ecolmodel.2015.05.031.

Delach, A., Caldas, A., Edson, K.M., Krehbiel, R., Murray, S., Theoharides, K.A., Vorhees, L.J., Malcom, J.W., Salvo, M.N., Miller, J.R.B., 2019. Agency plans are inadequate to conserve US endangered species under climate change. Nat. Clim. Chang. 9, 999–1004. https://doi.org/10.1038/s41558-019-0620-8.

Dell, A.I., Pawar, S., Savage, V.M., 2014. Temperature dependence of trophic interactions are driven by asymmetry of species responses and foraging strategy. J. Anim. Ecol. 83, 70–84. https://doi.org/10.1111/1365-2656.12081.

Dennison, P.E., Brewer, S.C., Arnold, J.D., Moritz, M.A., 2014. Large wildfire trends in the western United States, 1984–201. Geophys. Prospect. 41, 2928–2933. https://doi.org/10.1002/2014GL061184.Received.

Díaz, S., Settele, J., Brondízio, E., Ngo, H.T., Guèze, M., Agard Trinidad, J., Arneth, A., Balvanera, P., Brauman, K., Butchart, S., Chan, K., Garibaldi, L., Ichii, K., Liu, J., Subramanian, S.M., Midgley, G., Miloslavich, P., Molnar, Z., Obura, D., Pfaff, A., Polasky, S., Purvis, A., Razzaque, J., Reyers, B., Chowdhury, R.R., Shin, Y.-J., Visseren-Hamakers, I., Willis, K., Zayas, C., 2019. Summary for Policymakers of the Global Assessment Report on Biodiversity and Ecosystem Services of the Intergovernmental Science-policy Platform on Biodiversity and Ecosystem Services. Secretariat of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services, Bonn, Germany.

Dijkstra, J.A., Lambert, W.J., Harris, L.G., 2013. Introduced species provide a novel temporal resource that facilitates native predator population growth. Biol. Invasions 15, 911–919. https://doi.org/10.1007/s10530-012-0339-1.

Dodgen, D., Donato, D., Kelly, N., La Greca, A., Morganstein, J., Reser, J., Ruzek, J., Schweitzer, S., Shimamoto, M.M., Tart, K.T., Ursano, R., 2016. Ch. 8: mental health and well-being. He Impacts of Climate Change on Human Health in the United States: A Scientific Assessment. U.S. Global Change Research Program, Washington, D.C., USA, pp. 217–246.

Domke, G., Williams, C.A., Birdsey, R., Coulston, J., Finzi, A., Gough, C., Haight, B., Hicke, J., Janowiak, M., Jong, B. de, Kurz, W.A., Lucash, M., Ogle, S., Olguín-Álvarez, M., Pan, Y., Skutsch, M., Smyth, C., Swanston, C., Templer, P., Wear, D., Woodall, C.W., 2018. Forests. In: Cavallaro, N., Shrestha, G., Birdsey, R., Mayes, M.A., Najjar, R.G., Reed, S.C., Romero-Lankao, P., Zhu, Z. (Eds.), Second State of the Carbon Cycle Report (SOCCR2). U.S. Global Change Research Program, Washington, D.C., USA.

Donatuto, J., Grossman, E.E., Konovsky, J., Grossman, S., Campbell, L.W., 2014. Indigenous community health and climate change: integrating biophysical and social science indicators. Coast. Manag. 42, 355–373. https://doi.org/10.1080/08920753.2014.923140.

Dunn, P.O., Møller, A.P., 2014. Changes in breeding phenology and population size of birds. J. Anim. Ecol. 83, 729–739. https://doi.org/10.1111/1365-2656.12162.

Eakin, C.M., Sweatman, H.P.A., Brainard, R.E., 2019. The 2014–2017 global-scale coral bleaching event: insights and impacts. Coral Reefs 38, 539–545. https://doi.org/10.1007/s00338-019-01844-2.

Eastman, L.M., Morelli, T.L., Rowe, K.C., Conroy, C.J., Moritz, C., 2012. Size increase in high elevation ground squirrels over the last century. Glob. Chang. Biol. 18, 1499–1508. https://doi.org/10.1111/j.1365-2486.2012.02644.x.

Ebi, K.L., Nealon, J., 2016. Dengue in a changing climate. Environ. Res. 151, 115–123. https://doi.org/10.1016/j.envres.2016.07.026.

Elsen, P.R., Tingley, M.W., 2015. Global mountain topography and the fate of montane species under climate change. Nat. Clim. Chang. 5, 5–10. https://doi.org/10.1038/nclimate2656.

Elsner, J.B., Kossin, J.P., Jagger, T.H., 2008. The increasing intensity of the strongest tropical cyclones. Nature 455, 92–95. https://doi.org/10.1038/nature07234.

EPA, 2017. Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990–2015, EPA 430-P-17-001. Washington, D.C. https://doi.org/10.6009/jjrt.2015_JSRT_71.10.1027.

Epstein, G., Smale, D.A., 2017. Undaria Pinnatifida : A Case Study to Highlight Challenges in Marine Invasion Ecology and Management. , pp. 8624–8642. https://doi.org/10.1002/ece3.3430.

Estrada, A., Morales-Castilla, I., Caplat, P., Early, R., 2016. Usefulness of species traits in predicting range shifts. Trends Ecol. Evol. 31, 190–203. https://doi.org/10.1016/j.tree.2015.12.014.

Ewald, N.C., Hartley, S.E., Stewart, A.J.A., 2013. Climate change and trophic interactions in model temporary pond systems: the effects of high temperature on predation rate depend on prey size and density. Freshw. Biol. 58, 2481–2493. https://doi.org/10.1111/fwb.12224.

Executive Office of the President of the United States, 2015. M-16-01: Incorporating Ecosystem Services Into Federal Decision Making.

Fair, J., Hunt, L., 2015. Headwater Meadow Restoration in the Sierra Nevada: Adapting to Climate Change [WWW Document]. Clim. Chang. Resour, Cent.

Ferrario, F., Beck, M.W., Storlazzi, C.D., Micheli, F., Shepard, C.C., Airoldi, L., 2014. The effectiveness of coral reefs for coastal hazard risk reduction and adaptation. Nat. Commun. 5, 1–9. https://doi.org/10.1038/ncomms4794.

Field, J.C., Elliger, C., Baltz, K., Gillespie, G.E., Gilly, W.F., Ruiz-Cooley, R.I., Pearse, D., Stewart, J.S., Matsubu, W., Walker, W.A., 2013. Foraging ecology and movement patterns of jumbo squid (Dosidicus gigas) in the California Current System. Deep. Res. Part II Top. Stud. Oceanogr. 95, 37–51. https://doi.org/10.1016/j.dsr2.2012.09.006.

Fischer, J., Lindenmayer, D.B., Manning, A.D., 2006. Biodiversity , Ecosystem Function , and Resilience : Ten Guiding Principles for Commodity Production Landscapes.

Foden, W.B., Young, B.E., 2016. IUCN SSC Guidelines for Assessing Species' Vulnerability to Climate Change. Cambridge, England and Gland, Switzerland. https://doi.org/10.1038/scientificamerican0315-S1.

Foster, J.R., D'Amato, A.W., 2015. Montane forest ecotones moved downslope in northeastern USA in spite of warming between 1984 and 2011. Glob. Chang. Biol. 21, 4497–4507. https://doi.org/10.1111/gcb.13046.

Fox, R.J., Donelson, J.M., Schunter, C., Ravasi, T., Gaitán-Espitia, J.D., 2019. Beyond buying time: the role of plasticity in phenotypic adaptation to rapid environmental change. Philos. Trans. R. Soc. B Biol. Sci. 374. https://doi.org/10.1098/rstb.2018.0174.

Franks, S.J., Weber, J.J., Aitken, S.N., 2014. Evolutionary and plastic responses to climate change in terrestrial plant populations. Evol. Appl. 7, 123–139. https://doi.org/10.1111/eva.12112.

Fu, Y.H., Zhao, H., Piao, S., Peaucelle, M., Peng, S., Zhou, G., Ciais, P., Song, Y., Vitasse, Y., Zeng, Z., Janssens, I. a, Huang, M., Menzel, A., Pen, J., 2015. Declining global warming effects on the phenology of spring leaf unfolding. Nature 526, 104–107. https://doi.org/10.1038/nature15402.

Galloway, J.N., Townsend, A.R., Erisman, J.W., Bekunda, M., Cai, Z., Freney, J.R., Martinelli, L. a, Seitzinger, S.P., Sutton, M. a, 2008. Transformation of the nitrogen cycle: recent trends, questions, adn potential solutions. Science (80-.) 320, 889–892.

García Molinos, J., Halpern, B.S.S., Schoeman, D.S.S., Brown, C.J.J., Kiessling, W., Moore, P.J.J., Pandolfi, J.M.M., Poloczanska, E.S.S., Richardson, A.J.J., Burrows, M.T.T., García Molinos, J., Halpern, B.S.S., Schoeman, D.S.S., Brown, C.J.J., Kiessling, W., Moore, P.J.J., Pandolfi, J.M.M., Poloczanska, E.S.S., Richardson, A.J.J., Burrows, M.T.T., 2015. Climate velocity and the future global redistribution of marine biodiversity. Nat. Clim. Chang. 6, 4–11. https://doi.org/10.1038/nclimate2769.

Gardner, J.L., Peters, A., Kearney, M.R., Joseph, L., Heinsohn, R., 2011. Declining body size: a third universal response to warming? Trends Ecol. Evol. 26, 285–291. https://doi.org/10.1016/j.tree.2011.03.005.

Gergel, D.R., Nijssen, B., Abatzoglou, J.T., Lettenmaier, D.P., Stumbaugh, M.R., 2017. Effects of climate change on snowpack and fire potential in the western USA. Clim. Chang. 141, 287–299. https://doi.org/10.1007/s10584-017-1899-y.

Ghalambor, C.K., McKay, J.K., Carroll, S.P., Reznick, D.N., 2007. Adaptive versus nonadaptive phenotypic plasticity and the potential for contemporary adaptation in new environments. Funct. Ecol. 21, 394–407. https://doi.org/10.1111/j.1365-2435.2007.01283.x.

Giakoumi, S., Katsanevakis, S., Albano, P.G., Azzurro, E., Cardoso, A.C., Cebrian, E., Deidun, A., Edelist, D., Francour, P., Jimenez, C., Mačić, V., Occhipinti-Ambrogi, A., Rilov, G., Sghaier, Y.R., 2019. Management priorities for marine invasive species. Sci. Total Environ. 688, 976–982. https://doi.org/10.1016/j.scitotenv.2019.06.282.

Gittman, R.K., Popowich, A.M., Bruno, J.F., Peterson, C.H., 2014. Marshes with and without sills protect estuarine shorelines from erosion better than bulkheads during a category 1 hurricane. Ocean Coast. Manag. 102, 94–102. https://doi.org/10.1016/j.ocecoaman.2014.09.016.

Glick, P., Stein, B.A., Edelson, N.A., 2011. Scanning the Conservation Horizon: A Guide to Climate Change Vulnerability Assessment.

Gomulkiewicz, R., Kingsolver, J.G., Carter, P.A., Heckman, N., 2018. Variation and evolution of function-valued traits. Annu. Rev. Ecol. Evol. Syst. 49, 139–164. https://doi.org/10.1146/annurev-ecolsys-110316-022830.

Gowda, P., Steiner, J.L., Olson, C., Boggess, M., Farrigan, T., Grusak, M.A., 2018. Agriculture and rural communities. In: Reidmiller, D.R., Avery, C.W., Easterling, D.R., Kunkel, K.E., Lewis, K.L.M., Maycock, T.K., Stewart, B.C. (Eds.), Impacts, Risks, and Adaptation in the United States: Fourth National Climate Assessment. II. U.S. Global Change Research Program, Washington, D.C., USA, pp. 391–437.

Graven, H.D., Keeling, R.F., Piper, S.C., Patra, P.K., Stephens, B.B., Wofsy, S.C., Santoni, G.W., Bent, J.D., 2013. Enhanced Seasonal Exchange of CO 2 by Northern Ecosystems Since 1960. 146 pp. 1085–1090.

Gregory, R., Failing, L., Harstone, M., Long, G., McDaniels, T., Ohlson, D., 2012. Structuring environmental management choices. Structured Decision Making: A Practical Guide to Environmental Management Choices. John Wiley & Sons, Ltd, Chichester, UK.

Grenier, S., Barre, P., Litrico, I., 2016. Phenotypic plasticity and selection: nonexclusive mechanisms of adaptation. Scientifica (Cairo) 2016. https://doi.org/10.1155/2016/7021701.

Grosholz, E.D., Ruiz, G.M., Dean, C.A., Shirley, K.A., Maron, J.L., Connors, P.G., 2000. The impacts of a nonindigenous marine predator in a California bay. Ecology 81, 1206–1224. https://doi.org/10.1890/0012-9658(2000)081[1206:TIOANM]2.0.CO;2.

Grossman, Z., Parker, A., 2012. Asserting Native Resilience: Pacific Rim Indigenous Nations Face the Climate Crisis. Oregan State University Press.

Guo, F., Lenoir, J., Bonebrake, T.C., 2018. Land-use change interacts with climate to determine elevational species redistribution. Nat. Commun. 9, 1–7. https://doi.org/10.1038/s41467-018-03786-9.

Hannah, L., Flint, L., Syphard, A.D., Moritz, M.A., Buckley, L.B., McCullough, I.M., 2014. Fine-grain modeling of species' response to climate change: holdouts, stepping-stones, and microrefugia. Trends Ecol. Evol. 29, 390–397. https://doi.org/10.1016/j.tree.2014.04.006.

Hare, J.A., Borggaard, D.L., Friedland, K.D., Anderson, J., Burns, P., Chu, K., Clay, P.M., Collins, M.J., Cooper, P., Fratantoni, P.S., Johnson, M.R., Manderson, J.P., Milke, L., Miller, T.J., Orphanides, C.D., Saba, V.S., 2016a. Northeast Regional Action Plan - NOAA Fisheries Climate Science Strategy.

Hare, J.A., Morrison, W.E., Nelson, M.W., Stachura, M.M., Teeters, E.J., Griffis, R.B., Alexander, M.A., Scott, J.D., Alade, L., Bell, R.J., Chute, A.S., Curti, K.L., Curtis, T.H., Kircheis, D., Kocik, J.F., Lucey, S.M., McCandless, C.T., Milke, L.M., Richardson, D.E., Robillard, E., Walsh, H.J., McManus, M.C., Marancik, K.E., Griswold, C.A., 2016b. A vulnerability assessment of fish and invertebrates to climate change on the northeast U.S. continental shelf. PLoS One 11, 1–30. https://doi.org/10.1371/journal.pone.0146756.

Harrisson, K.A., Pavlova, A., Telonis-Scott, M., Sunnucks, P., 2014. Using genomics to characterize evolutionary potential for conservation of wild populations. Evol. Appl. 7, 1008–1025. https://doi.org/10.1111/eva.12149.

Hember, R.A., Kurz, W.A., Coops, N.C., 2017. Relationships between individual-tree mortality and water-balance variables indicate positive trends in water stress-induced tree mortality across North America. Glob. Chang. Biol. 23, 1691–1710. https://doi.org/10.1111/gcb.13428.

Hendry, A.P., 2017. Eco-evolutionary Dynamics. Princeton University Press, Princeton, NJ.

Hendry, A.P., Kinnison, M.T., Heino, M., Day, T., Smith, T.B., Fitt, G., Bergstrom, C.T., Oakeshott, J., Jørgensen, P.S., Zalucki, M.P., Gilchrist, G., Southerton, S., Sih, A., Strauss, S., Denison, R.F., Carroll, S.P., 2011. Evolutionary principles and their practical application. Evol. Appl. 4, 159–183. https://doi.org/10.1111/j.1752-4571.2010.00165.x.

Herstoff, E., Urban, M.C., 2014. Will pre-adaptation buffer the impacts of climate change on novel species interactions? Ecography (Cop.) 37, 111–119. https://doi.org/10.1111/j.1600-0587.2013.00116.x.

Hilborn, E.D., Beasley, V.R., 2015. One health and cyanobacteria in freshwater systems: animal illnesses and deaths are sentinel events for human health risks. Toxins (Basel) 7, 1374–1395. https://doi.org/10.3390/toxins7041374.

Hobbs, R.J., Higgs, E., Harris, J.A., 2009. Novel ecosystems: implications for conservation and restoration. Trends Ecol. Evol. 24, 599–605. https://doi.org/10.1016/j.tree.2009.05.012.

Hobday, A.J., Alexander, L.V., Perkins, S.E., Smale, D.A., Straub, S.C., Oliver, E.C.J., Benthuysen, J.A., Burrows, M.T., Donat, M.G., Feng, M., Holbrook, N.J., Moore, P.J., Scannell, H.A., Sen Gupta, A., Wernberg, T., 2016. A hierarchical approach to defining marine heatwaves. Prog. Oceanogr. 141, 227–238. https://doi.org/10.1016/j.pocean.2015.12.014.

Hobday, A.J., Oliver, E.C.J., Gupta, A. Sen, Benthuysen, J.A., Burrows, M.T., Donat, M.G., Holbrook, N.J., Moore, P.J., Thomsen, M.S., Wernberg, T., Smale, D.A., 2018. Categorizing and naming marine heatwaves. Oceanography 31, 162–173. https://doi.org/10.5670/oceanog.2018.205.

Hobday, A.J., Hartog, J.R., Manderson, J.P., Mills, K.E., Oliver, M.J., Pershing, A.J., Siedlecki, S., 2019. Ethical considerations and unanticipated consequences associated with ecological forecasting for marine resources. ICES J. Mar. Sci. https://doi.org/10.1093/icesjms/fsy210.

Holden, Z.A., Swanson, A., Luce, C.H., Jolly, W.M., Maneta, M., Oyler, J.W., Warren, D.A., Parsons, R., Affleck, D., 2018. Decreasing fire season precipitation increased recent western US forest wildfire activity. Proc. Natl. Acad. Sci. U. S. A. 115, E8349–E8357. https://doi.org/10.1073/pnas.1802316115.

Holsman, K.K., Hazen, E.L., Haynie, A., Gourguet, S., Hollowed, A., Bograd, S.J., Samhouri, J.F., Aydin, K., 2019. Towards climate resiliency in fisheries management. ICES J. Mar. Sci. https://doi.org/10.1093/icesjms/fsz031.

Houser, S., Teller, V., MacCracken, M., Gough, R., Spears, P., 2001. Potential consequences of climate variability and change for native peoples and homelands. Climate Change Impacts on the United States. U.S. Global Change Research Program, Washington, D.C., USA.

Howard, J., Sutton-Grier, A., Herr, D., Kleypas, J., Landis, E., Mcleod, E., Pidgeon, E., Simpson, S., 2017. Clarifying the role of coastal and marine systems in climate mitigation. Front. Ecol. Environ. 15, 42–50. https://doi.org/10.1002/fee.1451.

Huntington, T.G., Hodgkins, G.A., Dudley, R.W., 2003. Historical trend in river ice thickness and coherence in hydroclimatological trends in Maine. Clim. Chang. 61, 217–236. https://doi.org/10.1023/A:1026360615401.

Invasive Species Advisory Committee, 2017. Managed Relocation : Reducing the Risk of Biological Invasion. pp. 1–6.

IPCC, 2013. Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Isaac-Renton, M.G., Roberts, D.R., Hamann, A., Spiecker, H., 2014. Douglas-fir plantations in Europe: a retrospective test of assisted migration to address climate change. Glob. Chang. Biol. 20, 2607–2617. https://doi.org/10.1111/gcb.12604.

Isaak, D.J., Wollrab, S., Horan, D., Chandler, G., 2012. Climate change effects on stream and river temperatures across the northwest U.S. from 1980-2009 and implications for salmonid fishes. Clim. Chang. 113, 499–524. https://doi.org/10.1007/s10584-011-0326-z.

Jacox, M.G., Alexander, M.A., Stock, C.A., Hervieux, G., 2017. On the skill of seasonal sea surface temperature forecasts in the California Current System and its connection to ENSO variability. Clim. Dyn. 0, 1–15. https://doi.org/10.1007/s00382-017-3608-y.

Jantarasami, L.C., Novak, R., Delgado, R., Marino, E., McNeeley, S., Narducci, C., Raymond-Yakoubian, J., Singletary, L., Whyte, K.P., 2018. Tribes and indigenous Peoples. In: Reidmiller, D.R., Avery, C.W., Easterling, D.R., Kunkel, K.E., Lewis, K.L.M., Maycock, T.K., Stewart, B.C. (Eds.), Impacts, Risks, and Adaptation in the United States: Fourth National Climate Assessment, Volume II. U.S. Global Change Research Program, Washington, D.C., USA.

Jay, A., Reidmiller, D.R., Avery, C.W., Barrie, D., DeAngelo, B.J., Dave, A., Dzaugis, M., Kolian, M., Lewis, K.L.M., Reeves, K., Winner, D., 2018. Overview. In: Reidmiller, D.R., Avery, C.W., Easterling, D.R., Kunkel, K.E., Lewis, K.L.M., Maycock, T.K., Stewart, B.C. (Eds.), Impacts, Risks, and Adaptation in the United States: Fourth National Climate Assessment. II. U.S. Global Change Research Program, Washington, D.C., USA, pp. 33–71.

Jeremias, G., Barbosa, J., Marques, S.M., Asselman, J., Gonçalves, F.J.M., Pereira, J.L., 2018. Synthesizing the role of epigenetics in the response and adaptation of species to climate change in freshwater ecosystems. Mol. Ecol. 27, 2790–2806. https://doi.org/10.1111/mec.14727.

Juanes, F., Gephard, S., Beland, K.F., 2004. Long-term changes in migration timing of adult Atlantic salmon (Salmo salar) at the southern edge of the species distribution. Can. J. Fish. Aquat. Sci. 61, 2392–2400. https://doi.org/10.1139/f04-207.

Jurgens, L.J., Gaylord, B., 2018. Physical effects of habitat-forming species override latitudinal trends in temperature. Ecol. Lett. 21, 190–196. https://doi.org/10.1111/ele.12881.

Katsanevakis, S., Wallentinus, I., Zenetos, A., Leppäkoski, E., Çinar, M.E., 2014. Impacts of invasive alien marine species on ecosystem services and biodiversity: a pan-European review. Acquat. Invasions 9, 391–423. https://doi.org/10.3391/ai.2014.9.4.01.

Keane, R.E., Ryan, K.C., Veblen, T.T., Allen, C.D., Logan, J., Hawkes, B., 2002. Cascading effects of fire exclusion in rocky mountain ecosystems: a literature review. USDA For. Serv. - Gen. Tech. Rep. RMRS-GTR 1–27.

Kemp, K.B., Blades, J.J., Klos, P.Z., Hall, T.E., Force, J.E., Morgan, P., Tinkham, W.T., 2015. Managing for climate change on federal lands of the western United States: perceived usefulness of climate science, effectiveness of adaptation strategies, and barriers to implementation. Ecol. Soc. 20. https://doi.org/10.5751/ES-07522-200217.

Keppel, G., Mokany, K., Wardell-Johnson, G.W., Phillips, B.L., Welbergen, J.A., Reside, A.E., 2015. The capacity of refugia for conservation planning under climate change. Front. Ecol. Environ. 13, 106–112. https://doi.org/10.1890/140055.

Kingsolver, J.G., Buckley, L.B., 2017. Quantifying thermal extremes and biological variation to predict evolutionary responses to changing climate. Philos. Trans. R. Soc. B Biol. Sci. 372. https://doi.org/10.1098/rstb.2016.0147.

Kitzberger, T., Falk, D.A., Westerling, A.L., Swetnam, T.W., 2017. Direct and indirect climate controls predict heterogeneous early-mid 21st century wildfire burned area across western and boreal North America. PLoS One 12, 1–24. https://doi.org/10.1371/journal.pone.0188486.

Kleisner, K.M., Fogarty, M.J., McGee, S., Barnett, A., Fratantoni, P., Greene, J., Hare, J.A., Lucey, S.M., McGuire, C., Odell, J., Saba, V.S., Smith, L., Weaver, K.J., Pinsky, M.L., 2016. The effects of sub-regional climate velocity on the distribution and spatial extent of marine species assemblages. PLoS One 11, 1–21. https://doi.org/10.1371/journal.pone.0149220.

Kleisner, K.M., Fogarty, M.J., McGee, S., Hare, J.A., Moret, S., Perretti, C.T., Saba, V.S., 2017. Marine species distribution shifts on the U.S. Northeast Continental Shelf under continued ocean warming. Prog. Oceanogr. 153, 24–36. https://doi.org/10.1016/j.pocean.2017.04.001.

Kopp, M., Matuszewski, S., 2014. Rapid evolution of quantitative traits: theoretical perspectives. Evol. Appl. 7, 169–191. https://doi.org/10.1111/eva.12127.

Kovach, R.P., Dunham, J.B., Al-Chokhachy, R., Snyder, C.D., Letcher, B.H., Young, J.A., Beever, E.A., Pederson, G.T., Lynch, A.J., Hitt, N.P., Konrad, C.P., Jaeger, K.L., Rea, A.H., Sepulveda, A.J., Lambert, P.M., Stoker, J., Giersch, J.J., Muhlfeld, C.C., 2019. An integrated framework for ecological drought across riverscapes of North America. Bioscience 69, 418–431. https://doi.org/10.1093/biosci/biz040.

Krakoff, S., 2008. American Indians, climate change, and ethics for a warming world. Denver Univ. Law Rev. 85, 865–898.

Lam, V.W.Y., Cheung, W.W.L., Reygondeau, G., Rashid Sumaila, U., 2016. Projected change in global fisheries revenues under climate change. Sci. Rep. 6, 6–13. https://doi.org/10.1038/srep32607.

Lany, N.K., Ayres, M.P., Stange, E.E., Sillett, T.S., Rodenhouse, N.L., Holmes, R.T., 2016. Breeding timed to maximize reproductive success for a migratory songbird: the importance of phenological asynchrony. Oikos 125, 656–666. https://doi.org/10.1111/oik.02412.

Latta, G., Temesgen, H., Adams, D., Barrett, T., 2010. Analysis of potential impacts of climate change on forests of the United States Pacific Northwest. For. Ecol. Manag. 259, 720–729. https://doi.org/10.1016/j.foreco.2009.09.003.

Lawrence, D.J., Stewart-Koster, B., Olden, J.D., Ruesch, A.S., Torgersen, C.E., Lawler, J.J., Butcher, D.P., Crown, J.K., 2014. The interactive effects of climate change, riparian management, and a nonnative predator on stream-rearing salmon. Ecol. Appl. 24, 895–912. https://doi.org/10.1890/13-0753.1.

Le Bris, A., Pershing, A.J., Gaudette, J., Pugh, T.L., Reardon, K.M., 2017. Multi-scale quantification of the effects of temperature on size at maturity in the American lobster (Homarus americanus). Fish. Res. 186, 397–406. https://doi.org/10.1016/j.fishres.2016.09.008.

Lefort, S., Aumont, O., Bopp, L., Arsouze, T., Gehlen, M., Maury, O., 2015. Spatial and body-size dependent response of marine pelagic communities to projected global climate change. Glob. Chang. Biol. 21, 154–164. https://doi.org/10.1111/gcb.12679.

Lehikoinen, A., Lindén, A., Karlsson, M., Andersson, A., Crewe, T.L., Dunn, E.H., Gregory, G., Karlsson, L., Kristiansen, V., Mackenzie, S., Newman, S., Røer, J.E., Sharpe, C., Sokolov, L.V., Steinholtz, Å., Stervander, M., Tirri, I.S., Tjørnløv, R.S., 2019. Phenology of the avian spring migratory passage in Europe and North America: asymmetric advancement in time and increase in duration. Ecol. Indic. 101, 985–991. https://doi.org/10.1016/j.ecolind.2019.01.083.

Lembrechts, J.J., Pauchard, A., Lenoir, J., Nuñez, M.A., Geron, C., Ven, A., Bravo-Monasterio, P., Teneb, E., Nijs, I., Milbau, A., 2016. Disturbance is the key to plant invasions in cold environments. Proc. Natl. Acad. Sci. U. S. A. 113, 14061–14066. https://doi.org/10.1073/pnas.1608980113.

Lenoir, J., Svenning, J.C., 2015. Climate-related range shifts - a global multidimensional synthesis and new research directions. Ecography (Cop.) 38, 15–28. https://doi.org/10.1111/ecog.00967.
Li, D., Wrzesien, M.L., Durand, M., Adam, J., Lettenmaier, D.P., 2017. How much runoff originates as snow in the western United States, and how will that change in the future? Geophys. Res. Lett. 44, 6163–6172. https://doi.org/10.1002/2017GL073551.
Link, J., 2016. Ecosystem-based Fisheries Management Policy of the National Marine Fisheries Service. National Oceanic and Atmospheric Administration.
Link, J.S., Griffis, R., Busch, S., 2015. Noaa Fisheries Climate Science Strategy (doi:NOAA Technical Memorandum NMFS-F/SPO-155).
Lipton, D., Rubenstein, M.A., Weiskopf, S.R., Carter, S., Peterson, J., Crozier, L., Fogarty, M., Gaichas, S., Hyde, K.J.W., Morelli, T.L., Morisette, J., Moustahfid, H., Muñoz, R., Poudel, R., Staudinger, M.D., Stock, C., Thompson, L., Waples, R., Weltzin, J.F., 2018. Ecosystems, ecosystem services, and biodiversity. In: Reidmiller, D.R., Avery, C.W., Easterling, D.R., Kunkel, K.E., Lewis, K.L.M., Maycock, T.K., Stewart, B.C. (Eds.), Impacts, Risks, and Adaptation in the United States: Fourth National Climate Assessment, Volume II. U.S. Global Change Research Program, Washington, D.C., USA.
Litschert, S.E., Brown, T.C., Theobald, D.M., 2012. Historic and future extent of wildfires in the Southern Rockies Ecoregion, USA. For. Ecol. Manag. 269, 124–133. https://doi.org/10.1016/j.foreco.2011.12.024.
Littell, J.S., Peterson, D.L., Riley, K.L., Liu, Y., Luce, C.H., 2016. A review of the relationships between drought and forest fire in the United States. Glob. Chang. Biol. 22, 2353–2369. https://doi.org/10.1111/gcb.13275.
Liu, Y., Oduor, A.M.O., Zhang, Z., Manea, A., Tooth, I.M., Leishman, M.R., Xu, X., van Kleunen, M., 2017. Do invasive alien plants benefit more from global environmental change than native plants? Glob. Chang. Biol. 23, 3363–3370. https://doi.org/10.1111/gcb.13579.
Liu, Z., Wimberly, M.C., Lamsal, A., Sohl, T.L., Hawbaker, T.J., 2015. Climate change and wildfire risk in an expanding wildland–urban interface: a case study from the Colorado Front Range Corridor. Landsc. Ecol. 30, 1943–1957. https://doi.org/10.1007/s10980-015-0222-4.
Loehman, R.A., Keane, R.E., Holsinger, L.M., Wu, Z., 2017. Interactions of landscape disturbances and climate change dictate ecological pattern and process: spatial modeling of wildfire, insect, and disease dynamics under future climates. Landsc. Ecol. 32, 1447–1459. https://doi.org/10.1007/s10980-016-0414-6.
Logan, J.A., Powell, J.A., 2009. Ecological consequences of climate change altered forest insect disturbance regimes. In: Wagner, F.H. (Ed.), Climate Change in Western North America: Evidence and Environmental Effects. University of Utah Press, Salt Lake City, Utah, USA, pp. 98–109.
Luce, C., Morgan, P., Dwire, K., Isaak, D., Holden, Z., Rieman, B., 2012. Climate change, forests, fire, water, and fish: building resilient landscapes, streams, and managers. USDA For. Serv. - Gen. Tech. Rep. RMRS-GTR 1–155.
Luce, C.H., Lopez-Burgos, V., Holden, Z., 2014. Sensitivity of snowpack storage to precipitation and temperature using spatial and temporal analog models. Water Resour. Res. 50, 9447–9462. https://doi.org/10.1111/j.1752-1688.1969.tb04897.x.
MacLean, S.A., Beissinger, S.R., 2017. Species' traits as predictors of range shifts under contemporary climate change: a review and meta-analysis. Glob. Chang. Biol. 23, 4094–4105. https://doi.org/10.1111/gcb.13736.
Mahmoud, M., Liu, Y., Hartmann, H., Stewart, S., Wagener, T., Semmens, D., Stewart, R., Gupta, H., Dominguez, D., Dominguez, F., Hulse, D., Letcher, R., Rashleigh, B., Smith, C., Street, R., Ticehurst, J., Twery, M., Delden, H. Van, Waldick, R., White, D., Winter, L., 2009. A formal framework for scenario development in support of environmental decision-making. Environ. Model. Softw. 24, 798–808. https://doi.org/10.1016/j.envsoft.2008.11.010.
Maldonado, J.K., Pandya, R.E., Colombi, B.J., 2013. Climate change and indigenous peoples in the United States: impacts, experiences, and actions. Clim. Chang. 120, 509–682.
Malmstadt, J.C., Elsner, J.B., Jagger, T.H., 2010. Risk of strong hurricane winds to Florida cities. J. Appl. Meteorol. Climatol. 49, 2121–2132. https://doi.org/10.1175/2010JAMC2420.1.
Marcinkowski, K., Peterson, D.L., Ettl, G.J., 2015. Nonstationary temporal response of mountain hemlock growth to climatic variability in the north cascade range, Washington, USA. Can. J. For. Res. 45, 676–688. https://doi.org/10.1139/cjfr-2014-0231.
Maynard, N.G., 1998. Native Peoples-native Homelands Climate Change Workshop: Lessons Learned. Final Report (Washington, D.C., USA).
Mayor, S.J., Guralnick, R.P., Tingley, M.W., Otegui, J., Withey, J.C., Elmendorf, S.C., Andrew, M.E., Leyk, S., Pearse, I.S., Schneider, D.C., 2017. Increasing phenological asynchrony between spring green-up and arrival of migratory birds. Sci. Rep. 7, 1902. https://doi.org/10.1038/s41598-017-02045-z.
McCann, E.L., Johnson, N.S., Pangle, K.L., 2017. Corresponding long-term shifts in stream temperature and invasive fish migration. Can. J. Fish. Aquat. Sci. 778, 1–7. https://doi.org/10.1139/cjfas-2017-0195.
McCluney, K.E., Sabo, J.L., 2016. Animal water balance drives top-down effects in a riparian forest - implications for terrestrial trophic cascades. Proc. R. Soc. B 283, 20160881.
Mcguire, J.L., Lawler, J.J., Mcrae, B.H., Nuñez, T.A., Theobald, D.M., 2016. Achieving Climate Connectivity in a Fragmented Landscape. , p. 113. https://doi.org/10.1073/pnas.1602817113.
McKenzie, D., Littell, J.S., 2017. Climate change and the eco-hydrology of fire: will area burned increase in a warming western USA. Ecol. Appl. 27, 26–36. https://doi.org/10.1002/eap.1420.
Mecklenburg, C.W., TA, M., Sheiko, B.A., Steinke, D., 2016. Pacific Arctic marine fishes. Monitoring Series Report No 23. Conservation of Arctic Flora and Fauna.
Melillo, J.M., Frey, S.D., DeAngelis, K.M., Werner, W.J., Bernard, M.J., Bowles, F.P., Pold, G., Knorr, M.A., Grandy, A.S., 2017. Long-term pattern and magnitude of soil carbon feedback to the climate system in a warming world. Science (80-.) 358, 101–105. https://doi.org/10.1126/science.aan2874.
Merilä, J., 2012. Evolution in response to climate change: in pursuit of the missing evidence. BioEssays 34, 811–818.
Merilä, J., Hendry, A.P., 2014. Climate change, adaptation, and phenotypic plasticity: the problem and the evidence. Evol. Appl. https://doi.org/10.1111/eva.12137.
Millar, C.I., Stephenson, N.L., 2015. Temperate forest health in an era of emerging megadisturbance. Science (80-.) 349, 823–826.
Millennium Ecosystem Assessment, 2005. Ecosystems and Human Well-being: Synthesis. Island Press, Washington, D.C.
Mills, K.E., Pershing, A.J., Brown, C.J., Chen, Y., Chiang, F.-S., Holland, D.S., Lehuta, S., Nye, J.A., Sun, J.C., Thomas, A.C., 2013. Fisheries management in a changing climate: lessons from the 2012 ocean heat wave in the Northwest Atlantic. Oceanography 26, 191–195.
Möller, I., Kudella, M., Rupprecht, F., Spencer, T., Paul, M., Van Wesenbeeck, B.K., Wolters, G., Jensen, K., Bouma, T.J., Miranda-Lange, M., Schimmels, S., 2014. Wave attenuation over coastal salt marshes under storm surge conditions. Nat. Geosci. 7, 727–731. https://doi.org/10.1038/NGEO2251.
Monahan, W.B., Rosemartin, A., Gerst, K.L., Fisichelli, N.A., Ault, T., Schwartz, M.D., Gross, J.E., Weltzin, J.F., 2016. Climate change is advancing spring onset across the U.S. national park system. Ecosphere 7, 1–17. https://doi.org/10.1002/ecs2.1465.
Moore, S.K., Trainer, V.L., Mantua, N.J., Parker, M.S., Laws, E.A., Backer, L.C., Fleming, L.E., 2008. Impacts of climate variability and future climate change on harmful algal blooms and human health. Environ. Heal. A Glob. Access Sci. Source 7, 1–12. https://doi.org/10.1186/1476-069X-7-S2-S4.
Morelli, T.L., Daly, C., Dobrowski, S.Z., Dulen, D.M., Ebersole, J.L., Jackson, S.T., Lundquist, J.D., Millar, C.I., Maher, S.P., Monahan, W.B., Nydick, K.R., Redmond, K.T., Sawyer, S.C., Stock, S., Beissinger, S.R., 2016. Managing climate change refugia for climate adaptation. PLoS One 11, e0159909. https://doi.org/10.1371/journal.pone.0159909.
Morelli, T.L., Maher, S.P., Lim, M.C.W., Kastely, C., Eastman, L.M., Flint, L.E., Flint, A.L., Beissinger, S.R., Moritz, C., 2017. Climate change refugia and habitat connectivity promote species persistence. Clim. Chang. Responses 4, 1–12. https://doi.org/10.1186/s40665-017-0036-5.
Morishima, G., 2014. Climate Change and Indigenous Peoples: A Primer.
Morley, J.W., Batt, R.D., Pinsky, M.L., 2017. Marine assemblages respond rapidly to winter climate variability. Glob. Chang. Biol. 23, 2590–2601. https://doi.org/10.1111/gcb.13578.
Morris, K.A., Deterding, N.M., 2016. The emotional cost of distance: geographic social network dispersion and post-traumatic stress among survivors of Hurricane Katrina. Soc. Sci. Med. 165, 56–65.
National Fish Wildlife and Plants Climate Adaptation Partnership, 2012. National Fish, Wildlife, and Plants Climate Adaptation Strategy (WWW Document).
National Marine Fisheries Service, 2016. National Marine Fisheries Service Procedural Instruction 02-110-18: Guidance for Treatment of Climate Change in NMFS Endangered Species Act Decisions.
National Marine Fisheries Service, 2018. Fisheries Economics of the United States, 2016: Economics and Sociocultural Status and Trends Series. NOAA Tech. Memo. NMFS-F/SPO-187a. https://doi.org/10.1017/CBO9781107415324.004.
National Park Service, 2013. Resource Stewardship Strategy: Catoctin Mountain Park.
National Park System Advisory Board, 2012. Revisiting Leopold : Resource Stewardship in the National Parks.
National Wildlife Federation, 2010. Business Plan SIERRA NEVADA MEADOW.
Niemi, E., Buckley, M., Neculae, C., Reich, S., 2009. An Overview of Potential Economic Costs to Washington of a Business-As-Usual Approach to Climate Change. University of Oregon, Program on Climate Economics of the Climate Leadership Initiative, Eugene, OR.
NOAA Fisheries, 2015. Farmers reroute water for fish: Yakima irrigators use canals to keep streams flowing in drought [WWW document]. NOAA Fish. West Coast Reg.
NOAA Fisheries, 2016. 2015 Adult Sockeye Salmon Passage Report.
Norby, R.J., Hanson, P.J., O'Neill, E.G., Tschaplinski, T.J., Weltzin, J.F., Hansen, R.a., Cheng, W., Wullschleger, S.D., Gunderson, C.a., Edwards, N.T., Johnson, D.W., 2002. Enriched deciduous forest and the implications for carbon storage. Ecol. Appl. 12, 1261–1266. https://doi.org/10.1890/1051-0761(2002)012[1261:NPPOAC]2.0.CO;2.
Norby, R.J., Warren, J.M., Iversen, C.M., Medlyn, B.E., McMurtrie, R.E., 2010. CO 2 enhancement of forest productivity constrained by limited nitrogen availability. Proc. Natl. Acad. Sci. U. S. A. 107, 19368–19373. https://doi.org/10.1073/pnas.1006463107.
Norton-Smith, K., Lynn, K., Chief, K., Cozzetto, K., Donatuto, J., Redsteer, M.H., Kruger, L.E., Maldonado, J., Viles, C., Whyte, K.P., 2016. Climate Change and Indigenous Peoples : A Synthesis of Current Impacts and Experiences. Gen. Tech. Rep. PNW-GTR-944. pp. 1–142.
Novak, M., Wootton, J.T., Doak, D.F., Emmerson, M., Estes, J.A., Tinker, T., 2011. Predicting community responses to perturbations in the face of imperfect knowledge and network complexity. Ecology 92, 836–846.
Obradovich, N., Migliorini, R., Paulus, M.P., Rahwan, I., 2018. Empirical evidence of mental health risks posed by climate change. Proc. Natl. Acad. Sci. U. S. A. 115, 10953–10958. https://doi.org/10.1073/pnas.1801528115.
Ojima, D.S., Iverson, L.R., Sohngen, B.L., Vose, J.M., Woodall, C.W., Domke, G.M., Peterson, D.L., Littell, J.S., Matthews, S.N., Prasad, A.M., Peters, M.P., Yohe, G.W., Friggens, M.M., 2014. Risk assessment. In: Peterson, D.L., Vose, J.M., Patel-Weynand, T. (Eds.), Climate Change and United States Forests. Springer, Dordrecht, The Netherlands, pp. 223–244. https://doi.org/10.1007/978-94-007-7515-2.
Oliver, T.H., Heard, M.S., Isaac, N.J.B., Roy, D.B., Procter, D., Eigenbrod, F., Freckleton, R., Hector, A., Orme, C.D.L., Petchey, O.L., Proença, V., Raffaelli, D., Suttle, K.B., Mace, G.M., Martín-López, B., Woodcock, B.A., Bullock, J.M., 2015. Biodiversity and resilience

of ecosystem functions. Trends Ecol. Evol. 30, 673–684. https://doi.org/10.1016/j.tree.2015.08.009.
Oren, R., Ellsworth, D.S., Johnsen, K.H., Phillips, N., Ewers, B.E., Maier, C., Schäfer, K.V.R., McCarthy, H., Hendrey, G., McNulty, S.G., Katul, G.G., 2001. Soil fertility limits carbon sequestration by forest ecosystems in a CO2-enriched atmosphere. Nature 411, 469–472. https://doi.org/10.1038/35078064.
Oswalt, S.N., Smith, W.B., Miles, P.D., Pugh, S.A., 2014. Update of the 2010 RPA Assessment Forest Resources of the United States. 2012 p. 228.
Ozgul, A., Childs, D.Z., Oli, M.K., Armitage, K.B., Blumstein, D.T., Olson, L.E., Tuljapurkar, S., Coulson, T., 2010. Coupled dynamics of body mass and population growth in response to environmental change. Nature 466, 482–485. https://doi.org/10.1038/nature09210.
Pacifici, M., Visconti, P., Butchart, S.H.M., Watson, J.E.M., Cassola, F.M., Rondinini, C., 2017. Species' traits influenced their response to recent climate change. Nat. Clim. Chang. 7, 205–208. https://doi.org/10.1038/nclimate3223.
Pan, Y., Birdsey, R., Hom, J., McCullough, K., 2009. Separating effects of changes in atmospheric composition, climate and land-use on carbon sequestration of U.S. mid-Atlantic temperate forests. For. Ecol. Manag. 259, 151–164. https://doi.org/10.1016/j.foreco.2009.09.049.
Patricola, C.M., Wehner, M.F., 2018. Anthropogenic influences on major tropical cyclone events. Nature 563, 339–346. https://doi.org/10.1038/s41586-018-0673-2.
Pearson, K.D., 2019. Spring- and fall-flowering species show diverging phenological responses to climate in the Southeast USA. Int. J. Biometeorol. 63, 481–492. https://doi.org/10.1007/s00484-019-01679-0.
Peer, A.C., Miller, T.J., 2014. Climate change, migration phenology, and fisheries management interact with unanticipated consequences. North Am. J. Fish. Manag. 34, 94–110. https://doi.org/10.1080/02755947.2013.847877.
Peers, M.J.L., Wehtje, M., Thornton, D.H., Murray, D.L., 2014. Prey switching as a means of enhancing persistence in predators at the trailing southern edge. Glob. Chang. Biol. 20, 1126–1135. https://doi.org/10.1111/gcb.12469.
Pelletier, F., Coltman, D.W., 2018. Will human influences on evolutionary dynamics in the wild pervade the Anthropocene? BMC Biol. 16, 1–10. https://doi.org/10.1186/s12915-017-0476-1.
Pershing, A.J., Alexander, M.A., Hernandez, C.M., Kerr, L.A., Bris, A. Le, Mills, K.E., Nye, J.A., Record, N.R., Scannell, H.A., Scott, J.D., Sherwood, G.D., Thomas, A.C., 2015. Slow adaptation in the face of rapid warming leads to collapse of the Gulf ofMaine cod fishery. Science (80-.) 350, 350. https://doi.org/10.1126/science.aae0463.
Pershing, A.J., Alexander, M.A., Hernandez, C.M., Kerr, L.A., Bris, A. Le, Mills, K.E., Nye, J.A., Record, N.R., Scannell, H.A., Scott, J.D., Sherwood, G.D., Thomas, A.C., 2016. Response to comments on "slow adaptation in the face of rapid warming leads to collapse of the Gulf of Maine cod fishery". Science (80-.) 352, 423. https://doi.org/10.1126/science.aae0463.
Pershing, A.J., Mills, K.E., Dayton, A.M., Franklin, B.S., Kennedy, B.T., 2018. Evidence for adaptation from the 2016 marine heatwave in the Northwest Atlantic Ocean. Oceanography 31, 152–161. https://doi.org/10.5670/oceanog.2018.213.
Peters, M.P., Iverson, L.R., Matthews, S.N., 2015. Long-term droughtiness and drought tolerance of eastern US forests over five decades. For. Ecol. Manag. 345, 56–64. https://doi.org/10.1016/j.foreco.2015.02.022.
Peterson, D.L., Halofsky, J.E., 2018. Adapting to the effects of climate change on natural resources in the Blue Mountains, USA. Clim. Serv. 10, 63–71. https://doi.org/10.1016/j.cliser.2017.06.005.
Peterson, G.D., Cumming, G.S., Carpenter, S.R., 2003. Scenario planning: a tool for conservation in an uncertain world. Conserv. Biol. 17, 358–366. https://doi.org/10.1046/j.1523-1739.2003.01491.x.
Pinsky, M.L., Mantua, N.J., 2014. Emerging adaptation approaches for climate-ready fisheries management. Oceanography 27, 147–159. https://doi.org/10.5670/oceanog.2014.93.
Pinsky, M.L., Worm, B., Fogarty, M.J., Sarmiento, J.L., Levin, S.A., 2013. Marine taxa track local climate velocities. Science (80-.) 341, 1239–1242.
Pollock, M.M., Beechie, T.J., Wheaton, J.M., Jordan, C.E., Bouwes, N., Weber, N., Volk, C., 2014. Using beaver dams to restore incised stream ecosystems. Bioscience 64, 279–290. https://doi.org/10.1093/biosci/biu036.
Poloczanska, E.S., Brown, C.J., Sydeman, W.J., Kiessling, W., Schoeman, D.S., Moore, P.J., Brander, K., Bruno, J.F., Buckley, L.B., Burrows, M.T., Duarte, C.M., Halpern, B.S., Holding, J., Kappel, C.V., O'Connor, M.I., Pandolfi, J.M., Parmesan, C., Schwing, F., Thompson, S.A., Richardson, A.J., 2013. Global imprint of climate change on marine life. Nat. Clim. Chang. 3, 919–925. https://doi.org/10.1038/Nclimate1958.
Post, E., 2017. Implications of earlier sea ice melt for phenological cascades in arctic marine food webs. Food Webs 13, 60–66. https://doi.org/10.1016/j.fooweb.2016.11.002.
Powell, E.J., Tyrrell, M.C., Milliken, A., Tirpak, J.M., Staudinger, M.D., 2019. A review of coastal management approaches to support the integration of ecological and human community planning for climate change. J. Coast. Conserv. 23. https://doi.org/10.1007/s11852-018-0632-y.
Pugh, T.A.M., Lindeskog, M., Smith, B., Poulter, B., Arneth, A., Haverd, V., Calle, L., 2019. Role of forest regrowth in global carbon sink dynamics. Proc. Natl. Acad. Sci. U. S. A. 116, 4382–4387. https://doi.org/10.1073/pnas.1810512116.
Pyke, C.R., Thomas, R., Porter, R.D., Hellmann, J.J., Dukes, J.S., Lodge, D.M., Chavarria, G., 2008. Current practices and future opportunities for policy on climate change and invasive species. Conserv. Biol. 22, 585–592. https://doi.org/10.1111/j.1523-1739.2008.00956.x.
Radchuk, V., Reed, T., Teplitsky, C., van de Pol, M., Charmantier, A., Hassall, C., Adamík, P., Adriaensen, F., Ahola, M.P., Arcese, P., Miguel Avilés, J., Balbontin, J., Berg, K.S., Borras, A., Burthe, S., Clobert, J., Dehnhard, N., de Lope, F., Dhondt, A.A., Dingemanse, N.J., Doi, H., Eeva, T., Fickel, J., Filella, I., Fossøy, F., Goodenough, A.E., Hall, S.J.G., Hansson, B., Harris, M., Hasselquist, D., Hickler, T., Joshi, J., Kharouba, H., Martínez, J.G., Mihoub, J.-B., Mills, J.A., Molina-Morales, M., Moksnes, A., Ozgul, A., Parejo, D., Pilard, P., Poisbleau, M., Rousset, F., Rödel, M.-O., Scott, D., Senar, J.C., Stefanescu, C., Stokke, B.G., Kusano, T., Tarka, M., Tarwater, C.E., Thonicke, K., Thorley, J., Wilting, A., Tryjanowski, P., Merilä, J., Sheldon, B.C., Pape Møller, A., Matthysen, E., Janzen, F., Dobson, F.S., Visser, M.E., Beissinger, S.R., Courtiol, A., Kramer-Schadt, S., 2019. Adaptive responses of animals to climate change are most likely insufficient. Nat. Commun. 10, 1–14. https://doi.org/10.1038/s41467-019-10924-4.
Ralston, J., DeLuca, W.V., Feldman, R.E., King, D.I., 2017. Population trends influence species ability to track climate change. Glob. Chang. Biol. 23, 1390–1399. https://doi.org/10.1111/gcb.13478.
Rapp, J.M., Lutz, D.A., Huish, R.D., Dufour, B., Ahmed, S., Morelli, T.L., Stinson, K.A., 2019. Finding the sweet spot: shifting optimal climate for maple syrup production in North America. For. Ecol. Manag. 448, 187–197. https://doi.org/10.1016/j.foreco.2019.05.045.
Rasmann, S., Pellissier, L., Defossez, E., Jactel, H., Kunstler, G., 2014. Climate-driven change in plant-insect interactions along elevation gradients. Funct. Ecol. 28, 46–54. https://doi.org/10.1111/1365-2435.12135.
Rodriguez, A.B., Fodrie, F.J., Ridge, J.T., Lindquist, N.L., Theuerkauf, E.J., Coleman, S.E., Grabowski, J.H., Brodeur, M.C., Gittman, R.K., Keller, D.A., Kenworthy, M.D., 2014. Oyster reefs can outpace sea-level rise. Nat. Clim. Chang. 4, 493–497. https://doi.org/10.1038/nclimate2216.
Rosenblatt, A.E., Schmitz, O.J., 2014. Interactive effects of multiple climate change variables on trophic interactions: a meta-analysis. Clim. Chang. Responses 1, 8. https://doi.org/10.1186/s40665-014-0008-y.
Rowe, K.C., Rowe, K.M.C., Tingley, M.W., Koo, M.S., 2015. Spatially heterogeneous impact of climate change on small mammals of Montane California. Proc. R. Soc. London B Biol. Sci. 282, 20141857. https://doi.org/10.1098/rspb.2014.1857.
Rubenstein, M.A., Christophersen, R., Ransom, J.I., 2019. Trophic implications of a phenological paradigm shift: bald eagles and salmon in a changing climate. J. Appl. Ecol. 56, 769–778. https://doi.org/10.1111/1365-2664.13286.
Rudolf, V.H.W., 2019. The role of seasonal timing and phenological shifts for species coexistence. Ecol. Lett. 22, 1324–1338. https://doi.org/10.1111/ele.13277.
Runting, R.K., Bryan, B.A., Dee, L.E., Maseyk, F.J.F., Mandle, L., Hamel, P., Wilson, K.A., Yetka, K., Possingham, H.P., Rhodes, J.R., 2017. Incorporating climate change into ecosystem service assessments and decisions: a review supplementary materials. Glob. Chang. Biol. 23, 28–41. https://doi.org/10.1111/gcb.13457.
Sandifer, P.A., Sutton-Grier, A.E., 2014. Connecting stressors, ocean ecosystem services, and human health. Nat. Resour. Forum 38, 157–167. https://doi.org/10.1111/1477-8947.12047.
Sandifer, P.A., Sutton-Grier, A.E., Ward, B.P., 2015. Exploring connections among nature, biodiversity, ecosystem services, and human health and well-being: opportunities to enhance health and biodiversity conservation. Ecosyst. Serv. 12, 1–15. https://doi.org/10.1016/j.ecoser.2014.12.007.
Schindler, D.E., Rogers, D.E., Scheuerell, M.D., Abrey, C.A., 2005. Effect of changing climate on zooplakton and juvenile sockeye salmon growth in Southwestern Alaska. Ecology 86, 198–209. https://doi.org/10.1890/03-0408.
Schlaepfer, M.A., Runge, M.C., Sherman, P.W., Sherman, P.W., 2002. Ecological and evolutionary traps. Trends Ecol. Evol. 17, 474–480. https://doi.org/10.1016/0197-3975(91)90016-E.
Schluter, D., Price, T.D., Rowe, L., 1991. Conflicting selection pressures and life history tradeoffs. Proc. R. Soc. B Biol. Sci. 246, 11–17. https://doi.org/10.1098/rspb.1991.0118.
Schmitt, J.D., Peoples, B.K., Castello, L., Orth, D.J., 2019. Feeding ecology of generalist consumers: a case study of invasive blue catfish Ictalurus furcatus in Chesapeake Bay, Virginia, USA. Environ. Biol. Fish 102, 443–465. https://doi.org/10.1007/s10641-018-0783-6.
Schwartz, M.W., Hellmann, J.J., McLachlan, J.M., Sax, D.F., Borevitz, J.O., Brennan, J., Camacho, A.E., Ceballos, G., Clark, J.R., Doremus, H., Early, R., Etterson, J.R., Fielder, D., Gill, J.L., Gonzalez, P., Green, N., Hannah, L., Jamieson, D.W., Javeline, D., Minteer, B.A., Odenbaugh, J., Polasky, S., Richardson, D.M., Root, T.L., Safford, H.D., Sala, O., Schneider, S.H., Thompson, A.R., Williams, J.W., Vellend, M., Vitt, P., Zellmer, S., 2012. Managed relocation: integrating the scientific, regulatory, and ethical challenges. Bioscience 62, 732–743. https://doi.org/10.1525/bio.2012.62.8.6.
Sgrò, C.M., Lowe, A.J., Hoffmann, A.A., 2011. Building evolutionary resilience for conserving biodiversity under climate change. Evol. Appl. 4, 326–337. https://doi.org/10.1111/j.1752-4571.2010.00157.x.
Shen, G., Aydin, S.G., 2014. Highway freight transportation disruptions under an extreme environmental event: the case of Hurricane Katrina. Int. J. Environ. Sci. Technol. 11, 2387*2402.
Shilling, D., Nelson, M. (Eds.), 2018. Traditional Ecological Knowledge: Learning From Indigenous Methods for Environmental Sustainability. Cambridge University Press, Cambridge, UK.
Siedlecki, S.A., Kaplan, I.C., Hermann, A.J., Nguyen, T.T., Bond, N.A., Newton, J.A., Williams, G.D., Peterson, W.T., Alin, S.R., Feely, R.A., 2016. Experiments with seasonal forecasts of ocean conditions for the Northern region of the California current upwelling system. Sci. Rep. 6, 1–18. https://doi.org/10.1038/srep27203.
Sirami, C., Caplat, P., Popy, S., Clamens, A., Arlettaz, R., Jiguet, F., Brotons, L., Martin, J.L., 2017. Impacts of global change on species distributions: obstacles and solutions to integrate climate and land use. Glob. Ecol. Biogeogr. 26, 385–394. https://doi.org/10.1111/geb.12555.
Snell-Rood, E.C., Kobiela, M.E., Sikkink, K.L., Shephard, A.M., 2018. Mechanisms of plastic rescue in novel environments. Annu. Rev. Ecol. Evol. Syst. 49, 331–354. https://doi.org/10.1146/annurev-ecolsys-110617-062622.
Sohn, J.A., Saha, S., Bauhus, J., 2016. Potential of forest thinning to mitigate drought stress: a meta-analysis. For. Ecol. Manag. 380, 261–273. https://doi.org/10.1016/j.foreco.2016.07.046.

Spalding, M.D., Ruffo, S., Lacambra, C., Meliane, I., Hale, L.Z., Shepard, C.C., Beck, M.W., 2014. The role of ecosystems in coastal protection: adapting to climate change and coastal hazards. Ocean Coast. Manag. 90, 50–57. https://doi.org/10.1016/j.ocecoaman.2013.09.007.

Spencer, P.D., Nelson, M.W., Hollowed, A.B., Sigler, M.F., Hermann, A.J., 2019. Trait - based climate vulnerability assessments in data - rich systems : an application to eastern Bering Sea fish and invertebrate stocks. Glob. Chang. Biol., 1–18 https://doi.org/10.1111/gcb.14763.

Staudinger, M.D., Grimm, N.B., Staudt, A., Carter, S.L., Chapin, I.I.I.F.S., Kareiva, P., Ruckelshaus, M., Stein, B.A., 2012. Impacts of Climate Change on Biodiversity, Ecosystems, and Ecosystem Services: Technical Input to the 2013 National Climate Assessment. Coop. Rep. To 2013 Natl. Clim. Assess (296 p).

Staudinger, M.D., Morelli, T.L., Bryan, A.M., 2015. Integrating Climate Change Into Northeast and Midwest State Wildlife Action Plans (Amherst, MA).

Staudinger, M.D., Mills, K.E., Stamieszkin, K., Record, N.R., Hudak, C.A., Allyn, A., Diamond, A., Friedland, K.D., Golet, W., Henderson, M.E., Hernandez, C.M., Huntington, T.G., Ji, R., Johnson, C.L., Johnson, D.S., Jordaan, A., Kocik, J., Li, Y., Liebman, M., Nichols, O.C., Pendleton, D., Richards, R.A., Robben, T., Thomas, A.C., Walsh, H.J., Yakola, K., 2019. It's about time: a synthesis of changing phenology in the Gulf of Maine ecosystem. Fish. Oceanogr., 532–566 https://doi.org/10.1111/fog.12429.

Stein, B.A., Staudt, A., Cross, M.S., Dubois, N.S., Enquist, C., Griffis, R., Hansen, L.J., Hellmann, J.J., Lawler, J.J., Nelson, E.J., Pairis, A., 2013. Preparing for and managing change: climate adaptation for biodiversity and ecosystems. Front. Ecol. Environ. 11, 502–510. https://doi.org/10.1890/120277.

Stein, B.A., Glick, P., Edelson, N., Staudg, A., 2014. Climate-smart Conservation: Putting Adaptation Principles Into Practice. National Wildlife Federation, Washington, D.C.

Stephens, S.L., Collins, B.M., Fettig, C.J., Finney, M.A., Hoffman, C.M., Knapp, E.E., North, M.P., Safford, H., Wayman, R.B., 2018. Drought, tree mortality, and wildfire in forests adapted to frequent fire. Bioscience 68, 77–88. https://doi.org/10.1093/biosci/bix146.

Stewart, I.T., Cayan, D.R., Dettinger, M.D., 2005. Changes toward earlier streamflow timing across western. North Am. J. Clim. 18, 10.

Stock, C.A., Dunne, J.P., John, J.G., 2014. Drivers of trophic amplification of ocean productivity trends in a changing climate. Biogeosciences 11, 7125–7135. https://doi.org/10.5194/bg-11-7125-2014.

Sundby, S., Drinkwater, K.F., Kjesbu, O.S., 2016. The North Atlantic spring-bloom system—where the changing climate meets the winter dark. Front. Mar. Sci. 3, 28.

Sutton-Grier, A.E., Wowk, K., Bamford, H., 2015. Future of our coasts: the potential for natural and hybrid infrastructure to enhance the resilience of our coastal communities, economies and ecosystems. Environ. Sci. Pol. 51, 137–148. https://doi.org/10.1016/j.envsci.2015.04.006.

Sutton-Grier, A.E., Gittman, R.K., Arkema, K.K., Bennett, R.O., Benoit, J., Blitch, S., Burks-Copes, K.A., Colden, A., Dausman, A., DeAngelis, B.M., Hughes, A.R., Scyphers, S.B., Grabowski, J.H., 2018. Investing in natural and nature-based infrastructure: building better along our coasts. Sustain 10, 1–11. https://doi.org/10.3390/su10020523.

Swanston, C., Janowiak, M. (Eds.), 2012. Forest Adaptation Resources : Climate Change Tools and Approaches for Land Managers. U.S. Department of Agriculture, Forest Service, Northern Research Station, Newtown Square, PA Gen. Tech. Rep. NRS-87.

Tayleur, C., Caplat, P., Massimino, D., Johnston, A., Jonzén, N., Smith, H.G., Lindström, Å., 2015. Swedish birds are tracking temperature but not rainfall: evidence from a decade of abundance changes. Glob. Ecol. Biogeogr. 24, 859–872. https://doi.org/10.1111/geb.12308.

Taylor, P.C., Maslowski, W., Perlwitz, J., Wuebbles, D.J., 2017. Arctic changes and their effects on Alaska and the rest of the United States. Forth Natioanl Climate Assessment. I, pp. 303–332. https://doi.org/10.7930/J00863GK.

Thomas, A.C., Pershing, A.J., Friedland, K.D., Nye, J.A., Mills, K.E., Alexander, M.A., Record, N.R., Weatherbee, R., Henderson, M.E., 2017. Seasonal trends and phenology shifts in sea surface temperature on the North American northeastern continental shelf. Elem Sci Anth 5.

Timpane-Padgham, B.L., Beechie, T., Klinger, T., 2017. A systematic review of ecological attributes that confer resilience to climate change in environmental restoration. PLoS One 12, 1–23. https://doi.org/10.1371/journal.pone.0173812.

Tommasi, D., Stock, C.A., Hobday, A.J., Methot, R., Kaplan, I.C., Eveson, J.P., Holsman, K., Miller, T.J., Gaichas, S., Gehlen, M., Pershing, A., Vecchi, G.A., Msadek, R., Delworth, T., Eakin, C.M., Haltuch, M.A., Séférian, R., Spillman, C.M., Hartog, J.R., Siedlecki, S., Samhouri, J.F., Muhling, B., Asch, R.G., Pinsky, M.L., Saba, V.S., Kapnick, S.B., Gaitan, C.F., Rykaczewski, R.R., Alexander, M.A., Xue, Y., Pegion, K.V., Lynch, P., Payne, M.R., Kristiansen, T., Lehodey, P., Werner, F.E., 2017. Managing living marine resources in a dynamic environment: the role of seasonal to decadal climate forecasts. Prog. Oceanogr. 152, 15–49. https://doi.org/10.1016/j.pocean.2016.12.011.

Trosper, R.L., 2009. Resilience, Reciprocity and Ecological Economics: Northwest Coast Sustainability. Routledge, New York, New York.

Trottier, N., Groeneveld, E., Lavoie, C., 2017. Giant hogweed at its northern distribution limit in North America: experiments for a better understanding of its dispersal dynamics along rivers. River Res. Appl. 33, 1098–1106. https://doi.org/10.1002/rra.3149.

Tyrrell, T., 2019. Redfield Ratio. Encycl. Ocean Sci. , pp. 461–472. https://doi.org/10.1016/B978-0-12-409548-9.11281-3.

U.S. Environmental Protection Agency, 2016. Climate Change Indicators in the United States. Fourth edition. (doi:EPA 430-R-16-004).

U.S. Fish and Wildlife Service, 2008. Ndangered and threatened wildlife and plants; determination of threatened status for the polar bear (Ursus maritimus) throughout its range. Fed. Regist. 73, 28211–28303.

U.S. Fish and Wildlife Service, 2010. 12-Month finding on a petition to list the American Pika as threatened or endangered. Fed. Regist. 75, 6437–6471.

USDA, 2016. USDA Integrated Projections for Agriculture and Forest Sector Land Use Land-use Change, and GHG Emissions and Removals: 2015 to 2060 (Washington, D.C).

USFWS and NMFS, 2019. Recovery Plan for the Gulf of Maine Distinct Population Segment of Atlantic Salmon (Salmo salar).

USGCRP, 2018. Impacts, Risks, and Adaptation in the United States: Fourth National Climate Assessment. II. U.S. Global Change Research Program, Washington, D.C., USA.

Valéry, L., Fritz, H., Lefeuvre, J.C., Simberloff, D., 2009. Invasive species can also be native…. Trends Ecol. Evol. 24, 585. https://doi.org/10.1016/j.tree.2009.06.017.

Van Zuiden, T.M., Chen, M.M., Stefanoff, S., Lopez, L., Sharma, S., 2016. Projected impacts of climate change on three freshwater fishes and potential novel competitive interactions. Divers. Distrib. 22, 603–614. https://doi.org/10.1111/ddi.12422.

Verdeny-Vilalta, O., Moya-Laraño, J., 2014. Seeking water while avoiding predators: moisture gradients can affect predator-prey interactions. Anim. Behav. 90, 101–108. https://doi.org/10.1016/j.anbehav.2014.01.027.

Vergés, A., Steinberg, P.D., Hay, M.E., Poore, A.G.B., Campbell, A.H., Ballesteros, E., Heck, K.L., Booth, D.J., Coleman, M.A., Feary, D.A., Figueira, W., Langlois, T., Marzinelli, E.M., Mizerek, T., Mumby, P.J., Nakamura, Y., Roughan, M., van Sebille, E., Gupta, A. Sen, Smale, D.A., Tomas, F., Wernberg, T., Wilson, S.K., 2014. The tropicalization of temperate marine ecosystems: climate-mediated changes in herbivory and community phase shifts. Proc. R. Soc. B Biol. Sci., 281 https://doi.org/10.1098/rspb.2014.0846.

Vergés, A., Doropoulos, C., Malcolm, H.A., Skye, M., Garcia-Pizá, M., Marzinelli, E.M., Campbell, A.H., Ballesteros, E., Hoey, A.S., Vila-Concejo, A., Bozec, Y.-M., Steinberg, P.D., 2016. Long-term empirical evidence of ocean warming leading to tropicalization of fish communities, increased herbivory, and loss of kelp. Proc. Natl. Acad. Sci. 113, 13791–13796. https://doi.org/10.1073/pnas.1610725113.

Vernon, M.J., Sherriff, R.L., van Mantgem, P., Kane, J.M., 2018. Thinning, tree-growth, and resistance to multi-year drought in a mixed-conifer forest of northern California. For. Ecol. Manag. 422, 190–198. https://doi.org/10.1016/j.foreco.2018.03.043.

Viers, J.H., Purdy, S.E., Peek, R.A., Fryjoff-Hung, A., Santos, N.R., Katz, J.V.E., Emmons, J.D., Dolan, D.V., Yarnell, S.M., 2013. Montane meadows in the Sierra Nevada. Cent. Watershed Sci. Tech. Rep. 63.

Vinyeta, K., Whyte, K.P., Lynn, K., 2015. Climate change through an intersectional lens: gendered vulnerability and resilience in indigenous communities in the United States. USDA For. Serv. - Gen. Tech. Rep. PNW-GTR-923, pp. 1–74.

Visser, M.E., Gienapp, P., 2019. Evolutionary and demographic consequences of phenological mismatches. Nat. Ecol. Evol. 3, 879–885.

Wallingford, P.D., Morelli, T.L., Allen, J.M., Beaury, E.M., Blumenthal6, D.M., Bradley, B.A., Dukes, J.S., Early9, R., Fusco, E.J., Goldberg, D.E., Ibáñez, I., Laginhas, B.B., Vilà, M., Sorte, C.J.B., n.d. Assessing impacts of climate-driven range shifts through the lens of invasion biology. Nat. Clim. Chang. Chang. (In review).

Walsh, H.J., Richardson, D.E., Marancik, K.E., Hare, J.A., 2015. Long-term changes in the distributions of larval and adult fish in the northeast U.S. shelf ecosystem. PLoS One 10, 1–31. https://doi.org/10.1371/journal.pone.0137382.

Walter, J., Jentsch, A., Beierkuhnlein, C., Kreyling, J., 2013. Ecological stress memory and cross stress tolerance in plants in the face of climate extremes. Environ. Exp. Bot. 94, 3–8. https://doi.org/10.1016/j.envexpbot.2012.02.009.

Wang, W.J., He, H.S., Thompson, F.R., Fraser, J.S., Dijak, W.D., 2017. Changes in forest biomass and tree species distribution under climate change in the northeastern United States. Landsc. Ecol. 32, 1399–1413. https://doi.org/10.1007/s10980-016-0429-z.

Wann, G.T., Aldridge, C.L., Seglund, A.E., Oyler-McCance, S.J., Kondratieff, B.C., Braun, C.E., 2019. Mismatches between breeding phenology and resource abundance of resident alpine ptarmigan negatively affect chick survival. Ecol. Evol., 7200–7212 https://doi.org/10.1002/ece3.5290.

Waples, R.S., Audzijonyte, A., 2016. Fishery-induced evolution provides insights into adaptive responses of marine species to climate change. Front. Ecol. Environ. 14, 217–224. https://doi.org/10.1002/fee.1264.

Warziniack, T.W., Elmer, M.J., Miller, C.J., Dante-Wood, S.K., Woodall, C.W., Nichols, M.C., Domke, G.M., Stockmann, K.D., Proctor, J.G., Borchers, A., 2018. Effects of climate change on ecosystem services. In: Halofsky, J.E., Peterson, D.L., Ho, J.., Little, N.J., Joyce, L.A. (Eds.), Climate Change Vulnerability and Adaptation in the Intermountain Region [Part 2]. U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station, Fort Collins, CO, pp. 376–403.

Wasmund, N., Nausch, G., Gerth, M., Busch, S., Burmeister, C., Hansen, R., Sadkowiak, B., 2019. Extension of the growing season of phytoplankton in the western Baltic Sea in response to climate change. Mar. Ecol. Prog. Ser. 622, 1–16. https://doi.org/10.3354/meps12994.

Wear, D.N., Coulston, J.W., 2015. From sink to source: regional variation in U.S. forest carbon futures. Sci. Rep. 5, 1–11. https://doi.org/10.1038/srep16518.

Weed, A.S., Ayres, M.P., Hicke, J.A., 2013. Consequences of climate change for biotic disturbances in North American forests. Ecol. Monogr. 83, 441–470. https://doi.org/10.1890/13-0160.1.

Weeks, B.C., Willard, D.E., Ellis, A.A., Witynski, M.L., Winger, B.M., 2019. Shared morphological consequences of global warming in North American migratory birds. Ecol. Lett. https://doi.org/10.1101/610329.

Wenger, S.J., Isaak, D.J., Luce, C.H., Neville, H.M., Fausch, K.D., Dunham, J.B., Dauwalter, D.C., Young, M.K., Elsner, M.M., Rieman, B.E., Hamlet, A.F., Williams, J.E., 2011. Flow regime, temperature, and biotic interactions drive differential declines of trout species under climate change. Proc. Natl. Acad. Sci. U. S. A. 108, 14175–14180. https://doi.org/10.1073/pnas.1103097108.

Wenzel, S., Cox, P.M., Eyring, V., Friedlingstein, P., 2016. Projected land photosynthesis constrained by changes in the seasonal cycle of atmospheric CO2. Nature 538, 499–501. https://doi.org/10.1038/nature19772.

West, J.M., Julius, S.H., Kareiva, P., Enquist, C., Lawler, J.J., Petersen, B., Johnson, A.E., Shaw, M.R., 2009. U.S. natural resources and climate change: concepts and approaches for

management adaptation. Environ. Manag. 44, 1001–1021. https://doi.org/10.1007/s00267-009-9345-1.
Westerling, A.L., 2016. Increasing western US forest wildfire activity: sensitivity to changes in the timing of spring. Philos. Trans. R. Soc. B Biol. Sci., 371 https://doi.org/10.1098/rstb.2015.0178.
Westerling, a.L., Hidalgo, H.G., Cayan, D.R., Swetnam, T.W., 2006. Warming and earlier spring increase western U.S. forest wildfire activity. Science (80-.) 313, 940–943. https://doi.org/10.1126/science.1128834.
Whiteley, A.R., Fitzpatrick, S.W., Funk, W.C., Tallmon, D.A., 2015. Genetic rescue to the rescue. Trends Ecol. Evol. 30, 42–49. https://doi.org/10.1016/j.tree.2014.10.009.
Whyte, K.P., Dockry, M.J., Baule, W., Fellman, D., 2014. Supporting tribal climate change adaptation planning through community participatory strategic foresight scenario development. In: Brown, D., Baule, W., Briley, L., Gibbons, E. (Eds.), Project Reports. Great Lakes Integrated Sciences and Assessments Center, Ann Arbor, MI.
Wiens, J.J., 2016. Climate-related local extinctions are already widespread among plant and animal species. PLoS Biol. 14. https://doi.org/10.1371/journal.pbio.2001104.
Yeruham, E., Shpigel, M., Abelson, A., Rilov, G., 2020. Ocean warming and tropical invaders erode the performance of a key herbivore. Ecology 101, 1–13. https://doi.org/10.1002/ecy.2925.
Young, K.R., 2014. Biogeography of the Anthropocene: novel species assemblages. Prog. Phys. Geogr. 38, 664–673. https://doi.org/10.1177/0309133314540930.
Zeidberg, L.D., Robison, B.H., 2007. Invasive range expansion by the Humboldt squid, Dosidicus gigas, in the eastern North Pacific. Proc. Natl. Acad. Sci. U. S. A. 104, 12948–12950. https://doi.org/10.1073/pnas.0702043104.
Zhang, K., Liu, H., Li, Y., Xu, H., Shen, J., Rhome, J., Smith, T.J., 2012. The role of mangroves in attenuating storm surges. Estuar. Coast. Shelf Sci. 102–103, 11–23. https://doi.org/10.1016/j.ecss.2012.02.021.
Zhao, C., Liu, B., Piao, S., Wang, X., Lobell, D.B., Huang, Y., Huang, M., Yao, Y., Bassu, S., Ciais, P., Durand, J.L., Elliott, J., Ewert, F., Janssens, I.A., Li, T., Lin, E., Liu, Q., Martre, P., Müller, C., Peng, S., Peñuelas, J., Ruane, A.C., Wallach, D., Wang, T., Wu, D., Liu, Z., Zhu, Y., Zhu, Z., Asseng, S., 2017. Temperature increase reduces global yields of major crops in four independent estimates. Proc. Natl. Acad. Sci. U. S. A. 114, 9326–9331. https://doi.org/10.1073/pnas.1701762114.
Zhu, Z., Piao, S., Myneni, R.B., Huang, M., Zeng, Z., Canadell, J.G., Ciais, P., Sitch, S., Friedlingstein, P., Arneth, A., Cao, C., Cheng, L., Kato, E., Koven, C., Li, Y., Lian, X., Liu, Y., Liu, R., Mao, J., Pan, Y., Peng, S., Peñuelas, J., Poulter, B., Pugh, T.A.M., Stocker, B.D., Viovy, N., Wang, X., Wang, Y., Xiao, Z., Yang, H., Zaehle, S., Zeng, N., 2016. Greening of the Earth and its drivers. Nat. Clim. Chang. 6, 791–795. https://doi.org/10.1038/nclimate3004.
Zimova, M., Mills, L.S., Nowak, J.J., 2016. High fitness costs of climate change induced camouflage mismatch in a seasonally colour moulting mammal. Ecol. Lett. 19, 299–307. https://doi.org/10.1111/ele.12568.

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Mitigating Greenhouse Gas and Ammonia Emissions from Beef Cattle Feedlot Production: A System Meta-Analysis

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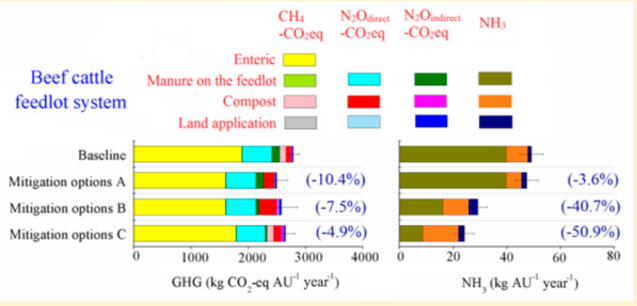
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Supporting Information

ABSTRACT: Beef cattle production systems are the largest contributors of greenhouse gas (GHG) and ammonia (NH_3) emissions in the livestock industry. Here, we present the first meta-analysis and integrated assessment of gaseous emissions and mitigation potentials for a typical beef cattle feedlot system, including methane (CH_4), nitrous oxide (N_2O), and NH_3 losses from enteric fermentation and manure management based on data from 104 studies. A total of 14 integrated emission factors (EF) and the mitigation efficiencies (ME) of 17 available options were provided. The estimated GHG and NH_3 emissions from the baseline feedlot system were 2786 ± 108 kg carbon dioxide equivalents (CO_2-eq) per animal unit (AU) per year and 49.1 ± 1.5 kg NH_3 AU^{-1} $year^{-1}$, respectively. Enteric CH_4 fermentation and manure on the feedlot contributed 67.5% and 80.8% of the total system GHG and NH_3 emissions, respectively. The highest ME values were found for lipid additives for enteric CH_4 fermentation and urease inhibitor additives (UI) for NH_3 emissions from manure on the feedlot, being −14.9% ($p < 0.05$) and −59.5% ($p < 0.001$), respectively. The recommended mitigation combinations of a low-crude-protein (CP) diet and a UI additive for manure on the feedlot could reduce the GHG of the system by 4.9% and NH_3 by 50.9%. The results of this study have important implications for developing sustainable beef cattle feedlot systems from the viewpoint of GHG and NH_3 mitigation.



1. INTRODUCTION

Greenhouse gas (GHG) and ammonia (NH_3) emissions are two major atmospheric issues that influence human health and the global environment. From the United Nations Framework Convention on Climate Change to the Kyoto Protocol and the Paris Agreement, human beings are more aware of the influence of GHG emissions, and urgent action should be taken to avoid the risk of a temperature rise of more than 2 °C.[1] Methane (CH_4) and nitrous oxide (N_2O) are identified as two major non-CO_2 GHGs that have strong global warming potentials (GWP), being 28 and 265 times higher than that of CO_2, respectively.[1] Reducing non-CO_2 global warming agents has garnered increasing attention in recent years.[2−4] The "immediacy" of the climate benefit and the co-benefit of their reduction are expected to provide a strong incentive for nations to consider adopting policies and take rapid responses.[5,6] NH_3, also contributes to a series of problems, including odor emanation, water eutrophication,[7] soil acidification,[8] and GHG emissions because NH_3 is a precursor of N_2O.[9] Furthermore, NH_3 stimulates the formation of secondary particulate matter (PM),[10] which has negative effects on people and the environment.

Livestock production represents the largest anthropogenic source of CH_4 and N_2O emissions[11,12] and contributes 18% of all anthropogenic GHG emissions.[13] Here, CO_2 emissions from livestock are not estimated because annual net CO_2 emissions are assumed to be zero; the CO_2 photosynthesized by plants is returned to the atmosphere as respired CO_2.[9] Nondairy cattle, predominantly beef cattle account for 53.9% of the global enteric CH_4 emissions, while the dairy sector takes second place with 19.1%.[14] Beef cattle are the largest single contributor of manure NH_3 emissions, accounting for 41.0% of all animal sectors.[15]

Beef cattle feedlot production is one of the most typical beef cattle production methods in intensive production systems.[16,17] In beef cattle feedlot systems, cattle excrete fresh

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manure (urine plus feces) onto the manure feedlot surface. After a period of time (120−365 days), machinery removes the dry manure from the feedlot into the manure stockpile area, where it is stored or composted prior to sale off-site or spreading as an organic fertilizer on agricultural land.[18,19] For beef feedlot manure management, only 1% of the excreted volatized solid (VS) and N is managed in sediment basins or retention ponds as liquid slurry; thus, the gas emissions from this liquid part are often not taken into account when considering the system-level gas emissions.[16,20]

Much work in the literature has evaluated gas emissions or mitigations targeted at one specific gas or one emission stage,[21−27] while little research has considered it in a comprehensive way. FAO conducted an LCA study on GHG emissions from beef meat production, though NH_3 emission was not considered in this study, and the study was not specified for beef cattle feedlot systems.[28] Watts et al.[19] reported emission factors of 75.0 kg NH_3 hd^{-1} $year^{-1}$, 3.16 kg N_2O hd^{-1} $year^{-1}$, and 0.84−1.69 kg CH_4 hd^{-1} $year^{-1}$ for the manure management chain of a beef cattle feedlot system in Australia, but enteric CH_4 emissions were not considered. In addition, neither of these two studies considered or evaluated gas mitigation for beef cattle production.[19,28] Considering the interactions between different gases and the mass flow causing linkage of gas emissions between the former and later stages,[29,30] evaluation of the impact of a combination of mitigation measures on simultaneous CH_4, N_2O, and NH_3 emissions is necessary, specifically for beef cattle feedlot systems.

The overall objective of this study was to make a quantitative assessment of GHG and NH_3 emissions from beef cattle feedlot production systems and the effects of (sets of) mitigation options on the CH_4, N_2O, and NH_3 emissions from the whole production chain using meta-analysis. A comprehensive data set was collated and developed for CH_4, N_2O, and NH_3 emission factors (EFs) for each stage of the feedlot production system, including enteric fermentation, manure on the feedlot, the manure composting or stockpiling stage, and the land application stage. This meta-analysis also quantified the efficiencies of 17 mitigation strategies, including 7 dietary manipulations, 5 management strategies for manure on the feedlot, 3 management strategies for manure composting and stockpiling, and 2 land application mitigation measures. System-level GHG and NH_3 emissions for the feedlot production system, with or without mitigation measures, were analyzed, and the most-effective designs for reduction of GHG and NH_3 emissions for the feedlot systems were recommended.

2. MATERIALS AND METHODS

2.1. Data Sources and Selection Criteria. The ISI Web of Knowledge database (www.isiwebofknowledge.com) and the Chinese journal database (www.cnki.net) were used to search all published datasets as of December 2017. Specific search terms were combined and used, including animal categories (beef, cattle, bull, steer, bovine, heifer, and livestock), manure, manure management (feedlot, pad, yard, open-lot, pen, compost, and stockpile), land application (surface spread, and incorporation), gaseous emissions (NH_3, CH_4, N_2O, and GHG gas), and mitigation measures (diet, crude protein, additive, amendment, urease inhibitor, biofilter, biotrickling, cover, nitrification inhibitor, incorporation, reduction, mitigation, and abatement). Literature sources used in this study were selected on the basis of following criteria: (1) the research object was beef cattle; (2) the study included at least one of the CH_4, N_2O, and NH_3 gases; (3) gas emission flux or gas emission factor was available; and (4) for literature related to mitigation, only studies that reported at least one control group were selected, so that emission mitigation efficiency (ME) could be calculated.

Application of the selection criteria resulted in 104 peer-reviewed papers containing 528 effective observations from experimental studies, which were used in the meta-analysis. Data were collected from both published tables and text for all selected research articles as well as extracted from published figures using the GetData Graph Digitizer software (version 2.22).[31] In addition to the gaseous emission data, related information allowing the interpretation of the observations such as beef cattle number, cattle weight, emission flux, and other gas emission relevant information such as study location, seasons, and manure property parameters were recorded (see data set S1 and tabs for raw data). The locations and distributions of the data used in this study are summarized in Figure 1, which was created by using ArcGIS software (version 10.0).[32] It can be seen that most studies were distributed in North American, Oceania, Europe, and East Asia.

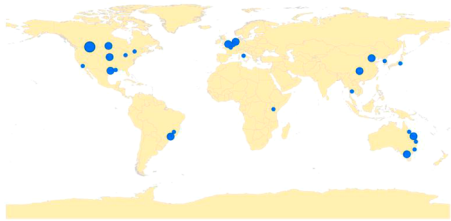


Figure 1. Location and distribution of the literature sources used in this study. Larger circles mean more literature was available in the specific region. (This figure was created using ArcGIS software.)

2.2. Data Analysis. *2.2.1. Calculation of Emission Factors in the Different Phases.* To perform statistical analysis, the various units of gas emissions from enteric fermentation and manure on the feedlot stage were converted into kg AU^{-1} $year^{-1}$ (1 AU [animal unit] being equal to one beef animal weighing 500 kg of live weight) using the calculation method presented in Table S1. The CH_4 EFs for manure management (compost and stockpile) were calculated as kg CH_4−C $(Mg\ DM)^{-1}$. The NH_3 and N_2O EFs for manure management (composting and stockpiling) and land application phases were calculated as the percentage of total nitrogen (TN), i.e., kg NH_3−N $(kg\ TN)^{-1}$ and kg N_2O−N $(kg\ TN)^{-1}$. When unit conversion was not possible due to lack of key information, the original emission data were excluded from the statistical analysis. The EFs for each phase of the feedlot production system, including the median, mean value, standard error and interquartile range (IQR), were calculated with SPSS software (version 20.0, SPSS, Inc., Chicago, IL). The results were not weighted according to sample size; therefore, all of the observations had equal impact on the results. Given the influence of a few measurements with very high values or very low values on the mean values, median values instead of means were used as the basis for subsequent calculations because median values are quite robust with regard to outliers.[33] The 95% confidence interval (95% CI) of the median was calculated using eq 1:

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$$95\%\ \mathrm{CI} = 1.58 \times \frac{IQR}{\sqrt{N}} \quad (1)$$

where N represent the number of observations for each emission factor.

2.2.2. Calculation of the Mitigation Efficiency of Each Measure. The efficiencies of individual mitigation measures for the corresponding phases were assessed by comparing the results of control and treatment groups using the following formula:

$$E_m = \left(\frac{ER_{trt}}{ER_{ctrl}} - 1\right) \times 100\% \quad (2)$$

where E_m is ME, ER_{trt} is the gas emissions in the experimental group with mitigation measures, and ER_{ctrl} is the gas emissions in the control group without mitigation measures. Thus, a negative or positive E_m value indicates that the selected measure can reduce or increase gas emissions, respectively. The median E_m values for each measure were calculated using an analytical approach adapted from Benayas et al.[34] and Tuomisto et al.[35] The normality of the data was tested using the Kolmogorov–Smirnov test. Not all of the E_m values for each mitigation measure were normally distributed; therefore, the Wilcoxon Signed-Rank test was used to determine if the median E_m values were significantly different from 0 when there were sufficient results for specific measures. SPSS 20.0 software was used for the statistical analyses.

2.2.3. Design of an Integrated Feedlot Production System and Calculation of System-Level GHG and NH_3 Emissions. Design of an Integrated Feedlot Production System. Usually, for the beef cattle feedlot system, breeds such as Angus cross-bred steers and Simmentals with entry weights typically ranging from 250 to 450 kg and exit weights ranging from 400 to 700 kg depending on market type were fattened on the feedlot.[19,36] The baseline scenario was designed based on the typical management manner of beef cattle feedlot systems, including enteric fermentation, manure deposited on the feedlot, manure composting, and land application by surface spreading (Figure 2). The integrated mitigation scenarios were set with individual mitigation options included into the corresponding phases of the feedlot production system (Figure 2), and these scenarios are displayed in Table S2.

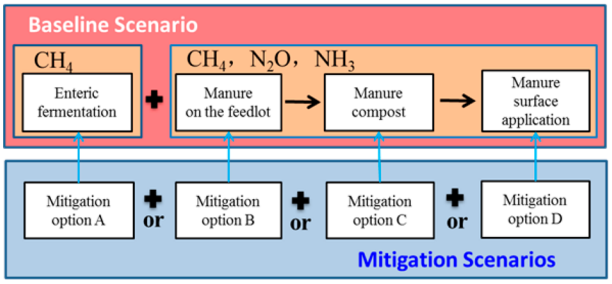


Figure 2. Block diagram of system gas emissions for the baseline scenario (red box) and the mitigation scenario (blue box) through the operation unit (black boxes).

Calculation of GHG and NH_3 Emissions for the Baseline and Mitigation Scenarios. The system GHG and NH_3 emissions for the baseline scenario of a beef-cattle feedlot system were calculated based on the summation method for CH_4 and mass flow for NH_3 and N_2O. The indirect N_2O emissions arising from N deposition and N leaching or runoff were also considered. The detailed calculation process is presented in section 1 of the Supporting Information.

The system gas emissions under mitigation scenarios for the feedlot production system were the sum of the emissions from each phase and were based on the numerous calculation schemes described in section 2 of the Supporting Information. The calculations are presented in data set S1 (see the "Feedlot system" tab).

2.2.4. Uncertainty Analysis. Monte Carlo simulations (10 000 runs) with R (version 3.3.1) were applied to estimate the uncertainty of the system-level emissions. The calculated median values of the gas emission factors and mitigation efficiency factors, as well as their 95% confidence intervals (CI), were included in the uncertainty analysis. The probability density functions (PDF) were assumed as normal distributions for each input data.[30]

3. RESULTS AND DISCUSSION

3.1. Gaseous Emission Factors for Each Phase of the Beef Cattle Feedlot System. *3.1.1. Enteric CH_4 Emissions.* A total of 100 observations of enteric CH_4 emissions were collected to analyze the beef cattle enteric CH_4 EFs, with 52 monitored using a sulfur hexafluoride (SF_6) tracer method and 48 monitored using a respiration chamber method. The world over median CH_4 EF for enteric fermentation is 67.2 kg AU^{-1} $year^{-1}$, with a 95% CI value of 62.0–72.4 kg AU^{-1} $year^{-1}$ (Table 1). The CH_4 EF varies with region, and North America and Western Europe showed higher enteric CH_4 EF values, while Latin America showed the lowest EF values (Figure 3), which may arise from differences of feed or the herd breed. For example, McGinn et al.[37] reported that the measured enteric CH_4 EF from Australia feedlot cattle is 22% lower than that from Canada feedlot cattle, and the difference was attributed to the lighter weight of the Australia cattle (and, consequently, their lower intake) and supplementation of their diet with lipids. It can be seen that the meta-analysis results for Asia are comparable with the Intergovernmental Panel on Climate Change (IPCC) recommended values, while for North America, Western Europe, Oceania, and Latin America, the discrepancy may arise from newly collected data from recent years (68 of 100 data were sourced from publication years after 2006), which may have been triggered by breed evolution or feed stuff improvement. For example, bulls having a lower residual feed intake (RFI) would be more feed efficient and would have a lower daily rate of CH_4 production, while RFI has been shown to be moderately heritable.[38] Australian cattle can now be commercially tested for RFI, and the estimated breeding values (EBVs) of bulls are used in sire selection,[39] thus causing the lower CH_4 EF in this region. This meta-analysis result could be used to support the refinement of the IPCC guidelines.

3.1.2. Gas Emissions from Manure on the Feedlot. CH_4 Emissions. The CH_4 emission rates from manure on the feedlot were measured using chamber methods, with an EF of 0.23 kg AU^{-1} $year^{-1}$ (95% CI, 0–0.83 kg AU^{-1} $year^{-1}$; Table 1), which is at the lowest level of IPCC recommended values of 0–31 kg CH_4 hd^{-1} $year^{-1}$.[9] The reason for the low manure CH_4 EF is that manure on the feedlot is dry based, with 99% of the organic matter being dry managed.[16,20]

NH_3 Emissions. The NH_3 EF from manure on the feedlot was 39.65 (95% CI, 34.18–45.12) kg AU^{-1} $year^{-1}$, which is higher than 8.52 (95% CI, 2.83–14.21) kg AU^{-1} $year^{-1}$ for

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Table 1. Emission Factors of CH_4, N_2O, and NH_3 from Each Stage of the Beef-Cattle Feedlot Production System and Their 95% Confidence Intervals (CIs)

	CH_4 (kg AU^{-1} $year^{-1}$)				N_2O (kg AU^{-1} $year^{-1}$)				NH_3 (kg AU^{-1} $year^{-1}$)			
grouping category	*n*	EF	CI	range	*n*	EF	CI	range	*n*	EF	CI	range
enteric	100	67.2	62.0−72.4	10.0−112.6	–	–	–	–	–	–	–	–
manure on the feedlot	16	0.23	0−0.83	0.01−3.18	19	1.96	0−13.37	0.00−42.56	58	39.65	34.18−45.12	17.00−106.49
		kg CH_4−C (Mg DM)$^{-1}$				kg N_2O−N (kg TN)$^{-1}$				kg NH_3−N (kg TN)$^{-1}$		
manure compost	10	6.16	4.40−7.92	0.36−15.36	11	0.0062	0−0.2744	0.0002−0.0202	3	0.2340	0.0716−0.3964	0.0600−0.4160
manure stockpile	20	6.31	3.56−9.06	1.51−41.99	20	0.0056	0.0016−0.0096	0−0.0432	15	0.0054	0.0004−0.0104	0.0010−0.0450
		kg CH_4−C (Mg DM)$^{-1}$				kg N_2O−N (kg TN)$^{-1}$				kg NH_3−N (kg TN)$^{-1}$		
manure surface spreading	–	–	–	–	13	0.0023	0.0015−0.0031	0.0004−0.0127	10	0.1042	0.0561−0.1523	0.0373−0.2018
manure incorporation	–	–	–	–	34	0.0006	0.0004−0.0008	0.0001−0.0331	11	0.0543	0.0113−0.0973	0.0177−0.1973

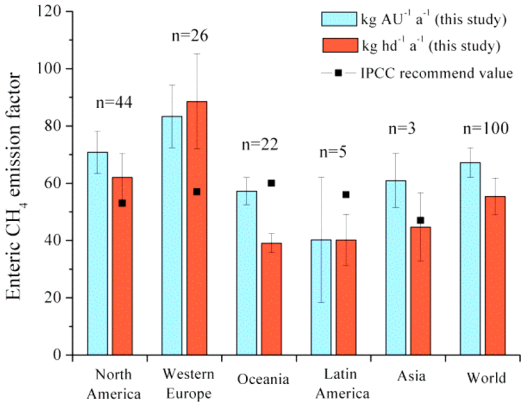


Figure 3. Regional enteric CH_4 emission factors of beef cattle expressed in terms of per AU or per herd (median ±95% CI); *n* = number of observations; squares indicate the IPCC recommended values.

beef cattle feeding and loafing yards in the United Kingdom[40,41] and 3.5 kg AU^{-1} $year^{-1}$ for a beef cattle bedding system.[42] The high NH_3 EF from manure on the feedlot occurred because it is managed under an open air environment. For beef cattle feeding and loafing yards, the floor would commonly be scraped once a week, thus not accumulating much manure[16,40] and leading to low NH_3 and N_2O emissions. For bedding systems, the bedding material can absorb part of the urine, and the occurrence of nitrification and denitrification microbes on the bedding material can also lead to the NH_3 being converted to N_2O, thus leading to the lowest NH_3 EF.[42]

N_2O Emissions. The median N_2O EF from beef cattle manure on the feedlot was 1.96 kg AU^{-1} $year^{-1}$, with the 95% CI being of 0−13.37 kg AU^{-1} $year^{-1}$ (Table 1). The EFs monitored with dynamic chamber or static chamber methods are usually lower than 1 kg AU^{-1} $year^{-1}$,[23−26,43] but the N_2O EFs appeared to be high at 12−42 kg AU^{-1} $year^{-1}$ when obtained with the wind tunnel method.[44,45] The air flow rate used in the two wind tunnels by Rahman et al.[44] and Borhan et al.[45] was high compared to the normally used wind tunnel flow rate for measuring N_2O emissions from the soil surface (1.75 versus 0.29 m^3 s^{-1}).[46,47] Moreover, the surface condition of the feedlot also influenced N_2O emissions. Surface conditions that are moist and muddy are localized microsites with physical and chemical conditions favoring intense microbial activity, thus presenting a median N_2O emission flux that was over 20 times greater and significantly higher than those for the other surface conditions, such as dry and loose conditions and flooded conditions.[48]

3.1.3. Manure Composting or Stockpiling Phase. CH_4 EFs. The CH_4 EFs from composting and stockpiling were 6.16 (95% CI, 4.40−7.92) and 6.31 (95% CI, 3.56−9.06) kg CH_4−C (Mg DM)$^{-1}$, respectively (Table 1). Stockpiling showed a relatively higher median value of CH_4 EF than composting, also with a higher variation than that of composting. The maximum CH_4 EF observed for stockpiling even reached 41.99 kg CH_4−C (Mg DM)$^{-1}$, which is much higher than that of 15.36 kg CH_4−C (Mg DM)$^{-1}$ for composting. Because the composting process usually resulted in an aerobic process, neither aeration nor pile turning happened during the manure stockpiling process; thus, the anaerobic environment caused high CH_4 emission during stockpiling.

N_2O EFs. The N_2O EFs of composting and stockpiling were 0.0062 (95% CI, 0−0.2744) and 0.0056 (95% CI, 0.0016−

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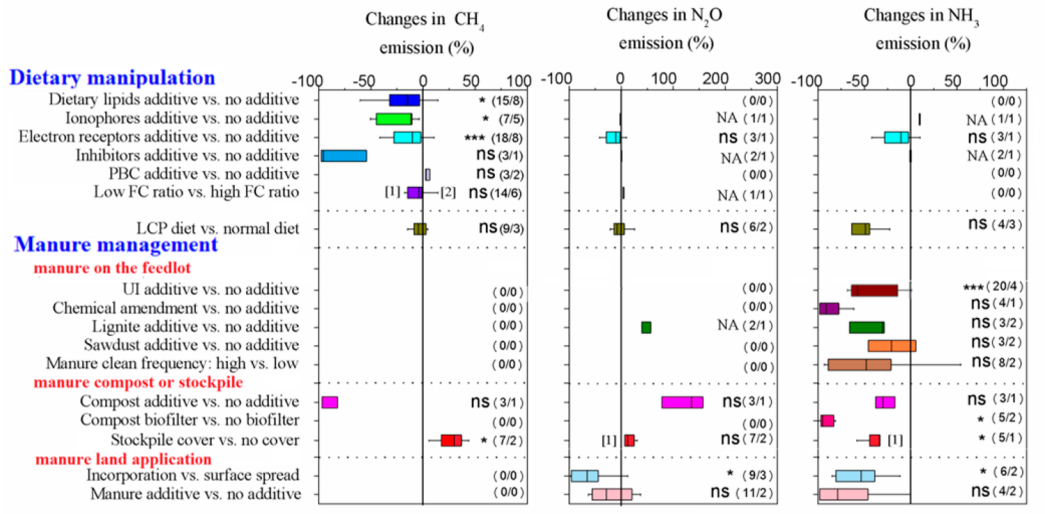


Figure 4. Box-and-whisker plots of the efficiencies of mitigation strategies for CH_4, N_2O, and NH_3 emissions (see Tables S6–S8 for numeric data). Vertical lines of the boxplot represent the median, upper, and lower quartiles. The whiskers show values that extend to 1.5 orders of the box length. The numbers in the square brackets represent the number of outliers (>1.5 orders of the box length). Values in parentheses indicate the number of observations for the statistical analysis and the number of studies from which the observations originated. Wilcoxon Signed Rank test: triple asterisks indicate $P < 0.001$, double asterisks indicate $P < 0.01$, and a single asterisk indicate $P < 0.05$; ns, not significantly different from zero; NA, not applicable. PBC, plant bioactive compounds; FC ratio, forage-to-concentrate ratio; LCP, low crude protein; and UI, urease inhibitor.

0.0096) kg N_2O–N (kg TN)$^{-1}$, respectively (Table 1). The 95% CI of composting was obviously higher than that of stockpiling, and the collected EF of composting was in the range of 0.0002–0.0202 kg N_2O–N (kg TN)$^{-1}$, indicating that the N_2O EFs for composting vary significantly under different conditions. Our collected N_2O EF data for beef cattle manure compost was lower than the IPCC recommended value of 0.006–0.1 kg N_2O–N (kg TN)$^{-1}$.[9] IPCC value was generally recommended for all kinds of animal manure, thus leading the exhibited higher range, and our results can be supplemented for the specific use of beef cattle manure compost. For solid stockpiling, the IPCC recommended an EF of 0.005 kg N_2O–N (kg TN)$^{-1}$,[9] which is comparable with the meta-analyzed results of this study.

NH_3 EFs. The NH_3 EF from beef cattle manure composting was obviously higher than that of stockpiling at 0.2340 (95% CI, 0.0716–0.3964) and 0.0054 (95% CI, 0.0004–0.0104) kg NH_3–N (kg TN)$^{-1}$, respectively (Table 1). The NH_3 EF of the composting process ranged from 0.060–0.416 kg NH_3–N (kg TN)$^{-1}$, and that of the stockpiling process ranged from 0.001–0.045 kg NH_3–N (kg TN)$^{-1}$. The ventilation process with aerobic composting leads to high NH_3 emissions during the composting process, which also leads to the high nutrient loss of composting.

3.1.4. Manure Land Application. For upland cropping systems, CH_4 emissions are low, and the cropping system is usually seen as a sink for CH_4.[49] As such, CH_4 emissions and mitigation during manure upland application are not considered in the following system-level emission calculations.

N_2O EFs. The N_2O EFs for the surface spreading and incorporation of beef cattle manure were 0.0023 (95% CI, 0.0015–0.0031) and 0.0006 (95% CI, 0.0004–0.0008) kg N_2O–N (kg TN)$^{-1}$, respectively (Table 1). For N_2O, EF varies greatly within one specific land application method. For instance, the N_2O EF values for incorporation ranged from 0.0001–0.0009 kg N_2O–N (kg TN)$^{-1}$ in the study by Chiyoka et al.,[50] while they are 0.0185–0.0331 kg N_2O–N (kg TN)$^{-1}$ in the study by Chang et al.[51] The complex N_2O production processes and the variable manure and soil properties in each study lead to the variability among N_2O emission results.[52] Moreover, the comparison revealed that the N_2O EF of surface spreading was significantly higher than that of incorporation ($p < 0.05$) because their 95% CIs did not overlap. Webb et al.[53] suggested that some stored farmyard manure (FYM) emitted N_2O at the time of spreading on the soil surface; however, if FYM is buried through ploughing, the increased length of the diffusion pathway through the soil matrix may lead to the reduction of N_2O emissions.

NH_3 EFs. Surface spreading showed the largest NH_3 EF of 0.1042 (95% CI, 0.0561–0.1523) kg NH_3–N kg (TN)$^{-1}$, while the EF was 0.0543 (95% CI, 0.0113–0.0973) kg NH_3–N kg (TN)$^{-1}$ for manure incorporation (Table 1). The NH_3 EF of beef cattle manure surface application seems low compared with that of other manure, with higher EF values in the range of 0.195–0.363 kg NH_3–N kg (TN)$^{-1}$ and 0.129–0.345 kg NH_3–N kg (TN)$^{-1}$ having been observed for poultry manure and pig manure surface application, respectively.[54−56] Beef cattle manure had been stored on the feedlot for a long time, leading to much of the easily decomposed N being lost during this phase and causing the low NH_3 emission during the final land application process. In addition, the low original N content of the freshly excreted beef cattle manure would also be a reason for the low NH_3 emission. Li[57] reported that the TN content of fresh swine manure was 154% higher than that of fresh beef cattle manure, being 8.94 g kg wet basis^{-1} (WB) and 3.52 g kg WB^{-1}, respectively.

3.2. Mitigation Measures. Various mitigation practices have been developed for reducing GHG and NH_3 emissions for the beef cattle production. The changes in CH_4, N_2O, and NH_3 emissions under different mitigation practices at each phase are presented in Figure 4.

3.2.1. Dietary Manipulation. Feed Additive. For ruminant production, feed additives are used to reduce enteric fermentation for reducing CH_4 emissions. Common feed additives include dietary lipids, ionophores, electron receptors, inhibitors, plant bioactive compounds (PBC), etc.[58] There

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were 21 publications found related to feed additives, among which 9 were related to dietary lipid additives, including coconut oil, crude glycerin supplements, sunflower oil, etc., and the ME for dietary lipid additives was −14.9% ($p < 0.05$; Figure 4). The most commonly used ionophore is monensin, and it showed a strong anti-methanogenic effect, leading to the ME being −11.5% ($p < 0.05$). However, ionophores are banned in the European Union and are therefore not applicable everywhere.[58] In the electron receptor category, nitrate, fumaric, and malic acids have been studied most, with the median mitigation effect being −15.2% ($p < 0.001$). Inhibitors such as bromochloromethane additives were quite effective in reducing enteric CH_4 emissions, with CH_4 reductions of −97.8%∼−54.3% in the study by Tomkins et al.[59] However, in the case of electron receptors and the inhibitors, the environmental and animal health implications are questionable.[59,60] The CH_4 mitigating effect of PBC in vivo remains controversial, and it was calculated that the PBC additives such as saponin and essential oil caused an increase of 2.8% on beef cattle CH_4 emission ($p = 0.109$). The CH_4 mitigation effect could be related to differences in feed retention times within the rumen as influenced by the level of saponin intake and composition of basal diet or in the quality of the PBC among experiments.[61] Thus, considering the mitigation effect along with the safety of each feed additive, dietary lipids were still the most recommended additive for enteric CH_4 mitigation. In addition, considering the potential negative effect of dietary lipids on feed intake, fiber digestibility, and overall animal productivity, the maximum recommended inclusion rate of dietary lipids in ruminant diets is 6% to 7% (total fat) of the dietary DM.[58]

Feed additives are mainly used for CH_4 mitigation from enteric fermentation, while little research has been performed related to N_2O and NH_3 mitigation with feed additives. Lee et al.[62] found no obvious effect on N_2O and NH_3 emissions from manure when the diet was amended with 1%, 2%, and 3% encapsulated calcium ammonium nitrate. Also, some additives such as ionophores may alter microbes in the rumen, which may lead to changes in volatile organic compound (VOC), such as ethanol (EtOH) and methanol (MeOH).[63] Because VOC can interact with nitrogen oxides (NOx) to form ozone (smog), which may impair human health and well being as well as the regional and global environment, it should also be considered in the future study.

Reducing the Forage-to-Concentrate Ratio. Reducing the FC ratio can lower CH_4 emission by −3.8% ($p = 0.221$). The reduced CH_4 output arising from the reduced FC ratio is due to a shift in ruminal fermentation patterns from acetate to propionate[64] and a decline in the ruminal pH.[65] When cattle were fed diets containing 90% or more concentrates, cattle CH_4 conversion factors (Ym) can be reduced by 50% compared with that from forage based diets.[9] However, compared to forage offered to cattle, concentrate was preferentially consumed due to its palatability, which would consequently contribute to more feed intake[66] and may, however, increase the enteric fermentation CH_4 emission, thus causing CH_4 mitigation efficiency from a low FC ratio to be low. The effect of low FC ratio on N_2O and NH_3 emissions was not appreciable.

Low Crude Protein Diet. The effect of a low crude protein (LCP) diet on CH_4 was not appreciable. However, a LCP diet is highly beneficial because it limits N at the source, resulting in a lower N content in the excreta (−12.8%, $p < 0.01$, Table S9) and, thus, may reduce N-related gaseous emissions during subsequent manure management phases. The effect of LCP on N_2O emission was not obvious, being of −3.5% ($p = 0.753$, Figure 4). However, it delivers an obvious mitigation potential for NH_3 emissions during the manure on the feedlot phase, being of −46.5% ($p = 0.068$). The only four observations collected for NH_3 mitigation caused the result to be not significant. LCP also provides other environmental co-benefits, such as reduced N losses in runoff and eutrophication.

3.2.2. Mitigation Measures for Manure on the Feedlot. No research was available on CH_4 mitigation from manure on the feedlot, and only one publication was available that considered both N_2O and NH_3 mitigation from manure on the feedlot.[26] Most studies about gas mitigation from beef cattle manure on the feedlot focus on the only subject of NH_3, mainly through the use of additives or increasing the manure clean frequency.

Manure Additives on the Feedlot. The commonly used additives for manure on the feedlot include urease inhibitors (UI), chemical amendments, lignite, and sawdust. The NH_3 mitigation mechanism for each additive varies. Urease inhibitors can block the hydrolysis of urea to ammonium[67] and, thereby, decrease NH_3 production. A total of 20 observations among the 34 observations collected in this study were about UI additives, and the median NH_3 ME of UI was −59.5% ($p < 0.001$). Considering that the inhibitor effect of the UI would be lower in soil conditions of high moisture, a high amount of UI should be applied when in high moisture conditions.[68,69] Chemical amendments such as alum ($Al_2(SO_4)_3$) and calcium chloride ($CaCl_2$) reduce NH_3 emissions by decreasing the pH and increasing the function of H^+ through cation exchange,[70] and the median NH_3 ME of chemical amendment was −85.0% ($p = 0.068$). For chemical amendment, only four observations were available for its specific use on beef cattle manure, resulting in an insignificant outcome ($p = 0.068$). The NH_3 mitigation mechanism of lignite is similar to that of chemical amendments. Lignite is acidic in nature (pH 3.69) and has a high cation exchange capacity.[71] In addition, lignite contains up to 20% labile carbon, which can absorb NH_4^+, and the high humic acid content can suppress urea hydrolysis.[71] The median NH_3 ME of lignite was −30.0%; because only three observations were available for its specific use on beef cattle manure, it resulted in an insignificant outcome ($p = 0.18$). Sun et al.[26] reported that N_2O emission increased from 0.10−0.14 to 0.14−0.22 g N_2O−N $head^{-1}$ day^{-1} with lignite additives for manure on the feedlot. However, considering the overall GHG emissions, the increase in direct N_2O emissions can be counteracted by the lower indirect N_2O emission due to decreased NH_3 volatilization (NH_3 emission decreased from 38.6−61.3 to 27.6−42.7 g NH_3−N $head^{-1}$ day^{-1}); thus, the lignite additive was effective in reducing the total GHG emission. Sawdust additive can widen the C-to-N ratio of the manure, showing a tendency to retain more nitrogen.[72] With the collected three observations, it was calculated that the sawdust additive can reduce NH_3 emission by 21% ($p = 0.285$). Among all of the additives, chemical amendment showed the highest NH_3 mitigation effect; however, the benefit-to-cost ratio was about a factor of 10 lower than that of UI.[70]

Increasing the Clean Frequency. No research monitored the effect of clean frequency on CH_4 and N_2O emissions. Only one study by Wilson et al.[73] reported that increasing the manure removal frequency (such as once a month, compared to the common frequency of once at the end of the feeding

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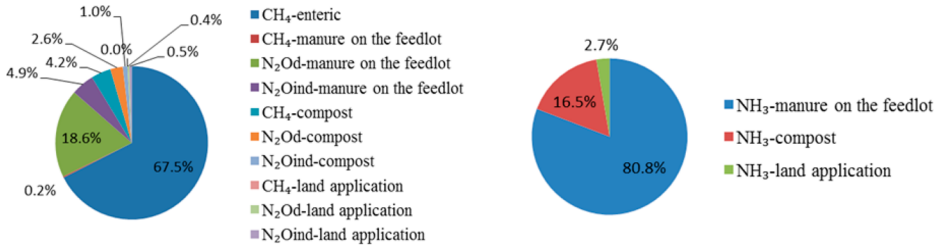


Figure 5. GHG and NH_3 emissions from the beef-cattle feedlot system by category of emissions.

period) can reduce NH_3 emissions by 19.1−20.8%. In addition, manure removal is also suggested to be used along with manure additives. For example, the effects of lignite will decline when the acidity is neutralized and the cation exchange capacity reduced through the accumulation of manure on the feedlot. Thus, after routine manure removal from pens, lignite needs to be reapplied to optimize the reduction of NH_3 emissions.[71]

3.2.3. Mitigation Measures for Manure Composting and Stockpiling. Compost Additives. There are only two papers that studied the impact of compost additives on gas emissions from beef cattle manure, with one study specified for CH_4 and N_2O[27] and the other for NH_3.[74] The results showed that additives can be effective in both CH_4 and NH_3 mitigation, with ME values of −97.0% (p = 0.102) and −30.0% (p = 0.109),[27,74] but it may increase N_2O emission by 135.0% (p = 0.109).[27] This is further explained by the phosphogypsum additive reducing N loss via NH_3 mitigation, while more N was retained in the form of NH_4^+-N in compost, which could thus serve as substrate for the nitrification and denitrification process, causing the increase of N_2O.[27]

Compost Biofilter. No research is available for the effect of biofilter on compost CH_4 and N_2O emissions specifically for beef cattle manure. The NH_3 emissions from compost can be reduced by 80.5−99.9% with compost biofilter,[75,76] with a median ME of 95% (p < 0.05). Because biofilters can only be used when the discharged air is being collected, and the manure from feedlot systems is usually being composted in an open air, this method is not considered in our system-level mitigation design.

Stockpile Covering. For beef manure stockpiling, CH_4 and N_2O emissions can be increased by 29.8% (p < 0.05) and 13.0% (p = 0.128) with straw or sawdust coverings, respectively; however, NH_3 emission could be reduced by 33.0% (p < 0.05). Covering caused an anaerobic environment in the pile, thus leading to higher CH_4 emission. Meanwhile, simultaneous aerobic and anaerobic conditions formed at the surface of pile under the cover, and the carbon input sourcing from the straw and sawdust stimulating the nitrification and denitrification process in the pile both triggered the increased N_2O emissions. However, one of the total seven observations collected by Zhu et al.[77] indicated that the N_2O emission may be reduced, with the reason being unclear, causing the result to be insignificant (p = 0.128).

3.2.4. Mitigation Measures for Land Application. Among the different manure application methods, manure incorporation can decrease N_2O and NH_3 emission simultaneously in comparison to surface application in some conditions. Incorporation can decrease N_2O emission by 65.0% (p < 0.05) in comparison to manure surface application, and it showed a significant NH_3 mitigation effect of 64.8% (p < 0.05). As indicated earlier in section 3.1.4, heavily textured soil inhibition of the N_2O diffusion pathway was caused by incorporation, thus decreasing N_2O emission. Combined with the advantage of nutrient conservation and odor reduction, beef cattle manure incorporation can be a highly recommended alternative application method.

Manure additives such as biochar and nitrification inhibitors resulted an integrated N_2O mitigation efficiency of −28.0% (p = 0.100). The biochar additions cannot always keep the N_2O emissions being reduced, causing the integrated N_2O mitigation effect to be not significant.[78] Manure additives such as lava meal can reduce NH_3 emission by 62.5% (p = 0.068). The adsorption of NH_4^+ by the lava meal, and also the precipitation of NH_4^+-N into struvite due to the presence of some P and especially Mg salts in the lava meal, cause the NH_3 emission being reduced.[79] However, only four observations was collected for the additives effect on NH_3, causing the result to be not significant.

3.2.5. Other Mitigation Options. When the collected manure was used for anaerobic fermentation, biogas recovery and utilization can exhibit a high GHG mitigation potential. However, CH_4 leakage from biogas digester, and the CH_4, N_2O, and NH_3 emissions from the digested slurry storage and land application stages should all be considered when calculating the mitigation effect. Unfortunately, no literature with a direct comparison of biogas digesters versus the baseline scenario for beef cattle manure was identified. Therefore, we could not give quantitative data on the mitigation efficiency of biogas digester.

3.3. Gas Emissions from the Baseline Scenario of a Beef Cattle Feedlot Production System. *3.3.1. GHG Emission.* The GHG emission from a baseline scenario of beef cattle feedlot production system is 2786 ± 108 kg CO_2-eq AU^{-1} $year^{-1}$. Among the gases, CH_4 contributed most of the GHG emissions, accounting for 72.0% of the total GHG emissions. The enteric CH_4 emission was 1882 ± 3 kg CO_2-eq kg AU^{-1} $year^{-1}$, accounting for 67.5% of the total GHG emissions (Figure 5). The GHG emission arising from manure management is 904 ± 127 kg CO_2-eq kg AU^{-1} $year^{-1}$. Among the manure on the feedlot stage, the manure composting stage, and the land application stage account for 23.8%, 7.8%, and 0.9% of the overall GHG emissions, respectively. The GHG mitigation priority should be focused on the enteric CH_4 emissions and manure N_2O emissions on the feedlot.

The N_2O emissions for manure on the feedlot stage, compost stage, and land application stage are 1.96, 0.28, and 0.04 kg N_2O AU^{-1} $year^{-1}$, respectively, which totaled 2.28 kg N_2O AU^{-1} $year^{-1}$. The calculated N_2O emission from Watts et al.[19] was 2.20, 0.69, and 0.28 kg N_2O AU^{-1} $year^{-1}$, respectively, for each stage of manure management and totaled to 3.17 kg N_2O AU^{-1} $year^{-1}$. The higher N_2O emissions from Watts' study may have arisen from the higher N excreta data used (75.2 kg $herd^{-1}$ $year^{-1}$), which was higher than the ASAE

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(2005) recommended value of 62.05 kg N AU^{-1} $year^{-1}$ used in this study.[80]

3.3.2. NH_3 Emission. The total NH_3 emissions from a beef cattle feedlot system is 49.1 ± 1.5 kg NH_3 AU^{-1} $year^{-1}$. The manure on the feedlot stage was the leading sector, accounting for 80.8% of the total NH_3 emissions, while the manure composting and land application stages accounted for 16.5% and 2.7%, respectively (Figure 5). Nearly 60% of the total N excreta was lost from manure on the feedlot, and only 9−19% of the excreted N was transferred to the next stage.[81] Watts et al.[19] estimated that 85%, 9%, and 6% of the total NH_3 emissions were from the manure on the feedlot stage, stockpiling stage and land application stage, respectively, which is similar to the results of this study. The lower percentage of 9% for the manure stockpiling stage in Watts's study was lower than the 16.5% found in our study, which may have been caused by the lower NH_3 emissions from stockpiling compared to composting.

3.4. Gas Emissions of Beef Cattle Feedlot Production Systems under Mitigation Scenarios. Considering the major emission sources, efficiency and operability of mitigation options, 11 mitigation scenarios were designed for beef-cattle feedlot production systems. The GHG and NH_3 emissions from the scenarios are presented in Figure 6.

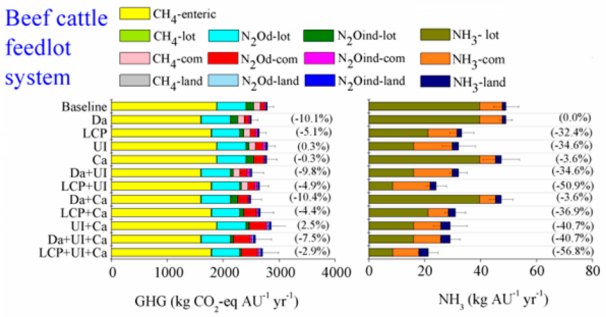


Figure 6. GHG and NH_3 emissions of baseline scenarios and mitigation scenarios for beef cattle feedlot production systems, with the baseline scenarios defined in Figure 2. The numbers in parentheses indicate the mitigation efficiency. N_2Od, direct N_2O emission; N_2Oind, indirect N_2O emission; lot, manure on the feedlot; com, compost; land, land application; LCP, low crude protein, Da, diet lipid addition; UI, UI additive for manure on the lot; Ca, compost additive; and AU, animal unit (1 AU = 500 kg).

The system-level GHG mitigation efficiencies of all mitigation scenarios were less than 11% (Figure 6). Of all of the mitigation strategies, dietary additives (Da) showed a high GHG mitigation potential for the whole system, with GHG emissions of 2505 ± 113 kg CO_2-eq AU^{-1} $year^{-1}$ for the solo use of Da, a 10.1% reduction from the baseline.

For system-level NH_3 mitigation, the most effective mitigation design was the combination of a LCP diet, a UI additive for manure on the feedlot, and compost additive (LCP plus UI plus Ca). The NH_3 emission was 21.2 ± 3.5 kg NH_3 AU^{-1} $year^{-1}$, with an efficiency of −56.8% compared with the baseline emissions. The single use of UI additive for manure on the feedlot or a LCP diet could reduce the overall system NH_3 emissions by 34.6% and 32.4%, respectively (Figure 6). The combination of LCP and UI lead to the system NH_3 emission being 24.1 ± 3.7 kg NH_3 AU^{-1} $year^{-1}$ (−50.9%), which was similar to the most effective NH_3 mitigation design of LCP plus UI plus Ca. This result also reveals that controlling the NH_3 emissions from the manure on the feedlot stage is fundamental for system-level NH_3 mitigation.

Considering the mitigation effect of each mitigation scenario, as well as the economy and simplicity of each option, the most recommended mitigation scenario is the combination of LCP and UI (LCP plus UI). The GHG and NH_3 emissions under the LCP plus UI scenario were 2648 ± 162 kg CO_2-eq AU^{-1} $year^{-1}$ (−4.9%) and 24.1 ± 3.7 kg NH_3 AU^{-1} $year^{-1}$ (−50.9%), respectively.

3.5. Implications of Results. This study provides the first insights into the simultaneous evaluation of GHG and NH_3 emissions and mitigations for beef cattle feedlot management systems, based on the database of the EFs and MEs for CH_4, N_2O, and NH_3 during each stage of the beef cattle feedlot production system. Both EFs and MEs were valuable for evaluating the gas emissions and identifying abundant mitigation options. These EFs could be applied to support the revision or refinement of the IPCC default EFs. However, the application of EFs or recommended mitigation strategies should take into account local circumstances, including climate, weather, and soil properties in different locations. In addition, the economic feasibility for the mitigation measures should also be further considered.

Scenario analysis for the beef cattle feedlot system implies that NH_3 emissions could be reduced by 30%−50% and that the highest system-level GHG emissions mitigation potential was only 10.1%. With the increasing demand for beef production and to decrease GHG emissions after the Paris Agreement, low emission beef cattle production systems are urgently needed. The results of our analysis have important implications for developing sustainable beef cattle feedlot systems from the viewpoint of GHG and NH_3 mitigation.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acs.est.8b02475.

A brief description of the detailed methods, equations, parameters, and assumptions for calculating the emissions for baseline and mitigation scenarios of each phase and whole systems for beef cattle feedlot production. Tables showing the unit conversion method, a detailed set of the baseline scenario and the mitigation scenarios and calculated gas emission factors for beef cattle feedlot systems in four stages, gas mitigation efficiency of each mitigation option, and other parameters used in gas emission calculation (PDF)

Tables showing the gas emissions calculation process, the parameters used for calculation, and raw data from the literature (XLSX)

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The manuscript was written through contributions of all authors. All authors have given approval to the final version of the manuscript.

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Notes

The authors declare no competing financial interest.

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■ REFERENCES

(1) Intergovernmental Panel on Climate Change (IPCC). *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*; Cambridge University Press: Cambridge, United Kingdom, 2013.

(2) Li, L.; Xu, J.; Hu, J.; Han, J. Reducing nitrous oxide emissions to mitigate climate change and protect the ozone layer. *Environ. Sci. Technol.* **2014**, *48* (9), 5290−5297.

(3) Montzka, S.; Dlugokencky, E.; Butler, J. Non-CO_2 greenhouse gases and climate change. *Nature* **2011**, *476* (7358), 43−50.

(4) Rao, S.; Riahi, K. The role of non-CO_2 greenhouse gases in climate change mitigation: Long-term scenarios for the 21st century. *Energy J.* **2006**, *27* (3), 177−200.

(5) Hansen, J.; Sato, M.; Ruedy, R.; Lacis, A.; Oinas, V. Global warming in the twenty-first century: An alternative scenario. *Proc. Natl. Acad. Sci. U. S. A.* **2000**, *97* (18), 9875−9880.

(6) Manne, A. S.; Richels, R. G. An alternative approach to establishing trade-offs among greenhouse gases. *Nature* **2001**, *410* (6829), 675−677.

(7) Bergström, A. N. N. K.; Jansson, M. Atmospheric nitrogen deposition has caused nitrogen enrichment and eutrophication of lakes in the northern hemisphere. *Glob. Change Biol.* **2006**, *12* (4), 635−643.

(8) Bouwman, A. F.; Boumans, L. J. M.; Batjes, N. H. Estimation of global NH_3 volatilization loss from synthetic fertilizers and animal manure applied to arable lands and grasslands. *Glob. Biogeochem. Cycles* **2002**, *16* (2), 1−14.

(9) Intergovernmental Panel on Climate Change (IPCC). *IPCC 2006 Guidelines for National Greenhouse Gas Inventories Vol. 4: Agriculture, Forestry, and Other Landuse*; Institute for Global Environmental Strategies: Hayama, Japan, 2006.

(10) Squizzato, S.; Masiol, M.; Innocente, E.; Pecorari, E.; Rampazzo, G.; Pavoni, B. A procedure to assess local and long-range transport contributions to PM 2.5, and secondary inorganic aerosol. *J. Aerosol Sci.* **2012**, *46* (2), 64−76.

(11) Intergovernmental Panel on Climate Change (IPCC). *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*; Cambridge University Press: Cambridge, United Kingdom, 2014.

(12) Davidson, E. A. The contribution of manure and fertilizer nitrogen to atmospheric nitrous oxide since 1860. *Nat. Geosci.* **2009**, *2* (9), 659−662.

(13) Steinfeld, H.; Gerber, P.; Wassenaar, T.; Castel, V.; Rosales, M.; De Haan, C. *Livestock's long shadow*; Food and Agriculture Organization of the United Nations (FAO): Rome, Italy, 2006.

(14) Food and Agriculture Organization of the United Nations (FAO). FAOSTAT of live animal production 2014. http://www.fao.org/faostat/en/#data/GE (accessed March 1, 2018).

(15) Paulot, F.; Jacob, D. J.; Pinder, R. W.; Bash, J. O.; Travis, K.; Henze, D. K. Ammonia emissions in the United States, European Union, and China derived by high-resolution inversion of ammonium wet deposition data: Interpretation with a new agricultural emissions inventory (MASAGE_NH_3). *J. Geophys Res.* **2014**, *119* (7), 4343−4364.

(16) Owen, J. J.; Silver, W. L. Greenhouse gas emissions from dairy manure management: a review of field-based studies. *Globa.l Change Biol.* **2015**, *21*, 550−565.

(17) United States Department of Agriculture. *2012 Census of Agriculture, United States, summary and state data, volume 1: Geographic area series, part 51*. https://www.agcensus.usda.gov/Publications/2012/Full_Report/Volume_1,_Chapter_1_US/usv1.pdf (accessed July 1, 2018).

(18) Parker, D. B.; Auvermann, B. W.; Stewart, B. A.; Robinson, C. A. Agricultural energy consumption, biomass generation, and livestock manure value in the Southern High Plains. In *Proc. Workshop No. 1, Livestock Waste Streams: Energy and Environment*; Texas Renewable Energy Industries Association: Austin, TX, 1997,1−18.

(19) Watts, P.; McGahan, E.; Bonner, S.; Wiedemann, S. *Feedlot mass balance and greenhouse gas emissions−a literature review*; Meat & Livestock Australia: Sydney, Australia, 2012.

(20) California Air Resources Board (CARB). *Annex 3B: Manure Management (IPCC 3A2) to the Technical Support Document for the 2000−2009 California's Greenhouse Gas Emissions Inventory*; California Air Resources Board: Sacramento, CA, 2011.

(21) Beauchemin, K. A.; McGinn, S. M. Enteric methane emissions from growing beef cattle as affected by diet and level of intake. *Can. J. Anim. Sci.* **2006**, *86* (3), 401−408.

(22) DeRamus, H. A.; Clement, T. C.; Giampola, D. D.; Dickison, P. C. Methane emissions of beef cattle on forages. *J. Environ. Qual.* **2003**, *32* (1), 269−277.

(23) Redding, M. R.; Devereux, J.; Phillips, F.; Lewis, R.; Naylor, T.; Kearton, T.; Hill, C.; Weidemann, S. Field measurement of beef pen manure methane and nitrous oxide reveals a surprise for inventory calculations. *J. Environ. Qual.* **2015**, *44* (3), 720−728.

(24) Borhan, M. S.; Capareda, S. C.; Mukhtar, S.; Faulkner, W. B.; McGee, R.; Parnell, C. B. Greenhouse gas emissions from ground level area sources in dairy and cattle feedyard operations. *Atmosphere* **2011**, *2* (3), 303−329.

(25) Costa, C., Jr.; Li, C.; Cerri, C. E.; Cerri, C. C. Measuring and modeling nitrous oxide and methane emissions from beef cattle feedlot manure management: First assessments under Brazilian condition. *J. Environ. Sci. Health, Part B* **2014**, *49* (9), 696−711.

(26) Sun, J.; Bai, M.; Shen, J.; Griffith, D. W.; Denmead, O. T.; Hill, J.; Lam, S. K.; Mosier, A. R.; Chen, D. Effects of lignite application on ammonia and nitrous oxide emissions from cattle pens. *Sci. Total Environ.* **2016**, *565*, 148−154.

(27) Hao, X.; Larney, F. J.; Chang, C.; Travis, G. R.; Nichol, C. K.; Bremer, E. The effect of phosphogypsum on greenhouse gas emissions during cattle manure composting. *J. Environ. Qual.* **2005**, *34* (3), 774−781.

(28) Opio, C.; Gerber, P.; Mottet, A.; Falcucci, A.; Tempio, G.; MacLeod, M.; Vellinga, T.; Henderson, B.; Steinfeld, H. *Greenhouse gas emissions from ruminant supply chains − A global life cycle assessment*; Food and Agriculture Organization of the United Nations (FAO): Rome, Italy, 2013.

(29) Hou, Y.; Velthof, G. L.; Oenema, O. Mitigation of ammonia, nitrous oxide and methane emissions from manure management chains: a meta-analysis and integrated assessment. *Glob. Change Biol.* **2015**, *21* (3), 1293−1312.

(30) Wang, Y.; Dong, H.; Zhu, Z.; Gerber, P. J.; Xin, H.; Smith, P.; Opio, C.; Steinfeld, H.; Chadwick, D. Mitigating Greenhouse Gas and Ammonia Emissions from Swine Manure Management: A System Analysis. *Environ. Sci. Technol.* **2017**, *51* (8), 4503−4511.

(31) Fedorov, S. *GetData Graph Digitizer version 2.24*. www.getdata-graph-digitizer.com (accessed October 1, 2017).

(32) Environmental Systems Research Institute (ESRI). ArcGIS Desktop 10.0. http://desktop.arcgis.com/en (accessed March 1, 2018).

DOI: 10.1021/acs.est.8b02475
Environ. Sci. Technol. 2018, 52, 11232−11242

(33) Larson-Hall, J.; Herrington, R. Improving data analysis in second language acquisition by utilizing modern developments in applied statistics. *Appl. Linguist.* **2010**, *31* (3), 368−390.
(34) Benayas, J. M. R.; Newton, A. C.; Diaz, A.; Bullock, J. M. Enhancement of biodiversity and ecosystem services by ecological restoration: a meta-analysis. *Science* **2009**, *325*, 1121−1124.
(35) Tuomisto, H. L.; Hodge, I. D.; Riordan, P.; Macdonald, D. W. Does organic farming reduce environmental impacts?−A meta-analysis of European research. *J. Environ. Manage.* **2012**, *112*, 309−320.
(36) Van Haarlem, R. P.; Desjardins, R. L.; Gao, Z.; Flesch, T. K.; Li, X. Methane and ammonia emissions from a beef feedlot in western Canada for a twelve-day period in the fall. *Can. J. Anim. Sci.* **2008**, *88* (4), 641−649.
(37) Mcginn, S. M.; Chen, D.; Loh, Z.; Hill, J.; Beauchemin, K. A.; Denmead, O. T. Methane emissions from feedlot cattle in Australia and Canada. *Aust. J. Exp. Agric.* **2008**, *48* (2), 183−185.
(38) Hegarty, R. S.; Goopy, J. P.; Herd, R. M.; McCorkell, B. Cattle selected for lower residual feed intake have reduced daily methane production. *J. Anim. Sci.* **2007**, *85* (6), 1479−1486.
(39) Arthur, P. F.; Archer, J. A.; Herd, R. M. Feed intake and efficiency in beef cattle: overview of recent Australian research and challenges for the future. *Aust. J. Exp. Agric.* **2004**, *44* (5), 361−369.
(40) Misselbrook, T.; Webb, J.; Chadwick, D.; Ellis, S.; Pain, B. Gaseous emissions from outdoor concrete yards used by livestock. *Atmos. Environ.* **2001**, *35* (31), 5331−5338.
(41) Misselbrook, T.; Webb, J.; Gilhespy, S. Ammonia emissions from outdoor concrete yards used by livestock—quantification and mitigation. *Atmos. Environ.* **2006**, *40* (35), 6752−6763.
(42) Demmers, T.; Phillips, V.; Short, L.; Burgess, L.; Hoxey, R.; Wathes, C. SE—Structure and Environment: Validation of ventilation rate measurement methods and the ammonia emission from naturally ventilated dairy and beef buildings in the United Kingdom. *J. Agric. Eng. Res.* **2001**, *79* (1), 107−116.
(43) Boadi, D. A.; Wittenberg, K. M.; Scott, S. L.; Burton, D.; Buckley, K.; Small, J. A.; Ominski, K. H. Effect of low and high forage diet on enteric and manure pack greenhouse gas emissions from a feedlot. *Can. J. Anim. Sci.* **2004**, *84* (3), 445−453.
(44) Rahman, S.; Borhan, M. S.; Swanson, K. Greenhouse gas emissions from beef cattle pen surfaces in North Dakota. *Environ. Technol.* **2013**, *34* (10), 1239−1246.
(45) Borhan, M.; Gautam, D.; Engel, C.; Anderson, V.; Rahman, S. Effects of pen bedding and feeding high crude protein diets on manure composition and greenhouse gas emissions from a feedlot pen surface. *J. Air Waste Manage. Assoc.* **2013**, *63* (12), 1457−1468.
(46) Drury, C. F.; Yang, X.; Reynolds, W. D.; Calder, W.; Oloya, T. O.; Woodley, A. L. Combining urease and nitrification inhibitors with incorporation reduces ammonia and nitrous oxide emissions and increases corn yields. *J. Environ. Qual.* **2017**, *46* (5), 939−949.
(47) Woodley, A. L.; Drury, C. F.; Reynolds, W.; Calder, M. W.; Yang, X. M.; Oloya, T. O. Improved acid trap methodology for determining ammonia volatilization. Canadian Journal of Soil Science. Improved acid trap methodology for determining ammonia volatilization in wind tunnel experiments. *Can. J. Soil Sci.* **2018**, *98*, 193−199.
(48) Aguilar, O. A. *Measurement and control of greenhouse gas emissions from beef cattle feedlots*. PhD thesis. Kansas State University, Manhattan, KS, 2013.
(49) Le Mer, J.; Roger, P. Production, oxidation, emission and consumption of methane by soils: a review. *Eur. J. Soil Biol.* **2001**, *37* (1), 25−50.
(50) Chiyoka, W.; Hao, X.; Zvomuya, F.; Li, X. Nitrous oxide emissions from Chernozemic soils amended with anaerobically digested beef cattle feedlot manure: A laboratory study. *Anim. Feed Sci. Technol.* **2011**, *166*, 492−502.
(51) Chang, C.; Janzen, H.; Cho, C. Nitrous oxide emission from long-term manured soils. *Soil Sci. Soc. Am. J.* **1998**, *62* (3), 677−682.
(52) Velthof, G. L.; Kuikman, P. J.; Oenema, O. Nitrous oxide emission from animal manures applied to soil under controlled conditions. *Biol. Fertility Soils* **2003**, *37* (4), 221−230.
(53) Webb, J.; Chadwick, D.; Ellis, S. Emissions of ammonia and nitrous oxide following incorporation into the soil of farmyard manures stored at different densities. *Nutr. Cycling Agroecosyst.* **2004**, *70* (1), 67−76.
(54) Li, J.; Su, F.; Huang, B.; Hu, X.; Ju, X.; Zhang, F. Ammonia volatilization from field-applied chicken manure in Beijing. *J. Agro-Environ. Sci.* **2009**, *28* (9), 1959−1964 (in Chinese with English abstract) .
(55) Webb, J.; Thorman, R.; Fernanda-Aller, M.; Jackson, D. Emission factors for ammonia and nitrous oxide emissions following immediate manure incorporation on two contrasting soil types. *Atmos. Environ.* **2014**, *82*, 280−287.
(56) Dinuccio, E.; Gioelli, F.; Balsari, P.; Dorno, N. Ammonia losses from the storage and application of raw and chemo-mechanically separated slurry. *Agric., Ecosyst. Environ.* **2012**, *153*, 16−23.
(57) Li, L. L. *Study on the Characteristic and Reduction for Greenhouse Gases and Ammonia Emissions during the Storage of Manure and Wastewater*. Master thesis. Chinese Academy of Agricultural sciences, Beijing, China, 2016 (in Chinese with English abstract).
(58) Gerber, P. J.; Hristov, A. N.; Henderson, B.; Makkar, H.; Oh, J.; Lee, C.; Meinen, R.; Montes, F.; Ott, T.; Firkins, J.; Rotz, A.; Dell, C.; Adesogan, A. T.; Yang, W. Z.; Tricarico, J. M.; Kebreab, E.; Waghorn, G.; Dijkstra, J.; Oosting, S. Technical options for the mitigation of direct methane and nitrous oxide emissions from livestock: a review. *Animal* **2013**, *7* (s2), 220−234.
(59) Tomkins, N.; Colegate, S.; Hunter, R. A bromochloromethane formulation reduces enteric methanogenesis in cattle fed grain-based diets. *Anim. Prod. Sci.* **2009**, *49* (12), 1053−1058.
(60) Leng, R. A. *The potential of feeding nitrate to reduce enteric methane production in ruminants*; Report to the Department of Climate Change; Commonwealth Government of Australia: Canberra, Australia. 2008.
(61) Li, W.; Powers, W. Effects of saponin extracts on air emissions from steers. *J. Anim. Sci.* **2012**, *90* (11), 4001−4013.
(62) Lee, C.; Araujo, R. C.; Koenig, K. M.; Hile, M. L.; Fabian-Wheeler, E. E.; Beauchemin, K. A. Effects of feeding encapsulated nitrate to beef cattle on ammonia and greenhouse gas emissions from their manure in a short-term manure storage system. *J. Environ. Qual.* **2016**, *45* (6), 1979−1987.
(63) Stackhouse-Lawson, K. R.; Calvo, M. S.; Place, S. E.; Armitage, T. L.; Pan, Y.; Zhao, Y.; Mitloehner, F. M. Growth promoting technologies reduce greenhouse gas, alcohol, and ammonia emissions from feedlot cattle. *J. Anim. Sci.* **2013**, *91* (11), 5438−5447.
(64) Benchaar, C.; Pomar, C.; Chiquette, J. Evaluation of dietary strategies to reduce methane production in ruminants: a modelling approach. *Can. J. Anim. Sci.* **2001**, *81* (4), 563−574.
(65) Van Kessel, J. A. S.; Russell, J. B. The effect of pH on ruminal methanogenesis. *FEMS Microbiol. Ecol.* **1996**, *20* (4), 205−210.
(66) Mc Geough, E. J.; O'Kiely, P.; Hart, K. J.; Moloney, A. P.; Boland, T. M.; Kenny, D. A. Methane emissions, feed intake, performance, digestibility, and rumen fermentation of finishing beef cattle offered whole-crop wheat silages differing in grain content. *J. Anim. Sci.* **2010**, *88* (8), 2703−2716.
(67) Varel, V. H.; Nienaber, J. A.; Freetly, H. C. Conservation of nitrogen in cattle feedlot waste with urease inhibitors. *J. Anim. Sci.* **1999**, *77* (5), 1162−1168.
(68) Faria, L. D. A.; do Nascimento, C. A. C.; Bardella, G. R.; de Moura, T. A.; Mendes, F. L.; Vitti, G. C. NH3 Volatilization from Urea-NBPT in Eucalyptus. *Commun. Soil Sci. Plant Anal.* **2016**, *47* (6), 769−774.
(69) Li, Q. Q. *Effect of urease inhibitor LIMUS on ammonia mitigation and crop yield and nitrogen use efficiency in different croplands of China*. PhD thesis. Chinese Agricultural University, Beijing, China, 2014 (in Chinese with English abstract).

DOI: 10.1021/acs.est.8b02475
Environ. Sci. Technol. 2018, 52, 11232−11242

(70) Shi, Y.; Parker, D.; Cole, N.; Auvermann, B.; Mehlhorn, J. Surface amendments to minimize ammonia emissions from beef cattle feedlots. *Trans. ASAE* **2001**, *44* (3), 677−682.
(71) Chen, D.; Sun, J.; Bai, M.; Dassanayake, K. B.; Denmead, O. T.; Hill, J. A new cost-effective method to mitigate ammonia loss from intensive cattle feedlots: application of lignite. *Sci. Rep.* **2015**, *5*, 16689.
(72) Lory, J.; Adams, J.; Eghball, B.; Klopfenstein, T.; Powers, J. F. Effect of sawdust or acid application to pen surfaces on nitrogen losses from open-dirt feedlots. Nebraska Beef Cattle Reports: Lincoln, NE, 2002; pp 52−53.
(73) Wilson, C. B.; Erickson, G. E.; Macken, C. N.; Klopfenstein, T. J. *Impact of cleaning frequency on nitrogen balance in open feedlot pens*. Nebraska Beef Cattle Reports: Lincoln, NE, 2004; pp 72−73.
(74) Lim, S. S.; Park, H. J.; Hao, X.; Lee, S. I.; Jeon, B. J.; Kwak, J. H.; Choi, W. J. Nitrogen, carbon, and dry matter losses during composting of livestock manure with two bulking agents as affected by co-amendments of phosphogypsum and zeolite. *Ecol. Eng.* **2017**, *102*, 280−290.
(75) Park, K. J.; Choi, M. H.; Hong, J. H. Control of composting odor using biofiltration. *Compost Sci. Util.* **2002**, *10* (4), 356−362.
(76) Xue, N.; Wang, Q.; Wu, C. F.; Zhang, L. H.; Xie, W. M. Enhanced removal of NH3 during composting by a biotrickling filter inoculated with nitrifying bacteria. *Biochem. Eng. J.* **2010**, *51* (1), 86−93.
(77) Zhu, H. S.; Zuo, F. Y.; Dong, H. M.; Luan, D. M. Effects of covering materials and sawdust covering depths on ammonia and greenhouse gase emissions from cattle manure during storage. *Transactions of the CSAE* **2015**, *31* (6), 223−229 (in Chinese with English abstract) .
(78) Watanabe, A.; Ikeya, K.; Kanazaki, N.; Makabe, S.; Sugiura, Y.; Shibata, A. Five crop seasons' records of greenhouse gas fluxes from upland fields with repetitive applications of biochar and cattle manure. *J. Environ. Manage.* **2014**, *144*, 168−175.
(79) Shah, G. M.; Shah, G. A.; Groot, J. C. J.; Oenema, O.; Lantinga, E. A. Irrigation and lava meal use reduce ammonia emission and improve N utilization when solid cattle manure is applied to grassland. *Agric., Ecosyst. Environ.* **2012**, *160* (4), 59−65.
(80) *ASAE Standards D384.1: Manure Production and Characteristics*; American Society of Agricultural Engineers: Saint Joseph, MI, 2004.
(81) Bierman, S.; Erickson, G.; Klopfenstein, T.; Stock, R. A.; Shain, D. Evaluation of nitrogen and organic matter balance in the feedlot as affected by level and source of dietary fiber. *J. Anim. Sci.* **1999**, *77* (7), 1645−1653.

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ARTICLES

REINING IN ANIMAL AGRICULTURE'S EMISSIONS BY SHRINKING THE HERD: EARLY SIGNS OF A NECESSARY GLOBAL POLICY SHIFT

BY
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We will be unable to achieve the temperature goals of the Paris Agreement without radically reforming our food systems. Despite animal agriculture's significant responsibility for climate change—emitting the majority of agricultural greenhouse gases (GHGs), likely 15% or more of all human-caused GHGs, around a third of anthropogenic methane and more than half of nitrous oxide (two climate super-pollutants)—policymakers have so far largely failed to rein in its emissions. In recent years, international bodies including the Intergovernmental Panel on Climate Change, U.N. Environment Programme, World Health Organization, and World Bank have begun to explicitly make the connection between animal agriculture's outsized emissions and the need to reduce consumption of animal products, especially in high-income, high-consuming countries. While national-level policy in the United States has not yet embraced these recommendations, policymakers in other countries—led by Europe—are experimenting with policies that would change diets and ultimately "shrink the herd," i.e., reduce the number of animals raised for food. Recent farmer protests and

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weakening of policy proposals in Europe illustrate the political realities of seeking reform in this area. But sooner government action would enable better outcomes, before the climate crisis forces changes to food systems. Developing effective and lasting policy on climate and animal agriculture will require consensus building, incremental approaches, attention to international equity, and a commitment to a just transition.

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I. INTRODUCTION

> Say the order of your time feels unjust and unsustainable and yet massively entrenched, but also falling apart before your eyes.
>
> ~Kim Stanley Robinson,
> *The Ministry for the Future*[1]

> [A]s the world keeps warming, it will become clear that political leaders' climate pledges require that we phase down all sorts of polluting machines: not just the metal ones that burn fossil fuels but also the ones that have brains, and hearts, and use up three-quarters of the world's agricultural land, and overheat the planet.

[1] KIM STANLEY ROBINSON, THE MINISTRY FOR THE FUTURE 124 (2020) (including a cover inscription by writer Jonathan Lethem describing it as "[t]he best science fiction nonfiction novel I've ever read").

~Noah Gordon,
Carnegie Endowment for
International Peace[2]

Despite the immense scale of greenhouse gas (GHG) emissions from the U.S. animal agriculture sector,[3] the federal government remains largely unwilling to espouse reductions to meat and dairy consumption as part of its climate mitigation strategy. Indeed, after a British tabloid article falsely implied that President Biden was planning to limit meat consumption in order to meet emissions targets and Republican politicians began spreading the story (some even calling him "The Hamburglar"), a Biden spokesperson was quick to post a reassuring photo of Biden smiling while grilling steaks.[4]

U.S. Agriculture Secretary Tom Vilsack, a former dairy lobbyist,[5] has downplayed the growing momentum—led by some other national governments and in the international arena[6]—around elevating plant-based foods to help the climate. Despite the unprecedented focus on food systems and dietary change at the Conference of the Parties to the U.N. Framework Convention on Climate Change in Dubai (COP28),[7] when asked about reducing meat consumption as part of climate mitigation, Secretary Vilsack replied: "I don't hear much about that."[8]

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[2] Noah Gordon, *No, the Government Isn't Coming for Your Burger—But Maybe It Should Be*, NEW REPUBLIC (Oct. 3, 2023), https://newrepublic.com/article/175875/no-government-isnt-coming-burgerbut-maybe.

[3] *E.g.*, *Sector at a Glance*, U.S. DEP'T AGRIC., ECON. RSCH. SERV., https://www.ers.usda.gov/topics/animal-products/cattle-beef/sector-at-a-glance (Aug. 30, 2023) (noting that the United States has "the world's largest fed-cattle industry" and "is also the world's largest consumer of beef"); GRAIN & INST. FOR AGRIC. & TRADE POL'Y, EMISSIONS IMPOSSIBLE: HOW BIG MEAT AND DAIRY ARE HEATING UP THE PLANET 6 (2018) [hereinafter EMISSIONS IMPOSSIBLE], https://grain.org/article/entries/5976-emissions-impossible-how-big-meat-and-dairy-are-heating-up-the-planet (identifying the United States as one of the "main culprits" for animal agriculture GHG emissions, which "have surplus production *and* high per capita consumption of meat and dairy").

[4] Katie Shepherd, *Biden's Climate Plan Doesn't Ban Meat. But Baseless Claims Left Republicans Fuming: 'Stay Out of My Kitchen*,' WASH. POST (Apr. 26, 2021, 4:58 AM), https://www.washingtonpost.com/nation/2021/04/26/republicans-meat-biden-climate-plan; David Bauder & Ali Swenson, *The Hamburglar? How a Story About Meat Limits Fell Apart*, ASSOCIATED PRESS (Apr. 28, 2021, 8:55 AM), https://apnews.com/article/joe-biden-new-york-climate-climate-change-media-529b0cb6d7393c225c8b9baf040c1904.

[5] Tom Philpott, *It's Official: A Former Dairy Exec Now Runs Biden's Agriculture Department*, MOTHER JONES (Feb. 23, 2021), https://www.motherjones.com/food/2021/02/its-official-a-former-dairy-exec-now-runs-bidens-agriculture-department.

[6] *See* discussion *infra* Parts III–IV.

[7] *See infra* notes 101–122 and accompanying text.

[8] Marcia Brown & Meredith Lee Hill, *Tom Vilsack at COP28*, POLITICO (Dec. 11, 2023, 10:00 AM), https://www.politico.com/newsletters/weekly-agriculture/2023/12/11/tom-vilsack-at-cop28-00131018. More than 250 advocacy groups and experts sent Secretary Vilsack a letter in response, noting the prominent discussions of meat and dairy reduction at COP28 and arguing that the United States must incorporate meat and dairy reduction into its climate strategies. Letter from Ctr. for Biological Diversity et al. to Thomas J. Vilsack, U.S. Sec'y of Agric. 2 (Jan. 11, 2024), https://www.biologicaldiversity.org/programs/population_and_sustainability/pdfs/usda_sec_vilsack_letter.pdf.

Other U.S. lawmakers did not share his insouciance. Commenting on ongoing food system discussions at COP28, U.S. Senator Chuck Grassley of Iowa asserted that the talks were "targeting farmers" and that "[t]hey're really after the livestock business."[9] Representative Mike Flood of Nebraska went so far as to propose that the U.S. House of Representatives adopt a resolution to express disapproval of the recommendations shared by the U.N. Food & Agriculture Organization (FAO) at COP28[10] and "oppose[] the use of any Federal resources to support attempts to reduce meat consumption."[11]

The reactionary posture of many U.S. lawmakers when it comes to the animal agriculture industry has been a frustration for decades for those who seek to address its numerous and significant externalized harms to people, animals, and the environment.[12] But changemakers may take inspiration from a nascent wave of policies around the world that would have the concomitant impact of reducing both GHG emissions and animal numbers. Such policies may address supply (e.g., by buying out farmers) or demand (e.g., by shifting dietary guidelines and procurement policies), and they may combine various approaches. This Article focuses on policies that would ultimately result in a reduction of the total number of animals (rather than technological approaches[13]) because policies that "shrink the herd" are the only ones that guarantee a reduction in emissions while at the same time reducing the other harmful externalities of industrial animal agriculture.

These are not new ideas.[14] What is new is the acceleration of policy proposals and activity over the last half decade. This Article aims to collect progress and challenges for policymakers and advocates who would look to learn from leading examples—and who may also be inspired by the degree of activity in a policy area that can sometimes seem intractable. Part II provides background on animal agriculture's role in the climate crisis, followed by an overview of global momentum and international signaling in Part III. Part IV describes examples of climate animal agriculture policies around the world. Recent farmer

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9 Marc Heller, *Grassley Laments Climate Talks 'Targeting' Farmers*, E&E DAILY (Dec. 6, 2023, 6:19 AM), https://subscriber.politicopro.com/article/eenews/2023/12/06/grassley-laments-climate-talks-targeting-farmers-00130164.

10 *See* discussion of the FAO Roadmap *infra* notes 111–115 and accompanying text.

11 H.R. Res. 920, 118th Cong. §§ 3–4 (2023); *see also* Press Release, Rep. Mike Flood, Rep. Flood Introduces Resolution Condemning UN's Anti-Beef Food Strategy (Dec. 11, 2023), https://flood.house.gov/media/press-releases/rep-flood-introduces-resolution-condemning-uns-anti-beef-food-strategy ("The resolution I'm introducing today makes it clear that the United States opposes any attempt to reduce or eliminate meat production.").

12 *See infra* notes 244–256 and accompanying text.

13 *See* discussion *infra* Section IV.E.

14 *E.g.*, Herve Guyomard et al., *Review: Why and How to Regulate Animal Production and Consumption: The Case of the European Union*, ANIMAL: INT'L J. ANIMAL BIOSCIS., Dec. 2021, No. 100383, at 9 (citing articles published in 2011 and 2017) ("In order to significantly diminish GHG emissions of food systems, it will be necessary to reduce livestock activity levels.").

protests in the Netherlands are described in Part V as an example of political headwinds, followed by a gathering of lessons in Part VI.

II. BACKGROUND: ANIMAL AGRICULTURE AND CLIMATE

Last year was the hottest year on record,[15] shattering prior temperatures and causing scientists to use words like "mind-boggling," "staggering," and "absolutely gobsmackingly bananas."[16] The summer of 2024 was the warmest on record,[17] and this year is "virtually certain" to be the warmest year on record, exceeding even the unprecedented temperatures of 2023.[18] While some of the recent warming was likely associated with the El Niño weather pattern, many scientists are concerned at what may be the beginning of an accelerating trend.[19]

Higher temperatures not only have major impacts around the world—including extreme heat and drought and associated wildfires, tropical cyclones, and major floods[20]—but are also concerning because of their ability to induce irreversible changes. Tipping points are changes to climatic systems that become self-perpetuating at certain levels of warming.[21] A 2023 report found that at least five major systems were at risk of reaching tipping points, namely: the Greenland and West Antarctic ice sheets, warm-water coral reefs, North Atlantic Subpolar Gyre circulation, and permafrost regions.[22] The report described the risk of triggering tipping points as amongst "the gravest threats faced by humanity," which would "severely damage our planet's life-support systems and threaten the stability of our societies."[23]

To confront this challenge collectively, nearly all countries in the world have signed onto the Paris Agreement, a climate change treaty.[24] The primary goals of the Agreement are to maintain global average

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[15] Press Release No. 24-008, Roxana Bardan, Nat'l Aeronautics & Space Admin., NASA Analysis Confirms 2023 as Warmest Year on Record (Jan. 12, 2024), https://www.nasa.gov/news-release/nasa-analysis-confirms-2023-as-warmest-year-on-record.

[16] Zeke Hausfather, Opinion, *I Study Climate Change. The Data Is Telling Us Something New.*, N.Y. TIMES (Oct. 13, 2023), https://www.nytimes.com/2023/10/13/opinion/climate-change-excessive-heat-2023.html.

[17] Sally Younger, *NASA Finds Summer 2024 the Hottest to Date*, NASA (Sept. 11, 2024), https://www.nasa.gov/earth/nasa-finds-summer-2024-hottest-to-date.

[18] Press Release, Eur. Comm'n et al., Copernicus: 2024 Virtually Certain to Be the Warmest Year and First Year Above 1.5ºC (Nov. 7, 2024), https://climate.copernicus.eu/copernicus-2024-virtually-certain-be-warmest-year-and-first-year-above-15degc.

[19] Hausfather, *supra* note 16.

[20] Press Release, World Meteorological Org., 2023 Shatters Climate Records, with Major Impacts (Nov. 30, 2023), https://wmo.int/news/media-centre/2023-shatters-climate-records-major-impacts.

[21] David I. Armstrong McKay et al., *Exceeding 1.5ºC Global Warming Could Trigger Multiple Climate Tipping Points*, 377 SCIENCE 1171 (2022).

[22] UNIV. OF EXETER GLOB. SYS. INST., GLOBAL TIPPING POINTS: SUMMARY REPORT 2023, at 5 (2023).

[23] *Id.* at 3.

[24] *The Paris Agreement*, U.N. FRAMEWORK CONVENTION ON CLIMATE CHANGE, https://unfccc.int/process-and-meetings/the-paris-agreement (last visited Sept. 16, 2024).

temperatures well below 2ºC above pre-industrial levels, and to use best efforts to limit the increase to 1.5ºC.[25] According to the Intergovernmental Panel on Climate Change (IPCC), the UN body responsible for assessing the science related to climate change,[26] limiting the temperature increase to as close as possible to 1.5ºC is necessary to avoid the worst effects of climate change.[27] But, on our current path, we will reach 3.2ºC by 2100.[28] 2024 is on track to be the first year averaging more than 1.5ºC above preindustrial temperatures.[29] While one year spent above an average of 1.5ºC does not breach the Paris Agreement targets—which require a sustained increase over a longer period[30]—there is a growing understanding amongst scientists that breaching 1.5ºC is, at this point, likely inevitable.[31] To increase the chances of a safer future, time is of the essence. In 2023, the United Nations advised that GHG emissions would need to be halved by the end of this decade, describing a looming "climate cataclysm."[32]

But policy makers the world over have so far largely failed to address a key contributor to climate change: animal agriculture.[33] It will not be possible to adhere to climate targets without addressing food systems.[34] Animal agriculture is the biggest factor,[35] accounting for

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[25] *Id.*

[26] INTERGOV'TAL PANEL ON CLIMATE CHANGE, https://www.ipcc.ch (last visited Sept. 16, 2024).

[27] U.N. INTERGOV'TAL PANEL ON CLIMATE CHANGE [IPCC], GLOBAL WARMING OF 1.5°C, at v–vi (Valérie Masson-Delmotte et al. eds., 2018) [hereinafter 2018 IPCC REPORT], https://www.ipcc.ch/sr15/download.

[28] WILLIAM R. SUTTON ET AL., RECIPE FOR A LIVABLE PLANET: ACHIEVING NET ZERO EMISSIONS IN THE AGRIFOOD SYSTEM (OVERVIEW), WORLD BANK 6 (2024), https://openknowledge.worldbank.org/server/api/core/bitstreams/a0431f46-c65e-441a-9eed-8783d8b00272/content.

[29] Eur. Comm'n et al., *supra* note 18.

[30] Paris Agreement art. 2, ¶ 1, *adopted* Dec. 12, 2015, T.I.A.S. No. 16-1104, 3156 U.N.T.S. 79.

[31] *E.g.*, Jeff Tollefson, *Is It Too Late to Keep Global Warming Below 1.5°C? The Challenge in 7 Charts*, NATURE (Nov. 21, 2023), https://www.nature.com/immersive/d41586-023-03601-6/index.html.

[32] U.N. DEP'T OF ECON. & SOC. AFFAIRS, THE SUSTAINABLE DEVELOPMENT GOALS REPORT 2023, at 38 (Jennifer Ross ed., 2023), https://unstats.un.org/sdgs/report/2023/The-Sustainable-Development-Goals-Report-2023.pdf.

[33] *E.g.*, Simona Vallone & Eric Lambin, *Public Policy and Vested Interests Preserve the Animal Farming Status Quo at the Expense of Animal Product Analogs*, 6 ONE EARTH 1213, 1221 (2023) ("Despite the climate and biodiversity crises and the urgency to implement effective mitigation measures, both the EU and U.S. governments are slow to act decisively to mitigate the environmentally damaging role played by the dominant animal production systems.").

[34] Michael A. Clark et al., *Global Food System Emissions Could Preclude Achieving the 1.5° and 2°C Climate Change Targets*, 370 SCIENCE 705, 705 (2020) ("[E]ven if fossil fuel emissions were immediately halted, current trends in global food systems would prevent the achievement of the 1.5°C target and, by the end of the century, threaten the achievement of the 2°C target. Meeting the 1.5°C target requires rapid and ambitious changes to food systems as well as to all nonfood sectors."); *see also* U.N. ENV'T PROGRAMME, EMISSIONS GAP REPORT 2022: THE CLOSING WINDOW—CLIMATE CRISIS CALLS FOR RAPID

nearly sixty percent of global food system emissions[36] and almost eighty percent of U.S. agricultural emissions.[37] Overall, animal agriculture is likely responsible for somewhere between 14.5% and 20% of global GHG emissions.[38]

Animal agriculture also bears outsized responsibility for emissions of the climate super-pollutants methane and nitrous oxide. Nitrous oxide is an exceptionally powerful GHG, around 280 times more potent than carbon dioxide over its first twenty years in the atmosphere.[39] According to a U.N. estimate, more than half of all nitrous oxide comes from animal agriculture.[40]

Animal agriculture is also responsible for almost one third of all anthropogenic methane emissions globally and 36% in the United States.[41] During its first twenty years after release, methane is about 80

TRANSFORMATION OF SOCIETIES, at xxv (2022), https://www.unep.org/emissions-gap-report-2022 ("To get on an emissions pathway aligned with the Paris Agreement temperature goal, . . . [r]equired transformations include shifting diets, protecting natural ecosystems, improving food production and decarbonizing the food value chain.").

35 2018 IPCC REPORT, *supra* note 27, at 327.

36 U.N. ENV'T PROGRAMME, WHAT'S COOKING? AN ASSESSMENT OF THE POTENTIAL IMPACTS OF SELECTED NOVEL ALTERNATIVES TO CONVENTIONAL ANIMAL PRODUCTS, at viii (2023) [hereinafter UNEP WHAT'S COOKING?], https://wedocs.unep.org/20.500.11822/44236.

37 PETER H. LEHNER & NATHAN A. ROSENBERG, FARMING FOR OUR FUTURE; THE SCIENCE, LAW, AND POLICY OF CLIMATE-NEUTRAL AGRICULTURE 43 (2021).

38 UNEP WHAT'S COOKING?, *supra* note 36, at viii; *see also* Dan Blaustein-Rejto & Chris Gambino, *Livestock Don't Contribute 14.5% of Global Greenhouse Gas Emissions*, BREAKTHROUGH INST. (Mar. 20, 2023), https://thebreakthrough.org/issues/food-agriculture-environment/livestock-dont-contribute-14-5-of-global-greenhouse-gas-emissions (describing prominent estimates of livestock's global emissions responsibility between 11.1% and 19.6%). The U.N. Food & Agriculture Organization's (FAO's) most recent estimate is the low end of that range, and the only one below 14.5%. U.N. FOOD & AGRIC. ORG., PATHWAYS TOWARDS LOWER EMISSIONS: A GLOBAL ASSESSMENT OF THE GREENHOUSE GAS EMISSIONS AND MITIGATION OPTIONS FROM LIVESTOCK AGRIFOOD SYSTEMS 4 (2023), https://www.fao.org/3/cc9029en/cc9029en.pdf. Given that FAO's prior estimates were higher (14.5% and 17.8%) and that a number of commentators have questioned the recent lower estimate, this Article provides the UNEP's recent description above: 14.5%–20%. *E.g.*, Blaustein-Rejto & Gambino, *supra* (noting that "FAO's [recent] analysis has several limitations and uncertainties," and that it may not accurately estimate GHG emissions of grazing and the impacts of deforestation and land-use change); Arthur Neslen, *Ex-Officials at UN Farming Body Say Work on Methane Emissions Was Censored*, GUARDIAN (Oct. 20, 2023).

39 Piers Forster et al., *The Earth's Energy Budget, Climate Feedbacks and Climate Sensitivity*, *in* CLIMATE CHANGE 2021: THE PHYSICAL SCIENCE BASIS 923, 1017 (Valérie Masson-Delmotte et al. eds., 6th ed. 2021).

40 P.J. GERBER ET AL., U.N. FOOD & AGRIC. ORG., TACKLING CLIMATE CHANGE THROUGH LIVESTOCK 15 (2013), https://www.fao.org/3/i3437e/i3437e.pdf (relying on 2004 and 2005 data).

41 U.S. ENV'T PROT. AGENCY, INVENTORY OF U.S. GREENHOUSE GAS EMISSIONS AND SINKS: 1990-2022, at ES-18 (2023), https://www.epa.gov/system/files/documents/2024-04/us-ghg-inventory-2024-main-text_04-18-2024.pdf; PETER H. LEHNER & NATHAN A. ROSENBERG, FARMING FOR OUR FUTURE: THE SCIENCE, LAW, AND POLICY OF CLIMATE-NEUTRAL AGRICULTURE 41 (2021); Jo-Anne McArthur, *Methane Emissions Are Driving Climate Change. Here's How to Reduce Them*, U.N. ENV'T PROGRAMME, (Aug. 20, 2021)

times more powerful than carbon dioxide.[42] But an average methane molecule only lasts in the atmosphere for about a decade, while carbon dioxide can persist for hundreds of years.[43] The potency of methane, combined with its shorter life in the atmosphere, creates a mitigation opportunity. As explained by the U.N. Environment Programme (UNEP): "[R]educing methane emissions now would have an impact in the near term and is critical for helping keep the world on a path to 1.5°C."[44] In light of both its emissions of climate super-pollutants and association with land use change, a "global phaseout" of animal agriculture over the next fifteen years "would have the same effect, through the end of the century, as a 68% reduction of CO_2 emissions."[45]

Nonetheless, animal agriculture has frequently benefitted from light or no environmental regulation around the world.[46] The United States is a particularly cogent example. In the climate realm, the United States has consistently and almost entirely exempted the animal agriculture industry from air pollution GHG regulation regimes.[47] Even in Europe—while ahead of the United States in addressing animal agriculture's climate impacts[48]—significant continent-wide policy has so far failed to address the climate harms of animal agriculture. Efforts to use the EU Industrial Emissions Directive (IED), which regulates pollutants from industrial facilities, to regulate GHG emissions from large-scale animal agriculture floundered in 2023 when industry lobbying resulted in the European Parliament removing all cattle farms and some targeted pig and poultry farms from the reach of the

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[hereinafter *UNEP Methane Emissions*], https://www.unep.org/news-and-stories/story/methane-emissions-are-driving-climate-change-heres-how-reduce-them.

[42] Forster et al., *supra* note 39, at 1017.

[43] *Overview of Greenhouse Gases*, U.S. ENV'T PROT. AGENCY, https://www.epa.gov/ghgemissions/overview-greenhouse-gases (Feb. 16, 2024); *Understanding Global Warming Potentials,* U.S. ENV'T PROT. AGENCY, https://www.epa.gov/ghgemissions/understanding-global-warming-potentials (Apr. 18, 2023); *UNEP Methane Emissions*, *supra* note 41.

[44] *UNEP Methane Emissions*, *supra* note 41; *see also* U.N. INTERGOV'TAL PANEL ON CLIMATE CHANGE, CLIMATE CHANGE 2023: SYNTHESIS REPORT 26 (Hoesung Lee & José Romero eds., 2023) [hereinafter IPCC SIXTH ASSESSMENT REPORT SYNTHESIS] ("Strong, rapid and sustained reductions in methane emissions can limit near-term warming and improve air quality by reducing global surface ozone (*high confidence*).").

[45] Michael B. Eisen & Patrick O. Brown, *Rapid Global Phaseout of Animal Agriculture Has the Potential to Stabilize Greenhouse Gas Levels for 30 Years and Offset 68 Percent of CO_2 Emissions This Century*, PLOS CLIMATE, Feb. 1, 2022, No. e0000010, at 2–3, 7, https://doi.org/10.1371/journal.pclm.0000010 (accounting for both the "emission reduction and biomass recovery" that would result from phaseout of animal agriculture).

[46] *See* Claire Regenstreif, *Animal Agricultural Exceptionalism in the 21st Century*, 37 J. ENV'T L. & LITIG. 249, 250 (2022); Charlotte E. Blattner & Odile Ammann, *Agricultural Exceptionalism and Industrial Animal Food Production: Exploring the Human Rights Nexus*, J. FOOD L. & POL'Y, Spring 2019, at 92, 117–18, 121–22; Alexander Zahar, *Agricultural Exceptionalism in the Climate Change Treaties*, 12 TRANSNAT'L ENV'T L. 42, 55–56 (2023).

[47] Ryan Levandowski, *Polluting 'til the Cows Come Home: How Agricultural Exceptionalism Allows CAFOs Free Range for Climate Harm*, 33 GEO. ENV'T L. REV. 151, 152–53 (2020).

[48] *See* discussion *infra* Part III.

regulation.[49] The decision to postpone the implementation of stronger animal agriculture emissions controls in the IED was recently identified as an "ambition gap" by the European Scientific Advisory Board on Climate Change,[50] an independent body established in 2021 by the European Climate Law to advise the EU on climate change.[51] Moreover, the removal of a reference from the EU 2040 Climate Roadmap to efforts to reduce non-carbon dioxide GHGs (primarily methane and nitrous oxide) in agriculture by at least 30% by 2040 was viewed by many as a capitulation to the industry.[52]

In addition to benefitting from regulatory exclusion and gaps, animal agriculture enjoys high levels of government support.[53] For example, a recent report from the European Scientific Advisory Board on Climate Change described how the EU Common Agricultural Policy's subsidization of "the livestock sector . . . is a direct subsidy for GHG-intensive food products and undermines the goal of having food products reflect their true costs."[54] Across the EU and United States, animal

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[49] *Questions and Answers on Revised EU Rules on Industrial Emissions*, EUR. COMM'N (Apr. 5, 2022), https://ec.europa.eu/commission/presscorner/detail/en/qanda_22_2239; Antonia Zimmerman, *EU Conservatives Score Big Win on Industrial Emissions Rules*, POLITICO (July 11, 2023), https://www.politico.eu/article/eu-conservative-big-win-industrial-emissions-directive.

[50] EUR. SCI. ADVISORY BD. ON CLIMATE CHANGE, TOWARDS EU CLIMATE NEUTRALITY: PROGRESS, POLICY GAPS, AND OPPORTUNITIES (ASSESSMENT REPORT 2024) 155 (2024) [hereinafter EU ASSESSMENT REPORT 2024], https://climate-advisory-board.europa.eu/reports-and-publications/towards-eu-climate-neutrality-progress-policy-gaps-and-opportunities.

[51] *About the Advisory Board*, EUR. SCI. ADVISORY BD. ON CLIMATE CHANGE, https://climate-advisory-board.europa.eu/about (last visited Mar. 8, 2024).

[52] *E.g.*, Maria Simon Arboleas, *EU Commission Backtracks on Agricultural Emissions Cuts*, EURACTIV (Feb. 6, 2024), https://www.euractiv.com/section/agriculture-food/news/eu-commission-backtracks-on-agricultural-emissions-cuts.

[53] Gordon, *supra* note 2 ("About a third of global public agricultural subsidies, which totaled $233 million in 2017, are for the production of meat, milk, or dairy—even though the livestock that feeds us is also responsible for around 15 percent of global greenhouse gas emissions. . . . In other words, governments are decidedly not trying to take away your burgers. . . ."); *see also* U.N. FOOD & AGRIC. ORG. ET AL., A MULTI-BILLION DOLLAR OPPORTUNITY: REPURPOSING AGRICULTURAL SUPPORT TO TRANSFORM FOOD SYSTEMS xvii (2021) ("[E]mission-intensive commodities (e.g. beef, milk, and rice) receive the most support worldwide, despite the potentially negative impacts on health as well as on climate change adaptation and mitigation, and the (relative) disincentives this support creates towards producing healthier and more nutritious foods, such as fruits and vegetables.").

[54] EU ASSESSMENT REPORT 2024, *supra* note 50, at 161–62; *see also id.* at 182 ("[T]he current CAP continues to financially support livestock production (policy inconsistency), which drives demand for land for feed production. . . . EU policies on agriculture should better reflect the need to maintain and expand the area of forests and wetlands for carbon sequestration purposes."); Elena Sánchez Nicolás & Carolin Sprick, *Dismay Over EU Plans to Keep Paying for Meat*, EUOBSERVER (May 29, 2022, 7:07 PM), https://euobserver.com/green-economy/ar0b815ce4 (analyzing EU Commission data and finding that the EU had spent €143 million to promote European meat products in last five years); *see also* Mose Apelblat, *Climate Change: Is the EU Doing Enough to Reduce Methane Emissions in Agriculture?*, BRUSSELS TIMES (May 7, 2023), https://www.brusselstimes.com/493849/climate-change-is-the-eu-doing-enough-to-reduce-

agriculture receives about one thousand times more government funding—including for research and development—than alternative products, even though it is dramatically more established.[55]

Meanwhile, global consumption of animal products continues to increase. Per the FAO, by 2030, global meat consumption will increase fourteen percent as compared to 2018–2020 levels.[56] Increasing consumption of animal products will increase their related GHG emissions (including the potential to undo any efficiency gains in production[57]) and exacerbate the many harms of the industry, including other environmental damage and harms to health, communities, and animals.[58]

III. GLOBAL MOMENTUM AND INTERNATIONAL SIGNALING

This Part describes emergent recognition from international and multinational bodies and in international agreements about the need to reduce GHG emissions from animal agriculture through dietary change. The first section provides a chronology of international and EU developments—with the EU highlighted because it is a leader in this area—and the second describes COP28 as an example both of progress and obstacles to change.

A. International and EU Activity

Widespread awareness of the significant contributions of animal agriculture to climate change goes back at least as far as the publication of the FAO report, *Livestock's Long Shadow*, in 2006.[59] The report did not shy away from animal agriculture's environmental impacts, noting in its opening lines that "[l]ivestock activities have significant impact on virtually all aspects of the environment, including air and climate change, land and soil, water and biodiversity" and that "[l]ivestock's impact on the environment is already huge, and it is growing and rapidly changing."[60] In the report, the FAO determined that animal agriculture "has such deep and wide-ranging environmental impacts that it should rank as one of the leading focuses for environmental policy" and estimated that the sector was responsible for 18% of all

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methane-emissions-in-agriculture (discussing the EU's commitment to the Global Methane Initiative, which does not reach agricultural emissions).

55 Vallone & Lambin, *supra* note 33, at 1213.

56 U.N. FOOD & AGRIC. ORG., OECD-FAO AGRICULTURAL OUTLOOK 2021–2030, at 164 (2021), https://doi.org/10.1787/19428846-en.

57 *See* discussion *infra* Section IV.E. Tech Fixes and Climate Efficiency Approaches

58 *See infra* notes 244–256 and accompanying text.

59 U.N. FOOD & AGRIC. ORG., LIVESTOCK'S LONG SHADOW: ENVIRONMENTAL ISSUES AND OPTIONS (2006) [hereinafter LIVESTOCK'S LONG SHADOW], https://www.fao.org/3/a0701e/a0701e.pdf.

60 *Id.* at 3.

global GHG emissions.[61] This was the first global emissions reckoning for the industry, which had not been evaluated as its own sector in any of the IPCC synthesis reports issued beginning in 1990.[62] These findings reportedly resulted in significant industry pushback on the FAO.[63] Several years later, the UNEP also commented on the environmental and climate profile of animal agriculture in a report aimed at identifying the highest impact goods: "Animal products, both meat and dairy, in general require more resources and cause higher emissions than plant-based alternatives."[64] In their reports, neither the FAO nor the UNEP explicitly called for a reduction in consumption of animal products as a part of the response to climate change.

Recent years have seen international bodies more willing to make that connection. In a 2018 report, the IPCC considered the differing impacts of global warming of 1.5ºC and 2.0ºC above preindustrial levels—concluding that the former was near certain to occur and the latter would be dramatically worse—along with GHG emission pathways to both scenarios.[65] The IPCC explicitly recognized the importance of reducing consumption of animal products—"particularly where consumption is higher than suggested human health guidelines"—as well as the uncertainty of the best policy pathways to achieve that end in the face of increasing consumption.[66] The report highlighted that "plant-based proteins" and "cultured meat" could "radically reduce agricultural and land-use emissions," "less resource-intensive diets" would reduce demand for land, and "[l]ower consumption of livestock products by 2050 could also substantially reduce deforestation and cumulative carbon losses."[67]

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[61] *Id.* at xxiv, 112.

[62] Viveca Morris & Jennifer Jacquet, *The Animal Agriculture Industry, US Universities, and the Obstruction of Climate Understanding and Policy*, CLIMATIC CHANGE, Mar. 2024, No. 41, at 2.

[63] Arthur Neslen, *Ex-Officials at UN Farming Body Say Work on Methane Emissions Was Censored*, GUARDIAN (Oct. 20, 2023), https://www.theguardian.com/environment/2023/oct/20/ex-officials-at-un-farming-fao-say-work-on-methane-emissions-was-censored; Arthur Neslen, *'The Anti-Livestock People Are a Pest': How UN Food Body Played Down the Role of Farming in Climate Change*, GUARDIAN (Oct. 20, 2023), https://www.theguardian.com/environment/2023/oct/20/the-anti-livestock-people-are-a-pest-how-un-fao-played-down-role-of-farming-in-climate-change; EMISSIONS IMPOSSIBLE, *supra* note 3, at 15; *see also* Susannah Savage et al., *The Global Power of Big Agriculture's Lobbying*, FIN. TIMES (Aug. 22, 2024), https://www.ft.com/content/5f4e0538-10a4-4c8f-bc3c-28f255f20f0b ("Henning Steinfeld, former head of the [FAO's] livestock analysis unit, says officials within the UN itself 'diminished' and 'defamed' his team for more than a decade after it published [*Livestock's Long Shadow*].").

[64] EDGAR G. HERTWICH ET AL., U.N. ENV'T PROGRAMME, ASSESSING THE ENVIRONMENTAL IMPACTS OF CONSUMPTION AND PRODUCTION: PRIORITY PRODUCTS AND MATERIALS 79 (2010).

[65] 2018 IPCC REPORT, *supra* note 27, at 4, 7–10, 12.

[66] *Id.* at 327 (internal citations omitted); *see also id.* at 382 (noting that the extent and feasibility of dietary shifts will "[d]epend[] on individual behavior, education, cultural factors and institutional support").

[67] *Id.* at 16, 112, 146; *see also id.* at 316 ("Shifts in dietary choices towards foods with lower emissions and requirements for land . . . could reduce emissions and increase adap-

Also in 2018, announcing the awarding of the Champions of the Earth Award in the Science and Innovation Category to the founders of two prominent plant-based meat companies, the UNEP issued a statement strikingly entitled "*Tackling the World's Most Urgent Problem: Meat*," and shared the awardees' views in these terms: "[O]ur use of animals as a food-production technology has brought us to the verge of catastrophe. . . . There is no pathway to achieve the Paris climate objectives without a massive decrease in the scale of animal agriculture . . . ."[68]

In 2019, the "EAT-*Lancet* Commission," a group of experts in human health, agriculture, political sciences, and sustainability, released an influential report.[69] The Commission described the effort as "the first attempt to set universal scientific targets for the food system that apply to all people and the planet."[70] The report concluded:

> Transformation to healthy diets by 2050 will require substantial dietary shifts. Global consumption of fruits, vegetables, nuts and legumes will have to double, and consumption of foods such as red meat and sugar will have to be reduced by more than 50%. A diet rich in plant-based foods and with fewer animal source foods confers both improved health and environmental benefits.[71]

Also in 2019, a joint report from the FAO and the World Health Organization (WHO) described "the combined health and environmental benefits of shifting towards a more plant-based diet."[72]

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tation options . . . ."); *see also* Cheikh Mbow et al., *Food Security*, *in* CLIMATE CHANGE AND LAND: AN IPCC SPECIAL REPORT ON CLIMATE CHANGE, DESERTIFICATION, LAND DEGRADATION, SUSTAINABLE LAND MANAGEMENT, FOOD SECURITY, AND GREENHOUSE GAS FLUXES IN TERRESTRIAL ECOSYSTEMS 437, 481 (Valérie Masson-Delmotte et al. eds., 2022) [hereinafter IPCC, CLIMATE CHANGE AND LAND] ("[A] dietary pattern that is higher in plant-based foods . . . and lower in animal-based foods is more health-promoting and is associated with lesser environmental impact (GHG emissions and energy, land, and water use) than is the current average 'meat-based' diet.").

[68] *Tackling the World's Most Urgent Problem: Meat*, U.N. ENV'T PROGRAMME: CHAMPIONS OF THE EARTH (Sept. 26, 2018), https://www.unep.org/championsofearth/news-and-stories/tackling-worlds-most-urgent-problem-meat (describing awarding of prize to Ethan Brown and Patrick O'Reilly Brown, founders of Beyond Meat and Impossible Foods, respectively).

[69] Walter Willett et al., *Food in the Anthropocene: The EAT*-Lancet *Commission on Healthy Diets from Sustainable Food Systems*, 393 LANCET 447 (2019); *see also* Ayesha I.T. Tulloch et al., *How the EAT*-Lancet *Commission on Food in the Anthropocene Influenced Discourse and Research on Food Systems: A Systematic Review Covering the First 2 Years Post-publication*, 11 LANCET GLOB. HEALTH e1125, e1133 (2023) (discussing popularity and impact of the report).

[70] EAT, SUMMARY REPORT OF THE EAT-*LANCET* COMMISSION 5 (2019), https://eatforum.org/eat-lancet-commission/eat-lancet-commission-summary-report.

[71] *Id.* at 3.

[72] U.N. FOOD & AGRIC. ORG. & WORLD HEALTH ORG., SUSTAINABLE HEALTHY DIETS: GUIDING PRINCIPLES 34 (2019), https://iris.who.int/bitstream/handle/10665/329409/9789241516648-eng.pdf.

In Europe, in September 2020, the European Commission recognized in a communication about its 2030 climate ambition that a "strong decrease of consumption of animal products for nutrition could potentially reduce emissions by more than 30 million tonnes by 2030."[73] The next month, in its strategy to reduce methane emissions, the Commission recognized that, "[g]iven the high share of methane emissions in agriculture that result from livestock, lifestyle and diet changes can also contribute significantly to reducing EU methane emissions."[74]

Then, in 2021, the European Parliament adopted its "Farm to Fork Strategy," which the European Commission described as "at the heart of the European Green Deal."[75] The Strategy aims to make food systems "fair, healthy and environmentally-friendly,"[76] recognizes both the health and environmental benefits of reducing meat consumption,[77] and commits to dedicating EU funds to research alternative proteins.[78] But advocates said that it was "deeply disappointing" that a call to end government spending on promoting meat production and consumption that had appeared in an earlier draft did not make it into the final strategy.[79] Moreover, as one European agriculture expert put it: "Remarkably, the EU Farm-to-Fork Strategy, while emphasizing the need to reduce methane and nutrient emissions from livestock, does not mention a reduction in total livestock numbers as either a goal or a policy option."[80]

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[73] *Stepping Up Europe's 2030 Climate Ambition: Investing in a Climate-Neutral Future for the Benefit of Our People*, at 5 n.2, COM (2020) 562 final (Sept. 17, 2020).

[74] *Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions on an EU Strategy to Reduce Methane Emissions*, at 3–4, COM (2020) 663 final (Oct. 14, 2020) [hereinafter *EU Strategy to Reduce Methane Emissions*]; *see also id.* at 11 (noting that, in addition to efficiency and technological improvements, further reductions in methane emissions could be achieved "by more sustainable diets").

[75] EUR. COMM'N, FARM TO FORK STRATEGY FOR A FAIR, HEALTHY AND ENVIRONMENTALLY-FRIENDLY FOOD SYSTEM 4 (2020) [hereinafter FARM TO FORK STRATEGY]. The European Green Deal is a set of policies that aims to make Europe the first climate-neutral continent by 2050. *The European Green Deal*, EUR. COMM'N, https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/european-green-deal_en (last visited Oct. 12, 2024).

[76] FARM TO FORK STRATEGY, *supra* note 75, at cover.

[77] *Id.* at 14 ("Moving to a more plant-based diet with less red and processed meat and with more fruits and vegetables will reduce not only risks of life threatening diseases, but also the environmental impact of the food system.").

[78] *Id.* at 16.

[79] *European Commission Will Start Supporting Plant-Based Diets in New Farm to Fork Strategy, but 'Chickened Out' of Removing EU Funding for Meat Promotion*, HUMANE SOC'Y INT'L (May 20, 2020), https://www.hsi.org/news-resources/european-commission-supports-plant-based-diets-farm-to-fork-strategy.

[80] Daan Boezeman et al., *Less Livestock in North-Western Europe? Discourses and Drivers Behind Livestock Buyout Policies*, EUROCHOICES, Aug. 2023, at 4, 4 (internal citation omitted). As discussed below, four years on, the promise of the Farm to Form Strategy has largely not been realized. *See infra* note 286.

According to the UNEP's 2021 Global Methane Assessment, "the adoption of healthy diets (vegetarian or with a lower meat and dairy content)" is one of three key measures to reduce emissions from animal agriculture.[81] Also in 2021, at COP26 in Glasgow more than a hundred countries signed the "Global Methane Pledge," undertaking to reduce methane emissions by 30 percent by 2030.[82] But the Pledge took quite different approaches to the other two main sectoral sources of methane than it did to agriculture, calling for "all feasible reductions in the energy and waste sectors" but only "abatement of agricultural emissions through technology innovation as well as incentives and partnerships with farmers."[83] The signatories apparently were not willing to commit to "all feasible reductions" in emissions from agriculture.

A 2022 IPCC report on "Climate Change and Land" identified "a shift toward plant-based diets" as one of the top three options (along with reducing deforestation and food waste) to reduce emissions from agriculture, forestry, and other land use.[84] Less clearly, the IPCC's Sixth Assessment Report released in March 2023 stated that "unbalanced diets" contribute to "agricultural expansion," "increase[] ecosystem and human vulnerability and lead[] to competition for land and/or water resources."[85] The report also recognized that, along with other measures, shifting to "sustainable healthy diets" could "reduce ecosystem conversion, and methane and nitrous oxide emissions, and free up land for reforestation and ecosystem restoration."[86]

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[81] U.N. ENV'T PROGRAMME, GLOBAL METHANE ASSESSMENT 13 (2021) [hereinafter GLOBAL METHANE ASSESSMENT], https://www.ccacoalition.org/sites/default/files/resources//2021_Global-Methane_Assessment_full_0.pdf.

[82] *COP26: Together for Our Planet*, UNITED NATIONS: CLIMATE ACTION, https://www.un.org/en/climatechange/cop26 (last visited Oct. 14, 2024).

[83] GLOBAL METHANE PLEDGE (Nov. 22, 2023), https://www.globalmethanepledge.org/sites/default/files/documents/2023-11/Global%20Methane%20Pledge.pdf; *see also* CHANGING MARKETS FOUND., BLINDSPOT: HOW LACK OF ACTION ON LIVESTOCK METHANE UNDERMINES CLIMATE TARGETS 8 (2021) [hereinafter BLINDSPOT], https://changingmarkets.org/report/blindspot-how-lack-of-action-on-livestock-methane-undermines-climate-targets ("[T]he Global Methane Pledge . . . ignore[s] the potential to reduce methane emissions by addressing people's overconsumption of meat and dairy—where some of the biggest cuts in emissions can be achieved.").

[84] IPCC, CLIMATE CHANGE AND LAND, *supra* note 67, at 49; *see also* Mustafa Babiker et al., *Cross-sectoral Perspectives, in* CLIMATE CHANGE 2022: MITIGATION OF CLIMATE CHANGE 1279 (Priyadarshi R. Shukla et al. eds., 2022) ("[M]itigation actions need to go beyond food producers and suppliers to incorporate dietary changes and consumers' behavioural patterns . . . .").

[85] IPCC SIXTH ASSESSMENT REPORT SYNTHESIS, *supra* note 44, at 50. A prior 2022 IPCC report had defined "balanced diets" as "featur[ing] plant-based foods, such as those based on coarse grains, legumes, fruits and vegetables, nuts and seeds, and animal-source foods produced in resilient, sustainable, and low-greenhouse gas emissions systems." INTERGOV'TAL PANEL ON CLIMATE CHANGE, CLIMATE CHANGE 2022: IMPACTS, ADAPTATION AND VULNERABILITY 12 n.32 (Hans-Otto Pörtner et al. eds., 2022).

[86] IPCC SIXTH ASSESSMENT REPORT SYNTHESIS, *supra* note 44, at 29; *see also id.* at 106. The IPCC defines "[s]ustainable healthy diets" as "promot[ing] all dimensions of individuals' health and well-being; hav[ing] low environmental pressure and impact; [being] accessible, affordable, safe and equitable; [and] culturally acceptable . . . ." *Id.* at 29 n.53.

According to reporting after the release of the 2023 report, more direct references to the climate impacts of animal agriculture were removed from drafts after pressure from delegates from Brazil and Argentina (both major meat-producing and exporting countries).[87] In particular, a leaked draft had reportedly included much more precise and definitive language:

> A shift to diets with a higher share of plant-based protein in regions with excess consumption of calories and animal-source food can lead to substantial reductions in GHG emissions . . . . Plant-based diets can reduce GHG emissions by up to 50% compared to the average emission intensive Western diet.[88]

The European Commission's Agricultural Outlook for 2022–2032 evaluated the impacts of reducing farm animal density in Europe to comply with nitrogen pollution and habitat protection laws. The Commission concluded that reductions would reduce GHG emissions in the EU, and that such measures should be paired with complementary policies (including dietary changes, improved emissions efficiency, and trade measures) to prevent "leakage," i.e., European consumers importing more animal products to meet demand.[89] Interestingly, the analysis showed that farmer incomes would grow even as production declined, as a result of higher prices for animal products and reduced feed costs.[90]

In late 2023, the European Union announced that, through the European Innovation Council, it would spend €50 million in 2024 to help scale up alternative proteins including precision fermentation.[91] And lest it seem that the United States is lagging entirely behind international bodies and the European Union in acknowledging the role of dietary shifts in climate mitigation, in late 2023, the Fifth National Climate Assessment addressed food systems for the first time, notably

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87 Michael Thomas, *How Meat and Fossil Fuel Producers Watered Down the Latest IPCC Report*, DISTILLED (Mar. 23, 2023), https://www.distilled.earth/p/how-meat-and-fossil-fuel-producers; *see also* Mustafa Zia et al., *Brazil Once Again Becomes the World's Largest Beef Exporter*, U.S. DEP'T OF AGRIC. (July 1, 2019), https://www.ers.usda.gov/amber-waves/2019/july/brazil-once-again-becomes-the-world-s-largest-beef-exporter; Maximilian Heath, *Argentina to Loosen Restrictions on Beef Exports*, REUTERS (Dec. 9, 2021, 3:58 PM), https://www.reuters.com/markets/commodities/argentine-meat-industry-says-fatter-cows-may-help-end-export-impasse-with-2021-12-09 ("Argentina is a key global supplier of beef . . . .").

88 Thomas, *supra* note 87.

89 DIRECTORATE-GEN. FOR AGRIC. & RURAL DEV., EUR. COMM'N, EU AGRICULTURAL OUTLOOK: FOR MARKETS, INCOME AND ENVIRONMENT 2022–2032, at 48, 53 (2022), https://agriculture.ec.europa.eu/system/files/2023-04/agricultural-outlook-2022-report_en_0.pdf.

90 *Id.* at 48, 52.

91 Cate Lawrence, *The EU Invests €50M to Help Startups Scale Up Alternative Proteins*, TECH EU (Dec. 15, 2023), https://tech.eu/2023/12/15/eics-eur50m-challenge-scaling-up-alternative-protein-production-in-europe.

acknowledging that shifts to plant-based and cultivated meats "offer the potential to reduce GHG emissions."[92]

In a January 2024 report on EU progress toward climate neutrality, the European Scientific Advisory Board on Climate Change included the following in its key recommendations:

> The [EU common agricultural policy] CAP should be better aligned with EU climate goals . . . [including by] shifting CAP support away from emission-intensive agricultural practices, including livestock production, and towards lower-emitting products . . . .
>
> [T]he EU should strengthen measures to encourage healthier, more plant-based diets, and develop a strategy for a just transition to a food system consistent with climate neutrality.[93]

The Board also noted that the EU's 2018 Long-Term Strategy was not ambitious enough in the timelines it considered for dietary change, and that "further (and faster) reductions in animal product consumption would be recommended," both for climate and health reasons.[94]

Most recently, a groundbreaking 2024 report from the World Bank on emissions from the agrifood system encouraged high-income countries to "decrease consumer demand for emissions-intensive, animal-source foods by fully pricing environmental and health externalities, repurposing subsidies, and promoting sustainable food options."[95] A lead author of the report commented that the recommendation is decidedly *not* to shift support away from agriculture, but rather to "use it in more effective ways that actually contribute to healthier diets and a healthier planet."[96]

In addition to the climate context, calls for dietary change away from animal products have emerged in relation to other critical and related global issues, most prominently public health and biodiversity. Such guidance is based not only on the specific risks that dietary change could help address (for example, zoonotic disease for public health and

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92 Carl H. Bolster et al., *Chapter 11: Agriculture, Food Systems, and Rural Communities*, *in* FIFTH NATIONAL CLIMATE ASSESSMENT 11-1, 11-12 (Allison Crimmins et al. eds., 2023) (internal citations omitted); Marianne Lavelle et al., *Report Charts Climate Change's Growing Impact in the US, While Stressing Benefits of Action*, INSIDE CLIMATE NEWS (Nov. 14, 2023), https://insideclimatenews.org/news/14112023/biden-national-cliimate-assessment.

93 EU ASSESSMENT REPORT 2024, *supra* note 50, at 11–12; *see also id.* at 153–54, 173, 179.

94 *Id.* at 173.

95 SUTTON ET AL., *supra* note 28, at 12. The World Bank estimated that prices that "reflect the true health, climate, and environmental costs of meat" would be 20%–60% higher than current prices. *Id.* at 13.

96 Agnieszka de Sousa, *Cut Aid for Livestock Farms to Help Climate Fight, World Bank Says*, BLOOMBERG (May 6, 2024), https://www.bloomberg.com/news/articles/2024-05-07/cut-aid-for-livestock-farms-to-help-climate-fight-world-bank-says.

deforestation for biodiversity[97]), but also because climate change will itself exacerbate public health and biodiversity risks.[98] In one prominent example, the Kunming-Montreal Global Biodiversity Framework (GBF), adopted by the parties to the Convention on Biological Diversity in 2022, requires establishment of national targets to encourage sustainable consumption choices and, "by 2030, [to] reduce the global footprint of consumption in an equitable manner."[99] Focusing on the food system in its plan for implementation of the GBF, the International Union for Conservation of Nature, a membership group of government and civil society organizations that advises and works at the intersection of development, economics, and conservation, called for "[m]inimizing impacts of food production on species by reducing consumption of animal protein . . . especially in developed countries [to limit] negative impacts on wild species."[100]

B. COP28

The meeting of the Conference of the Parties to the U.N. Framework Convention on Climate Change in Dubai in November 2023 (COP28), which included a flurry of activity around food systems, is a prominent, recent example of the growing energy around this issue on the global stage.[101] While this new focus was laudable, the fact that food systems had never before received this level of attention—despite their

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97 Matthew N. Hayek, *The Infectious Disease Trap of Animal Agriculture*, SCI. ADVANCES, Nov. 2022, No. eadd6681, at 3–4; Marta Kozicka et al., *Feeding Climate and Biodiversity Goals with Novel Plant-Based Meat and Milk Alternatives*, NATURE COMMC'NS., Sept. 12, 2023, No. 5316, at 6–7.

98 *E.g.*, Howard Frumkin et al., *Climate Change: The Public Health Response*, 98 AM. J. PUB. HEALTH 435, 435 (2008) (discussing potential and already experienced negative impacts of climate change on human health); K.R. Shivanna, *Climate Change and Its Impact on Biodiversity and Human Welfare*, 88 PROC. INDIAN NAT'L SCI. ACAD. 160, 164–66 (discussing climate change's detrimental effects on biodiversity).

99 Conference of the Parties to the Convention on Biological Diversity, *Kunming-Montreal Global Biodiversity Framework*, ¶ 13, U.N. Doc. CBD/COP/DEC/15/4, annex (Dec. 19, 2022).

100 INT'L UNION FOR CONSERVATION OF NATURE, GLOBAL SPECIES ACTION PLAN: SUPPORTING IMPLEMENTATION OF THE KUNMING-MONTREAL GLOBAL BIODIVERSITY FRAMEWORK 37 (2023), https://portals.iucn.org/library/node/51362; *Int'l Union for Conservation of Nature (IUCN)*, U.N. ENV'T PROGRAMME, https://www.unep.org/explore-topics/oceans-seas/what-we-do/working-regional-seas/partners/international-union (last visited Oct. 17, 2024).

101 One might wonder whether the prominence of food at COP28 was driven, at least in part, by the interest of its host country and president, Sultan Al Jaber, who is the CEO of the United Arab Emirates national fuel company, in diverting attention away from fossil fuels. Fiona Harvey, *Cop28 President Denies on Eve of Summit He Abused His Position to Sign Oil Deals*, GUARDIAN (Nov. 29, 2023, 12:17 PM), https://www.theguardian.com/environment/2023/nov/29/cop28-president-denies-on-eve-of-summit-he-abused-his-position-to-sign-oil-deals. Nonetheless, as described herein, COP28 was the most significant COP to date for food.

significant emissions—is illustrative of the lack of attention to the climate impacts of agriculture.[102]

1. COP28: Progress

During the second day of the meeting, the COP president announced the Emirates Declaration on Sustainable Agriculture, Resilient Food Systems and Climate Action, which more than 160 countries have signed.[103] The nonbinding declaration acknowledges that food systems "must urgently adapt and transform" to respond to the climate crisis.[104] Signatory countries committed to "[m]aximize the climate and environmental benefits—while containing and reducing harmful impacts—associated with agriculture and food systems [including] by . . . shifting from higher greenhouse gas-emitting practices to more sustainable production and consumption approaches . . . ."[105] The Declaration tasks governments, for the first time, with including agriculture in their Nationally Determined Contributions[106] by COP30 in 2025,[107] and commits countries to improve their approaches to bolstering animal and ecosystem health within agriculture and food systems.[108]

In a short video message prepared for COP28, WHO Director-General Tedros Adhanom Ghebreyesus recognized that food systems are harming people and the planet, and noted their significant climate

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[102] *See supra* text accompanying notes 34–36; *see also, e.g.*, Jan Dutkiewicz, *The Comforting Lie of Climate-Friendly Meat*, NEW REPUBLIC (Dec. 14, 2023) [hereinafter Dutkiewicz, *The Comforting Lie of Climate-Friendly Meat*], https://newrepublic.com/article/177575/never-trust-green-meat ("Given the urgency of the climate crisis, one would think that tackling the single biggest source of food-sector emissions would have been central to serious climate discussions for the past decade and a half.").

[103] *Declaration on Sustainable Agriculture, Resilient Food Systems, and Climate Action*, COP28 UAE [hereinafter COP28 UAE DECLARATION], https://www.cop28.com/en/food-and-agriculture (last visited Oct. 20, 2024); Daphne Ewing-Chow, *COP28 Leaders Transforming Food Systems in Face of Climate Change*, FORBES (Dec. 2, 2023, 3:25 AM), https://www.forbes.com/sites/daphneewingchow/2023/12/02/cop28-leaders-transforming-food-systems-in-face-of-climate-change.

[104] COP28 UAE DECLARATION, *supra* note 103.

[105] *Id.*

[106] *All About the NDCs*, U.N.: CLIMATE ACTION, https://www.un.org/en/climatechange/all-about-ndcs (last visited Oct. 11, 2024) (explaining that Nationally Determined Contributions, or NDCs, are a requirement of the Paris Agreement under which each party must create a climate action plan to reduce emissions and adapt to the effects of climate change, and update the plan every five years).

[107] SUTTON ET AL., *supra* note 28, at 18 ("147 of 167 second-round NDCs include [agriculture, food systems and/or land use] in their mitigation commitments."); Kenny Torrella, *There's Less Meat at the UN's COP28 Climate Talks. But There's Plenty of Bull.*, VOX (Nov. 30, 2023, 6:30 AM), https://www.vox.com/future-perfect/2023/11/30/23981529/cop28-meat-livestock-dairy-farming-plant-based-united-nations-dubai-uae (noting that all countries that already have agriculture mitigation NDCs are low- and middle-income countries—with relatively less animal product consumption).

[108] COP28 UAE DECLARATION, *supra* note 103.

impacts. Returning to the message of the WHO's 2019 report,[109] he called for transforming food systems by "shifting toward healthier, diversified, and more plant-based diets."[110]

During Food, Agriculture and Water Day—the first COP day ever dedicated to food systems[111]—the FAO announced its first "Roadmap" to achieve food security[112] without breaching the Paris Agreement goals.[113] The Roadmap addressed the differing climate impacts of food and the need for dietary change as follows: "High consumption of food products with high GHG footprints in some locations contribute unnecessarily to the emissions of agrifood systems. . . . The issue is to know not 'if' diets should change—for they absolutely must for human and planetary health—but how to obtain these results."[114] The Roadmap also recognized the need to consider environmental factors in national dietary guidelines and to utilize public food procurement programs to achieve climate goals.[115]

Also during COP28, references to food systems were included in the first-ever Global Stocktake of progress since the 2015 Paris Agreement,[116] although only after pressure from civil society and only in the adaptation (rather than mitigation[117]) section and in general terms.[118] In addition, UNEP released a report on the potential impacts

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109 FAO & WORLD HEALTH ORG., *supra* note 72.

110 World Health Org., *Our Food Systems Are Harming the Health of People and Planet*, YOUTUBE, at 0:40 (Dec. 21, 2023), https://www.youtube.com/watch?v=kHXJ5O5EDIc.

111 Brown & Hill, *supra* note 8.

112 Sustainable Development Goal 2 (SDG2), "Zero Hunger," aims for an end to hunger by 2030. *Goal 2: Zero Hunger*, U.N. SUSTAINABLE DEVELOPMENT GOALS, https://www.un.org/sustainabledevelopment/hunger (last visited Oct. 14, 2024).

113 U.N. FOOD & AGRIC. ORG., ACHIEVING SDG2 WITHOUT BREACHING THE 1.5C THRESHOLD: A GLOBAL ROADMAP 1–2 (2023) [hereinafter FAO ROADMAP], https://www.fao.org/interactive/sdg2-roadmap/assets/3d-models/inbrief-roadmap.pdf.

114 *Id.* at 19; *see also id.* at 1 ("Providing healthy food for all, today and tomorrow, is crucial; as is aligning agrifood systems transformation with climate actions.").

115 *Id.* at 19–21.

116 *Why the Global Stocktake Is Important for Climate Action This Decade*, UNFCCC, https://unfccc.int/topics/global-stocktake/about-the-global-stocktake/why-the-global-stocktake-is-important-for-climate-action-this-decade (last visited Oct. 13, 2024).

117 *Cf.* SUTTON ET AL., *supra* note 28, at 2 ("[A]ccording to scientists, we cannot adapt our way out of the climate crisis, and now is the time to put agriculture and food at the top of the mitigation agenda. If not, the world will be unable to ensure a livable future for future generations." (internal quotation and citation omitted)).

118 Silvia Mantilla, *Hope amid Challenges: Key Outcomes & Missed Opportunities at COP28*, WORLD FED'N FOR ANIMALS (Dec. 17, 2023), https://wfa.org/hope-amid-challenges-key-outcomes-missed-opportunities-at-cop28; *Good COP, Bad COP: Brighter Green's Take on COP28*, BRIGHTER GREEN (Dec. 20, 2023) [hereinafter *Good COP, Bad COP*], https://mailchi.mp/brightergreen/end-of-year-2023 (both noting that, before advocacy by environmental and animal NGOs, food systems seemed likely to be left out of the Global Stocktake altogether). The Global Stocktake calls for "the implementation of integrated, multisectoral solutions, such as . . . sustainable agriculture [and] resilient food systems," and for "[a]ttaining climate-resilient food and agricultural production and supply and distribution of food, as well as increasing sustainable and regenerative production and equitable access to adequate food and nutrition for all." Conference of the Parties Serving as the Meeting of

of meat and dairy alternatives.[119] A "key finding" of the report was that "[n]ovel plant-based meat, cultivated meat, and fermentation-derived foods show potential for reduced environmental impacts compared to many conventional [animal-sourced foods]. They also show promise for reduced risk of zoonoses and antimicrobial resistance . . . ."[120]

Last but not least in terms of pragmatic impact, following advocacy by youth groups and NGOs, the COP president adopted a "Climate Conscious Catering" plan with the stated goal of having two-thirds of the food served be vegan or vegetarian.[121] COP28 also featured a "Food for Climate Pavilion" and more than 650 food-related events.[122]

2. COP28: Critiques

While all of these COP firsts are undoubtedly steps forward, many are skeptical of their impact and seriousness. Environmental writer and activist George Monbiot pointedly observed that COP28 "was meant to be the first climate summit at which the impacts of the food system were properly considered. But by the time 120 meat and dairy lobbyists had done their worst, nothing meaningful came out of it."[123] Indeed, the meat and dairy industries reportedly had at least 120 delegates present in Dubai, about three times as many as had attended the COP the year before in Egypt.[124]

Another damning assessment of the transformative value of COP28 for animal agriculture emissions was published in the U.S. industry publication *Meatingplace*, which noted the lack of concrete outcomes: "Discussing the transition to plant-based meat and dairy was on the agenda during COP28, but as the annual event wraps up, the

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the Parties to the Paris Agreement, *Decision 1/CMA.5: Outcome of the First Global Stocktake*, ¶¶ 55, 63(b), U.N. Doc. FCCC/PA/CMA/2023/16/Add.1 (Mar. 15, 2024).

119 Press Release, U.N. Env't Programme, Novel Meat and Dairy Alternatives Could Help Curb Climate-Harming Emissions (Dec. 8, 2023), https://www.unep.org/news-and-stories/press-release/novel-meat-and-dairy-alternatives-could-help-curb-climate-harming.

120 UNEP WHAT'S COOKING?, *supra* note 36, at viii.

121 *Good COP, Bad COP, supra* note 118. Compare this to COP24 in 2018, where plant-based options were less common than meat and dairy dishes, which included beef with smoked bacon, gnocchi with ham, and cheeseburgers. FARM FORWARD ET AL., THE CLIMATE COST OF FOOD AT COP24 1 (2018), https://www.biologicaldiversity.org/programs/population_and_sustainability/sustainability/pdfs/COP24-menu-analysis-fact-sheet.pdf; *see also* Torrella, *supra* note 107 (discussing how COP28's catering decision marked a notable change from past, meat-heavy menus).

122 Philip Lymbery, *COP28 Climate Change Summit Saw Landmark Declaration that Should Dramatically Affect What We Eat*, SCOTSMAN (Dec. 15, 2023), https://www.scotsman.com/news/opinion/columnists/cop28-climate-change-summit-saw-landmark-declaration-that-should-dramatically-affect-what-we-eat-philip-lymbery-4445538; *Good COP, Bad COP, supra* note 118.

123 George Monbiot, *Call Me All the Names You Want—I Won't Stop Telling the Truth About Livestock Farming*, GUARDIAN (Dec. 14, 2023, 7:33 AM EST), https://www.theguardian.com/commentisfree/2023/dec/14/livestock-farming-soy-soyboy.

124 Rachel Sherrington et al., *Big Meat and Dairy Delegates Triple at COP28*, DESMOG (Dec. 8, 2023), https://www.desmog.com/2023/12/08/big-meat-dairy-delegates-triple-cop28.

conversation doesn't seem to have inspired any actual change."[125] The publication also observed that the FAO Roadmap "focused more on incremental improvements to the current food system without moves to change the animal agriculture sector or promote a move toward alt-meat and -dairy products."[126] Specifically as to the Declaration issued during the second day of COP28,[127] critics pointed out that its language "sidestepped" the "contentious issue" of meat consumption.[128]

Many observers were particularly critical of the shortcomings of the Roadmap issued by the FAO on Food Day,[129] noting that it did not adequately address the need for meat reduction, focused instead on technological fixes[130] and "intensified productivity,"[131] and "fail[ed] to express the urgency of reducing meat and dairy consumption and production to meet the targets set by the Paris climate agreement."[132] As observed by one expert in response to the Roadmap:

> This current draft puts a huge emphasis on incremental changes to the current industrial food system. But this is a flawed system that is wrecking nature, polluting the environment, and starving millions of

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125 Melissa Sue Sorrells, *Push for Meat Reduction MIA in COP28 Resolutions*, MEATINGPLACE (Dec. 12, 2023), https://www.meatingplace.com/Industry/News/Details/112595?allowguest=true.

126 *Id.*; *see also* Rachel Sherrington, *US Meat Lobby Delighted at 'Positive' Prospects for Industry After Cop28*, GUARDIAN (Apr. 8, 2024), https://www.theguardian.com/environment/2024/apr/08/us-meat-lobby-delighted-at-positive-prospects-for-industry-after-cop28.

127 *See supra* notes 103–108 and accompanying text.

128 Carissa Wong & Nature Magazine, *World Leaders Agree to a Climate Deal on Food for the First Time*, SCI. AM. (Dec. 11, 2023), https://www.scientificamerican.com/article/world-leaders-agree-to-a-climate-deal-on-food-for-the-first-time.

129 *See supra* notes 113–115 and accompanying text.

130 Dutkiewicz, *The Comforting Lie of Climate-Friendly Meat*, *supra* note 102; Statement, Animal Prot. Denmark et al., *A Collective Call for a Holistic Food Systems Approach in FAO's Roadmap*, WORLD FED'N FOR ANIMALS (Dec. 11, 2023), https://wfa.org/a-collective-call-for-a-holistic-food-systems-approach-in-faos-roadmap; Monbiot, *supra* note 123.

131 FAO ROADMAP, *supra* note 113, at 6.

132 Brown & Hill, *supra* note 8 (quoting Stephanie Feldstein, Center for Biological Diversity); *see also* Cleo Verkuijl et al., *FAO's 1.5°C Roadmap for Food Systems Falls Short*, 5 NATURE FOOD 264, 264–65 (2024). Comments by the FAO's Chief Economist Maximo Torero also garnered critical responses. Referring to the recommendation in the Roadmap that animal production be intensified "in relevant locations," Torero "said the way forward was for countries that are 'very efficient in producing livestock,' such as the Netherlands and New Zealand, to produce more meat and dairy and then ship those products across the world." Susannah Savage, *Ramp Up Meat Production to Address Health Challenge in Poorer Countries*, FIN. TIMES (Dec. 10, 2023), https://www.ft.com/content/2eb93884-0aa3-4590-98ec-5b15cc1d9f44. George Monbiot queried in response:

> Could he really be unaware that both these countries have been thrown into severe ecological and political crisis by the scale of their livestock industries? Yet now he wants them to produce even more—and for poorer nations to become dependent on these imports? Greetings to our visitor from Planet Meat.

Monbiot, *supra* note 123.

> people. . . . The next rounds of this process will need to go much further in proposing a real transformation of the status quo . . . .[133]

Immediately following the COP, the FAO released *Pathways Towards Lower Emissions*, a report analyzing options to mitigate the GHG impact of animal agriculture.[134] Experts and advocates criticized the report on a number of bases, including its focus on productivity and efficiency improvements, as well as for minimizing and questioning the positive climate impacts of dietary changes.[135] Two scientists whose studies were referenced in the report sent a letter to the FAO, requesting a retraction and stating that the report "seriously distort[ed]" their findings and underestimated the climate mitigation potential of dietary change.[136]

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While progress has thus been limited and imperfect, after a long lag following the FAO's first analysis of the climate harms of animal agriculture in 2006, since 2018 a picture begins to emerge of growing calls on the international stage and in the EU for reduced consumption of animal products in response to the climate crisis.

IV. POLICY OPTIONS AND EXAMPLES

What options are available to leaders who would follow this international guidance and signaling? In fact, there are many policies that could reduce the climate harms of animal agriculture. Not only are these policies known and quite well understood,[137] as discussed in this Part, they are each currently being tried or considered somewhere in the world.

Notably, this Part does not include examples of mandatory limitations on animal agriculture's emissions via regulation. At present,

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133 Fiona Harvey, *UN Sets Out Roadmap to Combat Global Hunger amid Climate Crisis*, GUARDIAN (Dec. 10, 2023), https://www.theguardian.com/environment/2023/dec/10/un-sets-out-roadmap-to-combat-global-hunger-amid-climate-crisis (quoting Emile Frison, member of the thinktank International Panel of Experts on Sustainable Food Systems). Despite the Roadmap's limitations, the same expert also acknowledged: "The FAO should be applauded for this first step in laying out a plan" to eliminate hunger and address the GHG emissions from the food system. *Id.*

134 FOOD & AGRIC. ORG. OF THE U.N., PATHWAYS TOWARDS LOWER EMISSIONS: A GLOBAL ASSESSMENT OF THE GREENHOUSE GAS EMISSIONS AND MITIGATION OPTIONS FROM LIVESTOCK AGRIFOOD SYSTEMS (2023), https://www.fao.org/3/cc9029en/cc9029en.pdf.

135 *E.g.*, Jessica Bridgers, *New FAO Report Provides Entry Points for Animal Advocates but also Poses Risks*, WORLD FED'N FOR ANIMALS (Dec. 20, 2023), https://wfa.org/new-fao-report-provides-entry-points-for-animal-advocates-but-also-poses-risks.

136 Letter from Paul Behrens, Leiden Univ. & Matthew Hayek, New York Univ., to Thanawat Tiensin, Dir. of Animal Prod. & Health Div., FAO (Apr. 9, 2024), https://www.universiteitleiden.nl/binaries/content/assets/science/cml/essays/retraction-request-pathways-to-lower-emissions.pdf.

137 *E.g.*, Gordon, *supra* note 2 ("One day, if governments really do come for your burgers, they will do it by expanding the policies for phasing out polluting [animals] that we are already familiar with today.").

no country is limiting GHG emissions from animal agriculture through caps or other such mechanisms.[138] This is not surprising, as it is only relatively recently that such limits are being imposed by some countries on emissions from the largest source of GHG emissions: fossil fuels.[139] While there is an increasing focus around the world on limiting methane emissions—exemplified by the contrasting approaches in the Global Methane Pledge discussed above[140]—the early mandatory methane regulations apply to the energy sector and not to animal agriculture.[141] This is despite the fact that, as discussed above, animal agriculture is one of the most significant sources of anthropogenic methane.[142] Even *disclosure* of supply chain GHG emissions from animal agriculture is, for the most part, not required or provided at present.[143]

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138 *See supra* notes 46–52 and accompanying text.

139 *E.g.*, Rosie Frost, *The End of Fossil Fuels: Which Countries Have Banned Exploration and Extraction?*, EURONEWS (Aug. 12, 2021), https://www.euronews.com/green/2021/08/12/the-end-of-fossil-fuels-which-countries-have-banned-exploration-and-extraction; Editorial, *The EPA Sends a Powerful Signal on Ending Fossil Fuels*, 618 NATURE 433 (2023), https://www.nature.com/articles/d41586-023-01825-0 (discussing proposed U.S. Environmental Protection Agency rule that would force fossil-fuel power plants to reduce their emissions).

140 *See supra* notes 82–83 and accompanying text.

141 Regulation 2024/1787 of the European Parliament and of the Council of 13 June 2024 on the Reduction of Methane Emissions in the Energy Sector and Amending Regulation 2019/942, 2024 O.J. (L) at 13–14; Press Release, U.S. Env't Prot. Agency, Biden-Harris Administration Finalizes Standards to Slash Methane Pollution, Combat Climate Change, Protect Health, and Bolster American Innovation (Dec. 2, 2023), https://www.epa.gov/newsreleases/biden-harris-administration-finalizes-standards-slash-methane-pollution-combat-climate (announcing new rule that will limit methane emissions from oil and gas).

142 *See supra* notes 41–45 and accompanying text.

143 Georgina Gustin & Phil McKenna, *Reducing Methane from Livestock Is Critical for Stabilizing the Climate, but Congress Continues to Block Farms from Reporting Emissions Anyway*, INSIDE CLIMATE NEWS (Dec. 22, 2023) ("We do have emissions estimating methodologies, which you can use if you know the number of animals and which manure management strategy is being used. But we don't even know how many animals are on these farms." (quoting a senior manager at environmental group Friends of the Earth)). At COP28, promises by six major dairy multinationals to disclose their methane emissions and develop methane action plans by 2024 were notable as far ahead of the industry norm. Leah Douglas, *COP28 Summit: Global Dairy Companies Join Alliance to Cut Methane*, REUTERS (Dec. 5, 2023), https://www.reuters.com/sustainability/climate-energy/global-dairy-companies-announce-alliance-cut-methane-cop28-2023-12-05. This will change, however, as new reporting requirements passed in the EU, California, and elsewhere begin to take effect and impose disclosure requirements (including Scope 3 supply chain emissions) on large animal agriculture companies and their business partners. Amanda Carter, *Corporate Climate Disclosure Has Passed a Tipping Point. Companies Need to Catch Up*, WORLD RES. INST. (May 6, 2024), https://www.wri.org/insights/tipping-point-for-corporate-climate-disclosure.

A. Public Relations and Information: Advertising Bans, Climate Labeling, and Confronting Industry Deception

One province and three cities in the Netherlands—first Haarlem in 2022, followed by the cities of Bloemendaal and Utrect and the province of Noord-Holland in 2023—are the first jurisdictions in the world to have banned meat and dairy advertising for climate reasons. The bans will apply to advertising spaces owned by the municiplaties, such as bus stops and billboards, and will take time to come into force (either because they have phase-in dates or will honor current contracts).[144] None of the bans are limited to meat and dairy; they also include other damaging industries and products such as fossil fuels, combustion engines, airline travel, alcohol, and gambling.[145]

A statement from the city of Bloemendaal explained that meat and dairy are included in the ban as part of necessary actions to reduce GHG emissions and deforestation.[146] When asked for the reasoning behind the ban, the leader of the Party for the Animals who had proposed it explained: "The main reason is that meat production leads to climate change. . . . Another reason is animal welfare."[147] A professor of sustainability from the University of Amsterdam observed that, while the bans may not be expected to directly change behavior, they have norm-setting power and can "stimulate the social debate."[148] As a case in point, he noted that the bans have been discussed well outside of the municipalities, indeed all over the world.[149]

In addition to such advertising limits, governments can set affirmative requirements for climate labeling on foods and also help police misleading claims. For example, in its Farm to Fork Strategy, the European Commission called for review of voluntary green claims and to creating a sustainability labelling framework to include climate impacts.[150] Similarly, in its Roadmap, the FAO recommends

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144 *Dutch Municipalities to Ban Meat and Dairy Ads in Public Spaces*, VEGCONOMIST (Nov. 6, 2023) [hereinafter *Dutch Municipalities to Ban Meat Ads*], https://vegconomist.com/politics-law/dutch-municipalities-ban-meat-dairy-ads-public-spaces; *Noord-Holland to Ban Ads for Meat and Fossil Fuels from Bus Shelters*, DUTCH NEWS (Jan. 5, 2023), https://www.dutchnews.nl/2023/01/noord-holland-to-ban-ads-for-meat-and-fossil-fuels-from-bus-shelters; *More Municipalities Banning Meat, Air Travel Ads in Bus Shelters*, NL TIMES (Nov. 16, 2023) [hereinafter *More Municipalities Banning Meat*], https://nltimes.nl/2023/11/16/municipalities-banning-meat-air-travel-ads-bus-shelters (explaining that most municipalities' bans will "take effect when existing contracts expire").

145 *Dutch Municipalities to Ban Meat Ads*, *supra* note 144; *More Municipalities Banning Meat, supra* note 144.

146 *Dutch Municipalities to Ban Meat Ads*, *supra* note 144.

147 *More Municipalities Banning Meat, supra* note 144 (quoting Maarten van Heuven).

148 *Id.*

149 *Id.*; *see also* Samantha Dixon, *No More Burger Ads: These Dutch Cities Are Going Vegetarian*, DUTCHREVIEW (Nov. 17, 2023), (explaining that whether or not the bans will reduce meat consumption is beside the point: "This is a way to convey a message. As a municipality, you make a statement with this." (quoting Sjoukje Goldman, a researcher in sustainable marketing at the Amsterdam University of Applied Sciences)).

150 FARM TO FORK STRATEGY, *supra* note 75, at 14.

improvements to food labeling to inform consumers of the environmental and social impacts of products.[151]

Governments are also starting to bring litigation to enforce consumer protection laws against animal agriculture companies that mislead the public about their climate impacts. In Sweden, the consumer protection agency successfully sued Arla Foods, a major dairy producer, obtaining an injunction preventing the company from continuing to pronounce that its dairy products have a "net-zero climate footprint."[152] Similarly, in a landmark U.S. lawsuit against the meat giant JBS, the New York State Attorney General alleges that JBS's "net zero by 2040" commitment is not only misleading to the public, but perhaps even impossible at JBS's current levels of production.[153]

B. Positive Supports: Shifting Subsidies, Food System Transition Plans, Dietary Guidelines, and Procurement

Most fundamentally, governments can shift subsidies and supports from animal agriculture to non-animal foods.[154] The industry is heavily subsidized around the world, with nearly a third of global agricultural support measures going to meat, milk, and other dairy production.[155] As discussed above, the World Bank has recently called for a shift of subsidies from high-emitting animal foods to alternatives,[156] and reformers decried the failure of the EU's Farm to Fork Strategy to end government subsidization of meat production and consumption.[157] At an EU meeting in late 2023, the Netherlands Minister of Agriculture, Nature, and Food Quality argued that, in line with its sustainability commitments, the European Union should stop providing subsidies for meat production.[158]

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151 FAO ROADMAP, *supra* note 113, at 20.

152 Andy Coyne, *Swedish Court Bans Arla's Net-Zero Advertising Claim*, JUST FOOD (Feb. 6, 2023), https://www.just-food.com/news/swedish-court-bans-arlas-net-zero-advertising.

153 Press Release, Letitia James, N.Y. State Att'y Gen., Attorney General James Sues World's Largest Beef Producer for Misrepresenting Environmental Impacts of Their Products (Feb. 28, 2024), https://ag.ny.gov/press-release/2024/attorney-general-james-sues-worlds-largest-beef-producer-misrepresenting.

154 *E.g.*, Vallone & Lambin, *supra* note 33, at 1221 ("[T]he lack of support to alternative technologies at a level sufficient to allow them to compete on the food market against a well-supported incumbent system [is] symptomatic of a sociotechnical system still resisting fundamental systemic changes.").

155 *See* Marco Springmann & Fabian Freund, *Options for Reforming Agricultural Subsidies from Health, Climate, and Economic Perspectives*, NATURE COMMC'NS, Jan. 10, 2022, No. 82, at 2 (2022) (analyzed by final use, 22% of agricultural support measures in 2017 were used for meat products and 10% for milk and dairy products).

156 SUTTON ET AL., *supra* note 28, at 13.

157 *See supra* notes 79–80 and accompanying text.

158 Jan Braakman, *Adema: Geen EU-Geld Naar Promotie Vlees*, BOERDIREJ (Nov. 2, 2023), https://www.boerderij.nl/adema-geen-eu-geld-naar-promotie-vlees; Hugo Struna, *Eleven EU Countries Call for More 'Flexibility' on CAP's Fallow Land Rules*, EURACTIV (Nov. 21, 2023), https://www.euractiv.com/section/agriculture-food/news/eleven-eu-

Breaking new ground, several countries have announced food system transition plans of varying ambition levels that seek to promote plant-based eating through a collection of policy approaches. For example, Taiwan has taken important steps in a 2023 climate law calling for government promotion of low-carbon diets, including plant-based and local foods and reduction of food waste.[159] Subsequent legislative resolutions in Taiwan also recognized the climate impact of dietary choices and that environmental impacts should be considered when developing dietary guidelines.[160] A private-public partnership in the Netherlands is developing a policy aimed at doubling consumption of legumes by 2030.[161] In late 2023, South Korea announced a national plant-based food promotion plan, describing development in this area as a "new growth engine," including for export.[162]

For the first time, Germany has budgeted significant funds (€38 million in 2024) for the promotion of alternative protein sources.[163] A Green Party elected representative described this investment as a "paradigm shift" and "a clear commitment to the protein transition."[164] Activities to be funded include: amendment of the national food and agriculture agency's protein crop strategy to focus primarily on proteins for human nutrition rather than for animal feed; a new center and stakeholder forum around the protein transition; €20 million for an

countries-call-for-more-flexibility-on-caps-fallow-land-rules (providing more information on the agriculture ministers' meeting). A U.S. industry publication referred to the Minister's comment as "an opening shot in a potential war on meat." Joanne Cleaver, *Netherlands Ag Minister Suggests No Subsidies for Meat Production*, MEATINGPLACE (Nov. 10, 2023), http://www.meatingplace.com/Industry/News/Details/112257?allowguest=true.

159 Climate Change Response Act art. 8, FAWUBU FAGUI ZILIAOKU, *translated in Climate Change Response Act*, L. & REGULS. DATABASE OF THE REPUBLIC OF CHINA (TAIWAN) (Feb. 15, 2023), https://law.moj.gov.tw/ENG/LawClass/LawAll.aspx?pcode=O0020098; *see also* Marissa Sheldon, *Taiwan's Climate Bill Requires Promotion of Low-Carbon Diets*, HUNTER COLL. N.Y.C. FOOD POL'Y CTR. (Jan. 31, 2023), https://www.nycfoodpolicy.org/food-policy-snapshot-taiwan-climate-bill-promotes-low-carbon-diets.

160 *Taiwan Nutrition Law Gives Nod to Animals and Climate, Though Falls Short of Full Embrace*, ENV'T & ANIMAL SOC'Y OF TAIWAN (Dec. 20, 2023), https://www.east.org.tw/en/8704.

161 Flora Southey, *The 'Master Plan' to Double Legume Consumption in the Netherlands by 2030*, FOOD NAVIGATOR EUR. (Feb. 20, 2023), https://www.foodnavigator.com/Article/2023/02/20/The-master-plan-to-double-legume-consumption-in-the-Netherlands-by-2030; *Five Major Players Launch Masterplan for Protein Transition as Economic Engine in The Netherlands*, WAGENINGEN UNIV. & RSCH. (Feb. 20, 2023), https://www.wur.nl/en/newsarticle/five-major-players-launch-masterplan-for-protein-transition-as-economic-engine-in-the-netherlands.htm.

162 India Bourke, *Denmark: The Major Pork Producer Trying to Wean Itself Off Eating Meat*, BBC (Dec. 1, 2023) https://www.bbc.com/future/article/20231201-denmark-the-major-meat-producer-switching-to-a-plant-based-diet; Torrella, *supra* note 107; *Korea Introduces More Rules to Enhance Oversight of Alternative Protein Foods,* KELLER & HECKMAN (Dec. 12, 2023), https://www.khlaw.com/insights/korea-introduces-more-rules-enhance-oversight-alternative-protein-foods.

163 *Paradigm Shift in German Federal Budget 2024: €38M for 'Conversion of Animal Husbandry' and Protein Transition*, VEGCONOMIST (Nov. 17, 2023), https://vegconomist.com/politics-law/german-federal-budget-38m-protein-transition.

164 *Id.*

"opportunity program" to encourage exits from animal husbandry and into alternatives; and €10 million for projects to support promotion and production of alternatives.[165]

The most groundbreaking plan to date was enacted by Denmark in October 2023.[166] This is especially notable because Denmark has a powerful animal agriculture industry: it is the only European country with more pigs than people.[167] Denmark's Action Plan for Plant-Based Foods includes nearly $10 million for promotion of plant-based foods and $195 million to support the plant-based food transition,[168] and the Danish government investments will be supplemented by additional EU funding.[169] The Plan calls for significant reductions in consumption and production of meat and dairy. The Danish approach includes a broad variety of complimentary measures, including grants to support innovation and research, behavior change efforts, voluntary state-reviewed climate labels, training for chefs, changes to public procurement, promotion of export markets for alternatives, efforts to attract expertise and learn from other countries, improvement of the regulatory approval process for new products, and more.[170] In developing the Plan, advocacy groups like the Vegetarian Society worked with farmers' unions and the food lobby, focusing on consensus building and positive opportunities around new products and job creation.[171] A Danish MP and former environment minister described the collaboration this way: "Get the farmers on board, get the unions on board, but also be clear in your vision: say this is where we're going and do it incrementally."[172] Notably, an explicit goal of the Plan is to "serve as an example for the rest of the world."[173]

Early in 2023 in a separate effort, the Danish Parliament created a "Fund for Plant-Based Foods" with an investment of more than €90 million to support the production of more plant-based foods.[174] A

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165 *Id.*

166 *See generally* MINISTRY OF FOOD, AGRICULTURE AND FISHERIES OF DENMARK, DANISH ACTION PLAN FOR PLANT-BASED FOODS (2023) [hereinafter DANISH PLANT-BASED ACTION PLAN], https://en.fvm.dk/Media/638484294982868221/Danish-Action-Plan-for-Plant-based-Foods.pdf; Daniela De Lorenzo, *How Denmark Made the Plant-Based Action Plan Possible*, FORBES (Nov. 23, 2023, 8:26 AM), https://www.forbes.com/sites/danieladelorenzo/2023/11/23/how-denmark-made-the-plant-based-action-plan-possible.

167 Bourke, *supra* note 162.

168 De Lorenzo, *supra* note 166; Henry Mance, *Denmark Leads the Way in Incentivising Low-Meat Diets*, FIN. TIMES (Jan. 24, 2024), https://www.ft.com/content/3f4d58f4-2a3b-4aef-88a8-83784b36c835.

169 De Lorenzo, *supra* note 166.

170 DANISH PLANT-BASED ACTION PLAN, *supra* note 166, *passim*.

171 Mance, *supra* note 168; De Lorenzo, *supra* note 166; Bourke, *supra* note 162.

172 Bourke, *supra* note 162.

173 DANISH PLANT-BASED ACTION PLAN, *supra* note 166, at 5.

174 *Denmark Invests Over €90 Million in Fund for Development of Plant-Based Foods*, FOOD NATION, https://foodnationdenmark.com/news/denmark-invests-over-eur-90-million-in-fund-for-development-of-plant-based-foods (last visited Oct. 13, 2024).

number of other countries have also announced funding for alternative proteins, including China, India, Japan, and the United Kingdom.[175]

In a sign of potential future developments in France, in mid-2023 the French Court of Accounts—which counsels the government on spending—advised the French government to develop "a strategy to reduce cattle herds" in order to achieve methane reduction targets, which the Court found "necessarily call for a significant reduction in livestock."[176] The Court recommended new policies to transition from existing subsidies to supports for sustainable farming and retraining for farmers.[177]

Dietary guidelines are another lever that policymakers can pull to reduce GHG emissions. To date, while most dietary guidelines do not incorporate environmental sustainability, a growing number do.[178] In its recent Roadmap, the FAO recommended that dietary guidelines should include environmental considerations.[179] Many of the supportive policies described above were preceded or accompanied by changes to dietary guidelines. For example, two years before Denmark adopted its comprehensive Action Plan for Plant-Based Foods, updates to its dietary guidelines called for reduction of the recommended adult meat consumption in line with EAT-*Lancet* guidelines.[180]

In other examples, Canada revised its dietary guidelines in 2019 to recommend that Canadians "consume plant-based more often,"[181] and in 2021 the U.K. National Food Strategy, an independent review commissioned by the government, called for a 30% decrease in meat production by 2032.[182] The Nordic Nutrition Recommendations, released in 2023 by the Nordic Council of Ministers,[183] integrates environmental

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175 Björn Ólafsson, *8 Alternative Protein Market Predictions for 2024*, SENTIENT FOOD (Jan. 18, 2024), https://sentientmedia.org/alternative-protein-market-predictions-2024; Mance *supra* note 168.

176 *French Farmers Up in Arms over Call to Cut Cow Numbers for Sake of Climate*, RFI (May 25, 2023), https://www.rfi.fr/en/france/20230525-french-farmers-up-in-arms-over-call-to-cut-cow-numbers-for-sake-of-climate.

177 *Id.*

178 *See* Genevieve James-Martin et al., *Environmental Sustainability in National Food-Based Dietary Guidelines: A Global Review*, 6 LANCET PLANETARY HEALTH e977, e977, e979 (2022) (noting that 37 of 83 national guidelines surveyed mentioned sustainability); *see also Analysis: U.S. Lags Behind Other G20 Nations at Adding Sustainability into Dietary Guidelines*, CTR. FOR BIOLOGICAL DIVERSITY (Sept. 12, 2023), https://biologicaldiversity.org/w/news/press-releases/analysis-us-lags-behind-other-g20-nations-at-adding-sustainability-into-dietary-guidelines-2023-09-12.

179 *See supra* text accompanying note 115.

180 Mance, s*upra* note 168; *see* discussion of the Eat-*Lancet* Commission *supra* notes 69–71 and accompanying text.

181 HEALTH CANADA, CANADA'S DIETARY GUIDELINES FOR HEALTH PROFESSIONALS AND POLICY MAKERS 9 (2019), https://food-guide.canada.ca/sites/default/files/artifact-pdf/CDG-EN-2018.pdf.

182 HENRY DIMBLEBY ET AL., NATIONAL FOOD STRATEGY: THE PLAN 142 (2021), https://assets.publishing.service.gov.uk/media/61684fe3e90e071979dfec4a/national-food-strategy-the-plan.pdf.

183 The Nordic Council of Ministers includes representatives from Denmark, Finland, Iceland, Norway, Sweden, Greenland, the Faroe Islands (an autonomous region of Den-

considerations for the first time. The Nordic Council described the Recommendations as "our bravest step yet" and "well aligned with our global commitments."[184] The Recommendations call for "a predominantly plant-based diet . . . , moderate intake of low fat dairy products, limited intake of red meat and poultry, and minimal intake of processed meat . . . ."[185] While the Recommendations are not binding and implementation is up to each individual country, they are usually widely followed and used for schools, hospitals, and elderly care.[186]

Another area of supportive policy is procurement, i.e., harnessing the government's purchasing power for dietary changes that are beneficial to the environment and to people's health. In a first step in its Farm to Fork Strategy, the European Commission committed to "determin[ing] the best way of setting minimum mandatory criteria for sustainable food procurement."[187] As a national-level example, a French climate law passed in 2021 requires school cafeterias to provide vegetarian meals once a week and public catering to offer vegetarian options.[188]

Many local governments around the world are using their authority and procurement power to move away from high-emitting animal-based foods.[189] For example, sixteen cities have signed onto the Good Food Cities Accelerator, committing to increase healthy plant-based food consumption and align food procurement with the EAT-*Lancet* "Planetary Health Diet" (about half the plate occupied by vegetables and fruit) by 2030.[190] The Good Food Purchasing Program in the United States, in which large municipalities like New York City participate, provides a set of tools and support to empower public institutions to

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mark), and Åland (an autonomous region of Finland). *About the Nordic Council of Ministers*, NORDIC CO-OPERATION, https://www.norden.org/en/information/about-nordic-council-ministers (last visited Oct. 14, 2024).

184 NORDIC COUNCIL OF MINISTERS, NORDIC NUTRITION RECOMMENDATIONS 2023: INTEGRATING ENVIRONMENTAL ASPECTS 7 (2023), https://norden.diva-portal.org/smash/get/diva2:1769986/FULLTEXT06.pdf.

185 *Id.* at 9.

186 Lisbeth Kirk, *Nordic Nutrition Guidelines Advise to Eat Less Meat—But Sweden Revolts*, EUOBSERVER (June 20, 2023), https://euobserver.com/nordics/157165. *But see id.* (noting that, even before the plant-forward Nordic Nutrition Recommendations were published, Sweden's Minister of Rural Affairs came out publicly against reduction of meat consumption).

187 FARM TO FORK STRATEGY, *supra* note 75, at 14.

188 Fiona Harvey, *Outrage and Delight as France Ditches Reliance on Meat in Climate Bill*, GUARDIAN (May 29, 2021), https://www.theguardian.com/world/2021/may/29/france-outrage-delight-meat-ditch-reliance-climate.

189 INT'L PANEL OF EXPERTS ON SUSTAINABLE FOOD SYS., FROM PLATE TO PLANET: HOW LOCAL GOVERNMENTS ARE DRIVING ACTION ON CLIMATE CHANGE THROUGH FOOD 18–19, 22 (2023), https://www.ipes-food.org/_img/upload/files/PlatetoPlanetEN.pdf (noting that national food policies are missing the opportunity to move away from GHG-intensive animal-sourced foods toward plant-based foods, and describing successful local efforts).

190 *Good Food Cities Accelerator*, C40 CITIES, https://www.c40.org/accelerators/good-food-cities (last visited Oct. 20, 2024); *The Planetary Health Diet*, EAT, https://eatforum.org/eat-lancet-commission/the-planetary-health-diet-and-you (last visited Mar. 9, 2024).

purchase food aligned with "five core values: local economies, health, valued workforce, animal welfare, and environmental sustainability."[191] New York City has also taken significant measures to decrease meat consumption, serving plant-based meals as the default option in public hospitals and twice weekly in public schools.[192] The City of Amsterdam adopted a motion put forward by the Party for the Animals aiming to make Amsterdam a "Plant-Based Capital," including plans to offer plant-based options and Vegan Fridays in public facilities and to move toward a set animal-plant protein ratio for public catering by 2030.[193] In a proposed comprehensive approach to food system change, thirty municipalities around the world, including Amsterdam, Edinburgh, and Los Angeles,[194] have called for the negotiation of a "Plant-Based Treaty" by which signatories would commit to: ending land use change for animal agriculture; promoting plant-based foods and transitioning away from animal-based foods; and restoring key ecosystems and reforesting.[195]

A final important type of supportive policy is regulatory approval for animal product alternatives in the context of cultivated meat. Cultivated or cultured meat is animal meat produced by cultivating cells.[196] Cultivated meat has already received regulatory approval for commercial sale in Singapore and the United States, and other countries may soon follow.[197]

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191 *Our Work*, CTR. FOR GOOD FOOD PURCHASING, https://goodfoodpurchasing.org (last visited Oct. 22, 2024); Errol Schweizer, *How New York City Is Revolutionizing Good Food Policy*, FORBES (Mar. 23, 2021, 9:45 AM), https://www.forbes.com/sites/errolschweizer/2021/03/23/how-new-york-city-is-revolutionizing-good-food-policy.

192 Mance, *supra* note 168.

193 *Amsterdam Becomes the First EU Capital City to Endorse the Call for a Plant Based Treaty in Response to the Climate Emergency*, PLANT BASED TREATY (Feb. 1, 2024), https://plantbasedtreaty.org/amsterdam-endorses-pbt.

194 *Plant Based Treaty Endorsers: Cities, Towns, and Regions*, PLANT BASED TREATY, https://plantbasedtreaty.org/cities (last visited Oct. 20, 2024).

195 *The Treaty*, PLANT BASED TREATY, https://plantbasedtreaty.org/the-pbt (last visited Oct. 14, 2024).

196 Elliot Swartz & Claire Bomkamp, *The Science of Cultivated Meat*, GOOD FOOD INST., https://gfi.org/science/the-science-of-cultivated-meat (last visited Oct. 14, 2024).

197 Ólafsson, *supra* note 175.

C. Taxes[198]

Taxes on meat production or consumption have long been contemplated as a possible approach to reducing associated GHG emissions.[199] While a tax of this type could generally be expected to impact low-income households disproportionately because they spend a greater proportion of their income on food, pairing taxes with subsidies can reduce regressivity and encourage shifts to more sustainable diets.[200]

The most prominent current example is the Danish Parliament's approval in late 2024 of the world's first emissions tax on animal agriculture, to take effect in 2030.[201] The tax will apply to emissions from cattle, sheep, and pigs.[202] As with the consensus-building approach that led to the Danish Action Plan for Plant-Based Foods,[203] the proposal was discussed and agreed upon amongst a group including policymakers, labor unions, industry, and environmental groups.[204]

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198 Another possible approach to limiting emissions from GHG-intensive products is rationing, or limiting each person's consumption below a specified cap. A recent survey of respondents from five countries on five continents found that, while rationing was about as accepted as taxation when applied to fossil fuels, taxation was consistently more acceptable than rationing when applied to meat. Oskar Lindgren et al., *Public Acceptability of Climate-Motivated Rationing*, HUMANS. & SOC. SCIS. COMMC'NS., Sept. 26, 2024, No. 1252, at 3. Of the countries surveyed, the United States had the lowest percentage (22%) who responded that meat rationing for climate protection purposes would be acceptable to them. *Id.* at 4. This research has not identified serious consideration of meat rationing anywhere in the world. *Id.* at 1.

199 *E.g.*, Marya Torrez, *Accounting for Taste: Trade Law Implications of Taxing Meat to Fight Climate Change*, 27 GEO. ENV'T L. REV. 61, 62 (2014); *see also* Zia Mehrabi et al., *Livestock Policy for Sustainable Development*, 1 NATURE FOOD 160, 164 (2020) (recommending "[r]aising taxes on food items for populations at risk of overconsumption" and suggesting that "[t]axes may focus on worst products or incorporate carbon and biodiversity costs, although care must be taken to not to [sic] reduce food access for the poor" (internal quotations and citations omitted)).

200 Dariush Mozaffarian et al., *The Real Cost of Food: Can Taxes and Subsidies Improve Public Health?*, 312 JAMA 889, 889 (2014). Increasing prices or imposing taxes may not be effective without supportive interventions. 2018 IPCC REPORT, *supra* note 27, at 383 ("[F]or dietary change, combining supply-side measures with value-driven communication and economic instruments may help make a lasting transition, while an economic instrument, such as enhanced prices or taxation, on its own may not be as robust.").

201 Isabelle Yr Carlsson, *Denmark Will Be First to Impose CO2 Tax on Farms, Government Says*, REUTERS (June 25, 2024, 3:30 AM), https://www.reuters.com/sustainability/denmark-will-be-first-impose-co2-tax-farms-government-says-2024-06-25; Somini Sengupta, *Taxing Farm Animals' Farts and Burps? Denmark Gives It a Try*, N.Y. TIMES (Nov. 26, 2024), https://www.nytimes.com/2024/11/26/climate/denmark-methane-farm-animal-tax.html.

202 Jan M. Olsen, *Gassy Cows and Pigs Will Face a Carbon Tax in Denmark, a World First*, ASSOCIATED PRESS, https://apnews.com/article/denmark-cow-tax-greenhouse-gases-9a570518639e0a1990806fd1a05ac11a (June 26, 2024, 8:19 AM).

203 The Danish Action Plan included a commitment to eventually institute an agricultural emissions tax. *See infra* note 327 and accompanying text.

204 Carlsson, *supra* note 201.

A tax on cow emissions proposed in New Zealand in 2022 by the center-left Labour Party was scrapped after the center-right National Party gained control in the October 2023 election.[205] The proposal had resulted in farmer protests and an outcry from the meat and dairy industries,[206] which have embraced the new government's plan.[207]

In 2022, the German government announced plans to spend €1 billion on investing in improving farmed animal housing and husbandry systems, for "animal welfare and climate protection."[208] One option being discussed to fund the proposal and other reforms to the animal agriculture sector is a tax on meat modeled on the existing coffee tax.[209]

D. Buyouts

Animal buyout programs, i.e., "schemes that compensate for the loss or decline in the value of production assets on livestock farms on the condition that production will be ceased permanently,"[210] are the most direct policy mechanism available to shrink the herd. While not common, animal buyouts have been used historically by governments for various reasons.[211] Past examples include the voluntary 1986 "Whole-Herd Buyout" program in the United States aimed at reducing the milk supply,[212] voluntary buyouts in the Netherlands and Flanders (the autonomous northern region of Belgium where Brussels in located)

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[205] Rachel Pannett, *How New Zealand Plans to Tackle Climate Change: Taxing Cow Burps*, WASH. POST (Feb. 1, 2023), https://www.washingtonpost.com/climate-solutions/interactive/2023/new-zealand-cows-burps-methane-tax; Renju Jose & Lucy Craymer, *New Zealand's National Party Clinches Deal to Form Government*, REUTERS (Nov. 23, 2023), https://www.reuters.com/world/asia-pacific/new-zealands-national-party-reaches-deal-form-government-2023-11-23; *New Zealand Scraps 'Burp Tax' on Livestock After Backlash from Farmers*, AL JAZEERA (June 11, 2024), https://www.aljazeera.com/economy/2024/6/11/new-zealand-scraps-burp-tax-on-livestock-after-backlash-from-farmers. A previous proposed tax in New Zealand on methane emissions, put forward in 2003, was dropped after industry opposition. BLINDSPOT, *supra* note 83, at 27.

[206] Pannett, *supra* note 205; *New Zealand Scraps 'Burp Tax' on Livestock*, *supra* note 205.

[207] Tracy Withers, *New Zealand Farmers Welcome Opposition's Agriculture Emissions Policy*, BLOOMBERG (June 11, 2023), https://www.bloomberg.com/news/articles/2023-06-12/new-zealand-farmers-welcome-opposition-s-agriculture-emissions-policy.

[208] Boezeman et al., *supra* note 80, at 8.

[209] Olivia Logan, *German Minister Announces Plan for Excise Tax on Meat*, I AM EXPAT (Feb. 7, 2024), https://www.iamexpat.de/lifestyle/lifestyle-news/german-minister-announces-plan-excise-tax-meat; Bundesministerium für Ernährung und Landwirtschaft [BMEL], Konzept zur Einführung einer Verbrauchsteuer auf bestimmte tierische Produkte [Concept for an Excise Duty on Certain Animal Products] (translation on file with author).

[210] Boezeman et al., *supra* note 80, at 4.

[211] *Id.* at 5–6.

[212] *Id.* at 6; Robert A. Hamilton, *U.S. Offers Dairymen a Buyout*, N.Y. TIMES (Mar. 23, 1986), https://www.nytimes.com/1986/03/23/nyregion/us-offers-dairymen-a-buyout.html; Mich. Farm Bureau, *Results of Past U.S. Dairy Supply Management—Will History Repeat Itself?*, MICH. FARM NEWS (May 13, 2019), https://www.michiganfarmnews.com/results-of-past-us-dairy-supply-management-will-history-repeat-itself.

starting around 2000 to reduce manure in order to comply with EU rules on nitrogen pollution,[213] and mandatory buyouts of mink in the Netherlands that were initially implemented in 2013 based on animal welfare concerns and then accelerated for public health reasons after coronavirus infections spread through mink farms.[214]

In order to achieve the intended population reductions and benefits, buyout programs must be carefully structured. For example, one expert advises that voluntary dairy cow buyout policies must ensure: additionality—in other words, that the animals who are removed are actually productive dairy cows (and not already at the end of milk production when they would be slaughtered anyway); that removed cows are not replaced, via some assurance of long-term stock diminishment; and that the program is attractive to farmers (a challenge when dairy production is profitable).[215]

In a leading example, the Dutch government appears to have been the first in the world to utilize an animal buyout program with an explicit purpose of reducing GHG emissions.[216] A 2019 pig buyout program that was initially requested by farmers to address odor problems was later granted additional government funding as a way of reaching climate and nitrogen pollution goals.[217] In addition, the 2019 Dutch Climate Agreement—the national policy to achieve emissions reductions in-line with the Paris Agreement—included plans for a voluntary buyout of dairy farmers in peat meadow areas, which are notable for their emissions reduction potential and biodiversity.[218] Provinces submitted initial buyout plans in late 2023.[219]

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213 Boezeman et al., *supra* note 80, at 6.

214 *Id.* at 4, 6; *Dutch to Permanently Ban Mink Farming from April 2021*, NL TIMES (Aug. 27, 2020), https://nltimes.nl/2020/08/27/dutch-permanently-ban-mink-farming-april-2021.

215 Jan Dutkiewicz, *Ireland Isn't Culling Cows for Climate. But Maybe It Should Be?*, BULL. OF THE ATOMIC SCIENTISTS (Oct. 25, 2023) [hereinafter Dutkiewicz, *Ireland Isn't Culling Cows*], https://thebulletin.org/2023/10/ireland-isnt-culling-cows-for-climate-but-maybe-they-should-be; *see also* Bruce L. Dixon et al., *Supply Impact of the Milk Diversion and Dairy Termination Programs*, AM. J. AGRIC. ECON. 633, 639 (1991) (evaluating buy-out programs and noting effectiveness limitations, including that some producers reentered the market immediately after the required cessation period and that strong product demand may have encouraged nonparticipating producers to increase production).

216 Boezeman et al., *supra* note 80, at 6, 9.

217 *Id.* at 7, 10; *European Commission: 'Dutch Plans to Buy Out Pig Farmers Are in Accordance with the EU Rules on State Aid*,' LOYENS & LOEFF (Oct. 23, 2019), https://www.loyensloeff.com/insights/news—events/news/european-commission-dutch-plans-to-buy-out-pig-farmers-are-in-accordance-with-the-eu-rules-on-state-aid.

218 Boezeman et al., *supra* note 80, at 7, 10; GOV'T OF THE NETHERLANDS, CLIMATE AGREEMENT 143–44 (2019), https://www.government.nl/documents/reports/2019/06/28/climate-agreement.

219 *Kamerbrief voortgang provinciale gebiedsprogramma's en eerste maatregelpakketten*, RIJKSOVERHEID (Oct. 24, 2023), https://www.rijksoverheid.nl/ministeries/ministerie-van-landbouw-natuur-en-voedselkwaliteit/documenten/kamerstukken/2023/10/24/voortgang-provinciale-gebiedsprogramma-s-en-eerste-maatregelpakketten; Letter from Christianne van der Wal-Zeggelink, Minister for Nature & Nitrogen, to the President of the House of

The Netherlands is perhaps a predictable place for the first buyouts related to climate goals, given that it has high farm animal densities, a serious nitrogen pollution problem with more than half of all nitrogen pollution coming from manure,[220] and a history of utilizing animal buyout programs for other purposes (e.g., odor control and reducing nitrogen pollution).[221] Nitrogen pollution can harm biodiversity and also contributes to climate change.[222] Measures that reduce nitrogen pollution also reduce emissions of the GHG nitrous oxide, the majority of which is formed when microbes process excess nitrogen from farmed animal manure and urine and from synthetic nitrogen fertilizer.[223]

Acute pressure on the Dutch government to reduce nitrogen pollution arose from a lawsuit filed in 2018 by a Dutch NGO against the national government.[224] The lawsuit alleged that high levels of nitrogen pollution in certain protected areas violated the EU Habitats Directive.[225] Eventually, the Court of Justice of the European Union agreed.[226] In response, the government announced plans to reduce the herd by as much as a third,[227] eventually identifying significant funds (€24.3 billion) for the transition, including to buy out 3,000 "peak emitter" farms at up to 120% of their value.[228] As of late 2024, 1,474 farmers had submitted applications for one or both of the buyout programs, with nearly a third committing to a buyout.[229] As described below in Part V.B, this Dutch "stikstofcrisis" (nitrogen crisis) resulted in widespread farmer protest and a significant political shakeup in the Netherlands. Indeed, buyout plans—while amongst the most direct

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Representatives of the States-General, at 1–2 (Jan. 23, 2024), https://open.overheid.nl/documenten/c9e74d60-5396-45bf-83f2-9132df5ae151/file.

220 Erik Stokstad, *Nitrogen Crisis from Jam-Packed Livestock Operations Has 'Paralyzed' Dutch Economy*, SCIENCE (Dec. 4, 2019), https://www.science.org/content/article/nitrogen-crisis-jam-packed-livestock-operations-has-paralyzed-dutch-economy.

221 Boezeman et al., *supra* note 80, at 6–7.

222 *Facts about Nitrogen Pollution*, U.N. ENV'T PROGRAMME, https://www.unep.org/facts-about-nitrogen-pollution (last visited Mar. 7, 2024).

223 *See* Klaus Butterbach-Bahl et al., *Nitrous Oxide Emissions from Soils: How Well Do We Understand the Processes and Their Controls?*, PHIL. TRANSACTIONS ROYAL SOC'Y LONDON, SERIES B, BIOLOGICAL SCIS., July 2013, No. 20130126, at 1–2 (explaining that dominant sources of both anthropogenic and natural nitrous oxide are "closely related to microbial production processes in soils, sediments and water bodies"); Alfi Syakila & Carolien Kroeze, *The Global Nitrous Oxide Budget Revisited*, 1 GREENHOUSE GAS MEASUREMENT & MGMT. 17–18 (2011) (quantifying global nitrous oxide sources).

224 Case C-293/17, Coöperatie Mobilisation for the Environment UA v. College van Gedeputeerde Staten van Limburg, ECLI:EU:C:2018:882 (Nov. 7, 2018).

225 *Id.* ¶¶ 50, 52; Kasja Pira, *The Dutch Nitrogen Crisis*, ACID NEWS, Dec. 2019, at 3.

226 *Coöperatie Mobilisation for the Environment UA*, ECLI:EU:C:2018:882, ¶¶ 69, 120.

227 Andy Bounds, *Dutch Farmers in Uproar over Plans to Curb Animal Numbers to Cut Nitrogen Emissions*, FIN. TIMES (Aug. 2, 2022), https://www.ft.com/content/90e38fb5-e942-4afd-994d-048dc40579a2.

228 Ashoka Mukpo, *In the Clash over Dutch Farming, Europe's Future Arrives*, MONGABAY (Sept. 8, 2023) [hereinafter *Clash over Dutch Farming*], https://news.mongabay.com/2023/09/in-the-clash-over-dutch-farming-europes-future-arrives.

229 *Lbv en Lbv-plus actueel*, RIJKSDIENST VOOR ONDERNEMEND NEDERLAND, https://www.rvo.nl/onderwerpen/lbv-plus-actueel (Nov. 26, 2024).

approaches to reducing GHG emissions from animal agriculture—can face significant opposition and political blowback if not structured and rolled out carefully.

Somewhat similar events played out in Flanders. In 2021, a climate policy committee advised the government that it should reduce animal numbers and encourage dietary shifts as part of meeting climate targets.[230] While the proposal was not taken up, after a ruling by the highest Flemish administrative court in 2021 ordering the government to reduce nitrogen pollution,[231] animal agriculture was again at the center of policy discussions. The responsive plan eventually approved by the government included both voluntary and mandatory animal buyouts, depending on their proximity to and impact on certain protected areas.[232] Uptake on the voluntary offers was low as of early 2024, reportedly with only seven pig farmers having accepted the buyout offer out of the 982 contacted by the government.[233] An industry publication explains: "The low interest in the scheme can be attributed to the economic trend of high pig prices, as well as criticism of the buyout conditions, such as limited benefits for older stables and restrictions on expanding other livestock activities on the farm."[234]

E. Tech Fixes and Climate Efficiency Approaches

> At this point it is naïve to expect that technological improvements alone will slow the impacts of growth and reduce the burden on the biosphere. And yet many still exhibit this naiveté.
>
> ~Kim Stanley Robinson,
> *The Ministry for the Future*[235]

The policy approaches discussed above have the potential to reduce the number of farmed animals or "shrink the herd," with animal food products replaced by more sustainable alternatives. There is another category of interventions that could be described as "climate efficiency" approaches—including feed additives, genetic engineering, and biogas digesters[236]—which aim to reduce emissions from animal agriculture by making each animal (or group of animals) more efficient in climate terms. An example of a climate efficiency policy is Canada's proposal

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230 Boezeman et al., *supra* note 80, at 7.

231 Karel Veuchelen & Els Empereur, *Nitrogen in Flanders: Will the Dust Finally Settle?*, PWC LEGAL (Mar. 27, 2023), https://www.pwclegal.be/en/news/nitrogen-in-flanders---will-the-dust-finally-settle-.html.

232 Boezeman et al., *supra* note 80, at 7–8.

233 *Belgium: Enthusiasm for the Buyout Scheme for Pig Farms Is Not Yet Great*, TRIDGE (Jan. 18, 2024), https://www.tridge.com/news/enthusiasm-for-buyout-scheme-for-flemish-pig-farms.

234 *Id.*

235 ROBINSON, *supra* note 1, at 165.

236 *See* discussion of biogas digesters *infra* notes 272–278 and accompanying text.

that would allow farmers to generate offset credits if they reduce enteric emissions from their cattle through strategies such as changing feed.[237]

Because such approaches do not challenge the fundamental structure or scale of the industry, they have been referred to as "industry-led" and "industry-friendly" and typically receive greater buy-in from industry actors.[238] For example, the authors of a recent survey of animal agriculture and climate policy in four countries in Western Europe note: "In general terms, in all countries, we observe the reproduction of a 'technology versus volume' discourse. Farmers' organisations and their supporting parties stress the importance of eco-efficiency and technical innovation to resolve environmental concerns. Environmental NGOs and green parties advocate reducing livestock production and changing human diets."[239]

This Article does not take the position that climate efficiency approaches are harmful or without merit.[240] The urgency of the climate crisis—which will affect all life on this planet, to varying degrees—demands that we act with urgency on all potentially helpful fronts.[241] But, for the reasons that follow, efficiency approaches by themselves will

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[237] ENV'T & CLIMATE CHANGE CANADA, DRAFT FEDERAL OFFSET PROTOCOL: REDUCING ENTERIC METHANE EMISSIONS FROM BEEF CATTLE 1 (2023), https://www.canada.ca/content/dam/eccc/documents/pdf/climate-change/ghg-offset/REME%20protocol%20-%20EN.pdf.

[238] *E.g.*, Morris & Jacquet, *supra* note 62, at 1 (referring to "industry-led climate 'solutions' that maintain production"); Torrella, *supra* note 107 (describing "industry-friendly changes like tinkering with how livestock are fed and farmed"); Dutkiewicz, *Ireland Isn't Culling Cows*, *supra* note 215 ("Emissions restrictions policies quite simply interfere with a profitable and entrenched business model, which explains why farming groups, where they have participated in discussion about policy proposals, have favored soft interventions like developing methane-inhibiting feed additives over harder interventions like voluntary culls."). One expert draws this analogy: "Much as the coal industry starting hawking 'clean coal' in 2008 to avoid policies promoting a phaseout, the meat industry and its defenders are now arguing for clean cows." Dutkiewicz, *The Comforting Lie of Climate-Friendly Meat*, *supra* note 102.

[239] Boezeman et al., *supra* note 80, at 9; *see also Clash over Dutch Farming*, *supra* note 228 ("[T]echnologies [that reduce emissions] could potentially allow [Dutch] farmers to dodge the tougher approach that some policymakers have in mind: big cuts to the number of livestock in the Netherlands.").

[240] *E.g.*, 2018 IPCC REPORT, *supra* note 27, at 146 ("[E]ven within existing livestock production systems, a transition from extensive to more productive systems bears substantial GHG abatement potential, while improving food availability." (internal citations omitted)); EU ASSESSMENT REPORT 2024, *supra* note 50, at 157 ("[Methane] emissions can be reduced by measures to reduce emissions from enteric fermentation (the digestion process of ruminant livestock such as cattle) and by improved manure management.").

[241] *See* Torrella, *supra* note 107 ("Numerous environmental scientists . . . have called on wealthy countries to cut back on meat and eat more plant-based meals . . . . Down another path lies the more politically palatable, yet far less effective, approach of continuing to eat record amounts of meat in the West while deploying a host of technologies and farming practices, each of which can only marginally shave off livestock emissions. The world needs a mix of both approaches, but policy makers, out of political expediency and corporate capture, are barreling down the second path, a choice they'll likely come to regret as climate change intensifies.").

not be sufficient and should not be pursued at the exclusion of or to the detriment of other approaches.[242]

Indeed, some advocates refer to efficiency approaches to the climate problem of animal agriculture as "false solutions" for several reasons.[243] First, and perhaps most essentially, reducing the GHG emissions of animals in industrial systems does nothing to address the many other externalities of those systems,[244] which include harms to environmental justice communities,[245] zoonotic disease risks[246] and antimicrobial resistance,[247] other public health harms,[248] dangerous and exploitative

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[242] Fredrik Hedenus et al., *The Importance of Reduced Meat and Dairy Consumption for Meeting Stringent Climate Change Targets*, 124 CLIMATIC CHANGE 79, 89 (2014) ("[D]ietary changes are crucial for meeting the 2°C target with high probability."); Willett et al., *supra* note 69, at 472 ("Although food production practices have an important role, many studies highlight that a dietary change towards increased adoption of plant-based diets has high mitigation potential, which is probably needed to limit global warming to a less than 2°C increase.").

[243] *E.g.*, Letter from Ctr. for Biological Diversity et al. to Thomas J. Vilsack, *supra* note 8 ("[F]alse solutions such as feed additives . . . have minimal impact in reducing emissions and aren't scalable, and biogas . . . worsens the problem of pollution and greenhouse gas emissions. Improving agricultural production is only one piece of the puzzle, and ignoring dietary shifts in consumption creates an ineffective and weak climate response.").

[244] *E.g.*, GLOBAL METHANE ASSESSMENT, *supra* note 81, at 116 ("Achieving very low emissions per kilogram of protein may involve large-scale industrialized agriculture, which can have other social and environmental impacts beyond greenhouse gas emissions and hence such policies need to be considered with care."); Cleo Verkuijl et al., *Climate Change, Public Health, and Animal Welfare: Towards a One Health Approach to Reducing Animal Agriculture's Climate Footprint*, FRONTIERS ANIMAL SCI., May 15, 2024, No. 1281450, at 9–10 ("[C]ommon climate mitigation interventions targeting animal agriculture have implications for public health and animal welfare. . . . When seeking to reduce the climate impacts of animal farming, it is thus crucial to look beyond GHG emissions alone: a wider set of social goods merits serious attention."); LIVESTOCK'S LONG SHADOW, *supra* note 59, at 267 ("[T]he livestock sector is a major stressor on many ecosystems and on the planet as whole. Globally it is one of the largest sources of greenhouse gases and one of the leading causal factors in the loss of biodiversity, while in developed and emerging countries it is perhaps the leading source of water pollution.").

[245] *E.g.*, Melba Newsome, *Unchecked Growth of Industrial Animal Farms Spurs Long Fight for Environmental Justice in Eastern NC*, N.C. HEALTH NEWS (Oct. 20, 2021), https://www.northcarolinahealthnews.org/2021/10/20/environmental-justice-and-industrial-farming-in-eastern-nc.

[246] ANN LINDER ET AL., ANIMAL MARKETS & ZOONOTIC DISEASE IN THE UNITED STATES 82 (2023), https://animal.law.harvard.edu/wp-content/uploads/Animal-Markets-and-Zoonotic-Disease-in-the-United-States.pdf ("In [concentrated animal feeding operations (CAFOs)], hundreds of thousands or millions of animals can be held together in intense confinement with limited air flow, making these facilities ripe for pathogen transmission among animals as well as between animals and workers."); *see also* Hayek, *supra* note 97, at 3–4.

[247] Christy Manyi-Loh et al., *Antibiotic Use in Agriculture and Its Consequential Resistance in Environmental Sources: Potential Public Health Implications*, MOLECULES, April 2018, No. 795, at 3–4, 17.

[248] *E.g.*, Nina G.G. Domingo et al., *Air Quality–Related Health Damages of Food*, PNAS, May 10, 2021, No. e2013637118, at 1 ("80% of the 15,900 annual deaths that result from food-related fine particulate matter . . . pollution are attributable to animal-based foods."); Amanda D. Emert et al., *Atmospheric Transport of Particulate Matter and Particulate-*

labor conditions,[249] systemic animal cruelty,[250] biodiversity loss[251] and habitat destruction,[252] soil and water pollution,[253] intensive water use,[254] market consolidation and antitrust abuses,[255] and harms to rural communities.[256] On a related note, while some recommend a species

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Bound Agrochemicals from Beef Cattle Feedlots: Human Health Implications for Downwind Agricultural Communities, SCI. TOTAL ENV'T, October 2023, No. 164678, at 12.

[249] *E.g.*, Fred Gerr, *Meatpacking Plant Workers: A Case Study of a Precarious Workforce*, 18 J. OCCUPATIONAL & ENV'T HYGIENE 154, 157 (2021); Leah Douglas, *Big U.S. Chicken Company, Mountaire, Asks Contractors to Oppose Transparency Rule*, REUTERS (Aug. 5, 2022, 10:04 AM), https://www.reuters.com/world/us/big-us-chicken-company-mountaire-asks-contractors-oppose-transparency-rule-2022-08-05 ("Poultry farmers have said for years that they fear publicly airing grievances with the tournament [payment] system because of potential retaliation from companies . . . .").

[250] *E.g.*, Nicholas Kristof, *The Ugly Secrets Behind the Costco Chicken*, N.Y. TIMES (Feb. 6, 2021), https://www.nytimes.com/2021/02/06/opinion/sunday/costco-chicken-animal-welfare.html ("[F]uture generations will look back at our mistreatment of livestock and poultry with pain and bafflement."); Letter from Rep. Veronica Escobar et al., Members of Congress, to Thomas J. Vilsack, Sec'y of Agric. & Dr. José Emilio Esteban, Undersec'y for Food Safety, U.S. Food Safety & Inspection Servs. (Dec. 6, 2023), https://escobar.house.gov/uploadedfiles/final_letter_to_secretary_vilsack_and_under_secretary_esteban_.pdf ("[U]ndercover footage has revealed widespread and entirely unnecessary abuse and neglect of pigs—particularly nonambulatory pigs—at certain facilities. In slaughterhouses, workers have been known to try to force [downed pigs] to move by kicking, dragging, shoving, or even electroshocking them" (internal citations and quotations omitted)).

[251] *E.g.*, U.N. FOOD & AGRIC. ORG., THE IMPACT OF LIVESTOCK ON BIODIVERSITY (2019) https://www.fao.org/3/ca4960en/ca4960en.pdf, ("Livestock is among the sectors with highest impacts on biodiversity."); Bradley J. Bergstrom, *Carnivore Conservation: Shifting the Paradigm from Control to Coexistence*, 98 J. MAMMALOGY 1, 2 (2017) (describing the killing of thousands of predator animals and noting that USDA's Wildlife Services' "field operations in the western United States have been criticized for their over-reliance on lethal means of resolving wildlife conflicts with livestock"); Jeremy Burke, *How Eating Meat Creates a 'Dead Zone' the Size of New Jersey in the Gulf of Mexico Every Year*," BUS. INSIDER (Apr. 7, 2018, 8:55 AM), https://www.businessinsider.com/eating-meat-affects-environment-dead-zone-2018-4.

[252] *E.g.*, TIM G. BENTON ET AL., CHATHAM HOUSE, FOOD SYSTEM IMPACTS ON BIODIVERSITY LOSS 6–7 (2021) ("Over the past 50 years, the biggest driver of habitat loss has been the conversion of natural ecosystems for crop production or pasture. . . . The rapid expansion of animal farming has been behind much of this land expansion.").

[253] *E.g.*, Laima Cesoniene et al., *The Impact of Livestock Farming Activity on the Quality of Surface Water*, 26 ENV'T SCI. & POLLUTION RSCH. 32678, 32684 (2019) ("One of the most dangerous pollution sources is intensive livestock facilities, whose production waste has a negative impact on soil and water quality.").

[254] *E.g.*, Brian D. Richter et al., *Water Scarcity and Fish Imperilment Driven by Beef Production*, 3 NATURE SUSTAINABILITY 319, 320 (2020) ("[I]rrigation of cattle-feed crops . . . is the single largest consumptive [water] user at both regional and national scales [in the United States], accounting for 23% of all water consumption nationally, 32% in the western US and 55% in the Colorado River basin.").

[255] *E.g.*, Shefali Sharma, *Mighty Giants: Leaders of the Global Meat Complex*, INST. FOR AGRIC. & TRADE POL'Y (Apr. 10, 2018), https://www.iatp.org/blog/leaders-global-meat-complex; Brianna L. Alderman et al., *Ruffled Feathers: The Chicken Cartel in the United States*, 68 ANTITRUST BULL. 47, 48 (2023); Tom Polansek, *Explainer: How Four Big Companies Control the U.S. Beef Industry*, REUTERS (June 17, 2021, 10:12 AM), https://www.reuters.com/business/how-four-big-companies-control-us-beef-industry-2021-06-17.

[256] *E.g.*, BROTHER DAVID ANDREWS & TIMOTHY J. KAUTZA, PEW COMM'N ON INDUS. FARM ANIMAL PROD., IMPACT OF INDUSTRIAL FARM ANIMAL PRODUCTION ON RURAL

shift to reduce GHG emissions, such shifts (for example, from cows to pigs, or pigs to chickens[257]) do nothing to address these other externalities of industrialized animal agriculture systems.[258] The vast majority of animal products in the United States are raised in industrial settings.[259]

Second, reducing per animal emissions will not necessarily lead to reductions in total emissions if production and consumption of animal products continues to rise as predicted.[260] Also, increasing the productivity of individual animals often requires additional inputs with attendant GHG emissions.[261] Moreover, efficiency improvements can sometimes paradoxically result in increased demand and production (for

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COMMUNITIES 35 (2008) ("[I]ndustrialization [of animal agriculture] draws wealth and life away from the very rural communities it purports to benefit and which once thrived as a result of diverse, and more sustainable, forms of livestock production.").

257 FAO ROADMAP, *supra* note 113, at 12 ("[S]hifting from large ruminant to small ruminant animals for meat products, and from ruminant to monogastric animals, in particular chicken, will reduce the GHG impacts of animal-food based [sic] products."); SUTTON ET AL., *supra* note 28, at 13 (proposing shifting subsidies from "red meat and dairy" to "low-emission foods, like *poultry* or fruits and vegetables" (emphasis added)).

258 Verkuijl et al., *supra* note 244, at 6–8. Looking specifically at animal welfare and the suffering of individual animals, it takes about 100 chickens to get the same amount of meat as one cow. Marina Bolotnikova & Kenny Torrella, *How Big Are Factory Farms? How Mega-Sized Factory Farms Took Over America's Food System, Explained in 9 Charts*, VOX (Feb. 26, 2024, 4:30 AM), https://www.vox.com/future-perfect/24079424/factory-farming-facts-meat-usda-agriculture-census.

259 Hannah Ritchie, *How Many Animals Are Factory Farmed?* OUR WORLD IN DATA (Sept. 25, 2023), https://ourworldindata.org/how-many-animals-are-factory-farmed (citing estimates based on USDA data that 99% of U.S. farm animals are raised on industrial-scale concentrated animal feeding operations, or "CAFOs," as defined by EPA, including 70% of cows, 98% of pigs and egg-laying hens, 99.9% of turkeys, and 99.97% of broiler (meat) chickens).

260 *See* IPCC, CLIMATE CHANGE AND LAND, *supra* note 67, at 440 ("Reductions in GHG emissions intensity (emissions per unit product) from livestock can support reductions in absolute emissions, *provided appropriate governance to limit total production is implemented at the same time* . . . ." (emphasis added)). Indeed, some animal agriculture companies have preferred to report on decreases in their per animal emissions while failing to be clear that overall emissions have increased because of growth in the size of the herd. *See* EMISSIONS IMPOSSIBLE, *supra* note 3, at 14–15. Similarly, campaigns like the "continuous improvement" campaign of the Meat Institute, a U.S.-based trade association, offer industry a comfortable baseline and will not necessarily result in emissions reductions. *See generally* N. AM. MEAT INST., IMPLEMENTING TOOLS: 2024 CONTINUOUS IMPROVEMENT REPORT (2024), https://meatinstitute.org/sites/default/files/documents /20241021%20Protein%20PACT%20continuous%20improvement%20report.pdf.

261 Gert-Jan Nabuurs et al., *Agriculture, Forestry and Other Land Uses*, *in* INTERGOV'TAL PANEL ON CLIMATE CHANGE, CLIMATE CHANGE 2022: MITIGATION OF CLIMATE CHANGE 750, 771 (Priyadarshi R. Shukla et al. eds., 2022) [hereinafter *IPCC Agriculture, Forestry and Other Land Uses*] ("[I]ncreased individual animal productivity generally requires increased inputs (e.g., feed) and this generates increased emissions . . . . In addition, the production of inputs to facilitate increased animal productivity, may indirectly drive further absolute GHG emissions along the feed supply chain.").

example as happened with more efficient cars and air conditioners),[262] or to shifts in production that undo emissions reductions.[263]

Third, many efficiency approaches are as yet unproven and potentially unscalable.[264] For example, an Irish government study found that, even if methane-inhibiting technologies and other mitigation measures were successfully implemented, agriculture would not be able to achieve Paris Agreement targets without also "limiting animal number increases and develop[ing] . . . new science."[265] Moreover, efficiency approaches usually come at a cost, and for that reason producers may be slow to implement them without regulatory pressure.[266] For example, the feed additive Bovaer has been shown to

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[262] This phenomenon is known as the "Jevons Paradox" (named after 19th century economist William Stanley Jevons) or the "Rebound Effect." Jaume Freire González, *The Jevons Paradox and Rebound Effect: Are We Implementing the Right Energy and Climate Change Policies?*, OECD F. NETWORK (Sept. 22, 2022), https://www.oecd-forum.org/posts/the-jevons-paradox-and-rebound-effect-are-we-implementing-the-right-energy-and-climate-change-policies.

[263] *E.g.*, David Styles et al., *Climate Mitigation by Dairy Intensification Depends on Intensive Use of Spared Grassland*, 24 GLOB. CHANGE BIOLOGY 681, 681 (2018) (undertaking life cycle assessment of potential indirect GHG effects of dairy intensification in the United Kingdom and describing replacement beef production in Brazil (because dairy cattle also become beef) resulting in a "small GHG savings for the UK GHG inventory, but . . . a net increase in international GHG emissions"). As observed in the recent EU Assessment Report, "reductions in the production and consumption of GHG-intensive agricultural products (especially livestock products) need to go hand in hand, otherwise emission reduction efforts risk being offset by increased imports (displacing emissions to other countries) or exports (maintaining EU emissions in spite of consumption changes)." EU ASSESSMENT REPORT 2024, *supra* note 50, at 155.

[264] *E.g.*, Dutkiewicz, *The Comforting Lie of Climate-Friendly Meat*, *supra* note 102 ("[T]he technologies proposed to reduce [methane from cows] might look good in small trials. But they haven't been implemented or shown to be effective or affordable at any meaningful scale."); *Novel Meat and Dairy Alternatives Could Help Curb Climate-Harming Emissions*, U.N. ENV'T PROGRAMME (Dec. 8, 2023), https://www.unep.org/news-and-stories/press-release/novel-meat-and-dairy-alternatives-could-help-curb-climate-harming ("[F]eed additives to reduce emissions from animal agriculture . . . have struggled so far to win government support and achieve impacts at the desired scale or speed."); *IPCC Agriculture, Forestry and Other Land Uses*, *supra* note 261, at 830 (identifying the need for more research into technological mitigation measures as a knowledge gap, including research regarding their practical use, feasibility, and impact on absolute GHG emissions).

[265] TEAGASC CLIMATE CTR., MARGINAL ABATEMENT COST CURVE 2023: EXECUTIVE SUMMARY 11 (2023), https://www.teagasc.ie/publications/2023/marginal-abatement-cost-curve-2023---executive-summary.php; *see also id.* at 9 (finding that further research is needed to determine whether feed additives are effective and whether they have constraints or pose risks).

[266] Ben Elgin, *This Quick Fix Reduces Methane Emissions from Cow Burps*, BLOOMBERG L. (June 28, 2023), https://www.bloomberglaw.com/product/blaw/bloombergterminalnews/bloomberg-terminal-news/RWY8O5T0AFB4 ("[C]orporate giants that have promised huge and rapid cuts to their greenhouse gas emissions, like Danone, Nestle, Starbucks and JBS . . . have publicly declared an interest in using methane-curbing feed additives with the farmers or feedlots who supply their ingredients, but have yet to follow through at any sort of magnitude.").

reduce enteric methane from cows by thirty percent.[267] But it costs about $100 per cow per year and uptake has been slow, even by large companies.[268] In the words of one campaigner: "If you're going to talk about [feed additives], buy them and do this. Invest the money and make it a part of your emission-reduction plan. Some companies are presenting this as a silver bullet, but they're not at all serious about scaling it up, probably because of the cost."[269]

Fourth, even if efficiency approaches were affordable, feasible, and implemented at scale, farmed animals—and cattle in particular—would still be significant sources of GHG emissions. For example, even if the Bezos Earth Fund is correct that its methane-inhibiting research could reduce emissions by as much as thirty percent, "that would still make cows the highest-emission part of the food system."[270] Shifting diets would be more effective.[271]

Fifth, where efficiency approaches make industrial animal agriculture more profitable or even encourage its expansion and entrenchment, such efforts can act contrary to climate mitigation goals. Anaerobic digesters, which are systems that cap manure lagoons to seek to capture emitted methane, are perhaps the best example. As discussed elsewhere in this volume,[272] digesters have been the target of sustained criticism on a number of fronts,[273] including that they can make large-scale animal agriculture more profitable and even encourage expansion of facilities.[274] In California, where digesters have benefitted from

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267 *Id.*

268 *Id.* (noting that JBS had previously vowed to use Bovaer but had then "gone silent" on the topic).

269 *Id.* (quoting Nusa Urbancic, campaigns director at Changing Markets Foundation).

270 Dutkiewicz, *The Comforting Lie of Climate-Friendly Meat*, *supra* note 102.

271 SUTTON ET AL., *supra* note 28, at 13 ("[T]he cost-effective mitigation potential from shifting diets away from meat is about twice as high as that from reducing enteric fermentation and other livestock production mitigation methods."); GLOBAL METHANE ASSESSMENT, *supra* note 81, at 13 ("Behavioural change measures and innovative policies are particularly important to prevent emissions from agriculture, given the limited potential to address the sector's methane emissions through technological measures.").

272 Randall S. Abate, *Putting Lipstick on a Pig: Biogas, Methane Digesters, and the Greenwashing Playbook*, 54 ENV'T L. 545 (2024).

273 *See, e.g.*, RUTHIE LAZENBY, VT. L. & GRADUATE SCH., RETHINKING MANURE BIOGAS: POLICY CONSIDERATIONS TO PROMOTE EQUITY AND PROTECT THE CLIMATE AND ENVIRONMENT 16 (2022), https://www.vermontlaw.edu/sites/default/files/2022-08/Rethinking_Manure_Biogas.pdf (discussing environmental harms resulting from digesters).

274 EU ASSESSMENT REPORT 2024, *supra* note 50, at 169 (noting that biogas digesters have the potential to "increase[] incentives to maintain livestock herd numbers"); MARTIN BOWMAN & KRYSIA WORONIECKA, FEEDBACK, GREEN GAS WITHOUT THE HOT AIR: DEFINING THE TRUE ROLE OF BIOGAS IN A NET ZERO FUTURE 57–60 (2020), https://feedbackglobal.org/wp-content/uploads/2020/09/Feedback-2020-Green-Gas-Without-the-Hot-Air-report.pdf (describing how intensive factory farming of pigs and chickens expanded in Northern Ireland following the institution of biogas subsidies); CHLOË WATERMAN & MOLLY ARMUS, FRIENDS OF THE EARTH, BIOGAS OR BULL****? THE DECEPTIVE PROMISE OF MANURE BIOGAS AS A METHANE SOLUTION 5 (2024), https://foe.org/wp-content/uploads/2024/03/Factory-Farm-Gas-Brief_final-0312.pdf ("CAFOs with digesters are more likely to

substantial government investment and support via the Low Carbon Fuel Standard and other programs,[275] some observers refer to a dangerous "manure gold rush."[276] In a recent piece on biogas digesters, a professor at UC Davis wrote:

> In colonial India, the British government wanted to reduce the number of cobras in Delhi, so it offered a bounty for dead cobras. Profit-seek[ers] responded by breeding cobras to receive the bounty. This phenomenon is known as the "cobra effect." There is a risk of the same thing happening when we pay people to capture methane from dairy cow manure.[277]

Moreover, digesters have benefitted from substantial government investment, an opportunity cost for other more beneficial mitigation approaches.[278]

Sixth, efficiency approaches can distract attention from other policy paths that prioritize the urgent need to reduce overall emissions from animal agriculture. In the parallel context of geoengineering (removing carbon from the atmosphere by technical means),[279] the U.N. Human Rights Council's Advisory Committee has warned that such approaches

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increase their herd sizes relative to statewide populations."); Aaron David Smith, *Cow Poop Is Now a Big Part of California Fuel Policy*, U.C. DAVIS: AG DATA NEWS (Jan. 22, 2024), https://asmith.ucdavis.edu/news/cow-poop-now-big-part-california-fuel-policy ("High profits from operating digesters create the incentive for farmers to expand dairy herds for the purpose of generating manure rather than for producing milk."). *But see* Aaron David Smith, *Where Are California's Dairy Cows?*, U.C. DAVIS: AG DATA NEWS (Feb. 16, 2024), https://asmith.ucdavis.edu/news/how-many-dairy-cows (reviewing recently released USDA agricultural census data and concluding that "[p]erhaps the digester programs accelerated consolidation or inspired some farmers to add cows, but it is difficult make definitive conclusions from these data").

275 Emma Foehringer Merchant, *A Battle Is Underway Over California's Lucrative Dairy Biogas Market*, INSIDE CLIMATE NEWS, https://insideclimatenews.org/news/28122023/milking-it-battle-underway-california-dairy-biogas-market (Dec. 28, 2023) ("[S]ome California dairies have seen a windfall unrelated to agricultural products; 131 of them have received state grants to install anaerobic digesters . . . ."); *see also* Pegga Mosavi, *Manure, Methane, and Money: The Anaerobic Digester Disaster in California*, 29 ANIMAL L. 41, 52–53 (2023).

276 Jessica Fu, *Brown Gold: The Great American Manure Rush Begins*, GUARDIAN (Feb. 2, 2023, 6:00 AM), https://www.theguardian.com/environment/2023/feb/02/manure-renewable-natural-gas-california; Phred Dvorak, *California's Green-Energy Subsidies Spur a Gold Rush in Cow Manure*, WALL ST. J. (Feb. 19, 2022, 9:00 AM), https://www.wsj.com/articles/californias-green-energy-subsidies-spur-a-gold-rush-in-cow-manure-11645279200; Aaron David Smith, *The Dairy Cow Manure Goldrush*, AG DATA NEWS BLOG (Feb. 2, 2022), https://asmith.ucdavis.edu/news/revisiting-value-dairy-cow-manure; *see also IPCC Agriculture, Forestry and Other Land Uses*, *supra* note 261, at 823 ("It is critical that [agricultural] intensification does not drive expansion of unsustainable practices. Increased productivity with associated economic reward could incentivise and reward agricultural land expansion, or environmentally and socially damaging practices . . . .").

277 Aaron David Smith, *Are Manure Subsidies Causing Farmers to Milk More Cows?*, U.C. DAVIS: AG DATA NEWS (Apr. 7, 2023), https://asmith.ucdavis.edu/news/are-digesters.

278 LAZENBY, *supra* note 273, at 9–14.

279 *Geoengineering*, SALATA INST. FOR CLIMATE & SUSTAINABILITY AT HARV. UNIV., https://salatainstitute.harvard.edu/sgrp (last visited Oct. 17, 2024).

may discourage immediate efforts to reduce emissions, "which makes disastrous future scenarios more probable."[280] Denmark's Minister for Global Climate Policy remarked about geoengineering: "It very easily becomes an excuse for not doing all the things that we already can do and that we know will work."[281]

Finally, efficiency approaches may delay large animal agriculture companies from seriously considering transformative change and investing in alternative production models. Looking past posturing about farmers and meat culture, these are profit-focused companies that (at least in theory and setting aside transition costs) should not have a vested interest in continuing to raise and slaughter animals.[282] Large meat and dairy companies have invested in non-animal alternatives[283] (although often not at the scale that they suggest),[284] and may to some extent identify as "protein" producers.[285]

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[280] Impact of New Technologies Intended for Climate Protection on the Enjoyment of Human Rights, Rep. of the Human Rights Council Advisory Comm., ¶ 12, U.N. Doc. A /HRC/54/47 (2023).

[281] Eric Niiler, *Scientists Resort to Once-Unthinkable Solutions to Cool the Planet*, WALL ST. J. (Feb. 14, 2024), https://www.wsj.com/science/environment/geoengineering-projects-cool-planet-weather-f0619bf7 (quoting Dan Jørgensen); *see also Clash over Dutch Farming*, *supra* note 228 ("There is a kind of technological optimism that leads us into delay, and . . . consolidation of existing power. And the [technologies] that do emerge and get funded are the ones that integrate nicely with the current model." (quoting environmental professor Adam Calo)). Responsible use of geoengineering approaches could mean using them in the short term to create time to make the policy and behavior choices that are necessary in the long-term. *See* Niiler, *supra.*

[282] *But see* Mack Graves, *Population Changes and Their Effect on Beef Production*, MEATINGPLACE (Feb. 15. 2024) https://www.meatingplace.com/Industry/Blogs/Details /113370?allowguest=true (arguing that, to "see our industry survive" we must address threats including climate change, dampened population growth, and changing diet recommendations, all of which "are existential threats to our collective livelihoods" that nonetheless "*can be won by beef*" (emphasis added)); *cf.* DANIEL JONES ET AL., FEEDBACK, IT'S BIG LIVESTOCK VERSUS THE PLANET: A CASE TO CUT OFF MEAT AND DAIRY CORPORATIONS' FINANCIAL FODDER 23 (2020), https://feedbackglobal.org/wp-content/uploads/2020/04 /Feedback-Big-Livestock-versus-the-Planet-Final-April-2020.pdf (noting that some meat and dairy company executives view plant-based products "as an addition to, not a subtraction from, their overall existing production models").

[283] Andy Coyne, *Eyeing Alternatives—Meat Companies with Stakes in Meat-Free and Cell-Based Meat*, JUST FOOD (July 13, 2023), https://www.just-food.com/features/eyeing-alternatives-meat-companies-with-stakes-in-meat-free-and-cell-based-meat.

[284] BLINDSPOT, *supra* note 83, at 38–39, 42.

[285] *E.g.*, *Tyson Food Facts*, TYSON FOODS: INV. RELS., https://ir.tyson.com/about-tyson /facts/default.aspx (last visited Oct. 18, 2024) ("Tyson Foods is a modern, multi-national protein-focused food company," but then detailing meat production and meat brands); Melissa Sue Sorrells, *Cargill, ENOUGH Expand Mycoprotein Partnership*, MEATINGPLACE (Feb. 21, 2024), https://www.meatingplace.com/Industry/News/Details /113456?allowguest=true (quoting the managing director of Cargill's meat and dairy alternatives discussing partnership with alternative protein company: "We remain committed to bringing alternative and traditional protein source options to the table").

V. POLITICAL REALITIES: THE EXAMPLE OF FARMER PROTESTS AND RETRENCHMENT IN EUROPE

As with all policy change, each of the approaches described above would benefit some stakeholders and not be aligned with the current interests of others. It is not surprising then that significant political pushback has arisen in response to the acceleration of policy around climate and animal agriculture.

As background, the last several years have seen widespread farmer protests in Europe, and abandonment of core agricultural reforms that would be necessary to achieve the promise of the Green New Deal and the Farm to Fork Strategy.[286] The protests share certain themes and motivations in common, but also differ significantly in their causes and contexts. For example, an interactive map of European farmer protests during 2023 prepared by Politico shows they were motivated by a variety of concerns including: cheap imports, electricity and fuel costs (including the removal of diesel fuel subsidies), low prices for farm products, delays in promised subsidy payments, and the EU requirement to leave four percent of land fallow.[287]

While not all of the farmers' grievances are closely connected to efforts to reduce animal agriculture's GHG emissions,[288] some of them are. Relevant themes include anger about the EU's Green Deal as well as frustration about responses to nitrogen pollution from manure.[289]

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[286] Piet Ruig, *Farm-to-Fork, to Protestors with Pitchforks: The Death of EU's Sustainable Food Policy*, EUOBSERVER (Apr. 28, 2024), https://euobserver.com/green-economy/arf1589b03 ("[F]armers' protests and industry pressures have forced the commission to drop most of the proposals."); PIERRE-MARIE AUBERT, IDDRI, THE FARM TO FORK STRATEGY: REASONS FOR FAILURE AND HOW TO MOVE FORWARD 2–3 (2024), https://www.iddri.org/sites/default/files/PDF/Publications/Catalogue%20Iddri/Autre%20Publication/NOTE%20Veblen%20paper%20agri%20EN.pdf. In late 2023, a pesticide reduction measure at the heart of the Farm to Fork Strategy was voted down by the European Parliament, and then abandoned altogether in early 2024. Ruig, *supra*; Somini Sengupta & Monika Pronczuk, *Making Farming More Climate-Friendly Is Hard. Just Ask Europe's Politicians*, N.Y. TIMES (Feb. 6, 2024), https://www.nytimes.com/2024/02/06/climate/europe-farming-protests-policy.html. Similarly, in April 2024, the European Parliament loosened environmental standards in the Common Agricultural Policy. Thin Lei Win, *Farmers' Protests Are About More Than Green Policies*, LAND CLIMATE (May 2, 2024), https://www.landclimate.org/farmers-protests-are-about-more-than-green-policies.

[287] Hanne Cokelaere & Bartosz Brzeziński, *Europe's Farmer Protests Are Spreading. Here's Where and Why*, POLITICO (Jan. 31, 2024, 9:08 PM), https://www.politico.eu/article/farmer-protest-europe-map-france-siege-paris-germany-poland; *see also* Orla Dwyer, *Analysis: How Do the EU Farmer Protests Relate to Climate Change?*, CARBONBRIEF (Feb. 5, 2024, 4:36 PM), https://www.carbonbrief.org/analysis-how-do-the-eu-farmer-protests-relate-to-climate-change (including a chart of protest motivations by country and dividing protests, roughly evenly, into three categories: climate/emissions, biodiversity/conservation, and neither).

[288] Win, *supra* note 286 (noting that the "protests have consistently been driven by local contexts" but have been framed "as a rebellion against environmental regulations" and policy responses have focused on "dismantling green policies but not much else").

[289] *See, e.g.*, Manuela Andreoni, *Europe Struggles to Balance Climate and Farming*, N.Y. TIMES: CLIMATE FORWARD (Feb. 6, 2024) (discussing farmer frustration with EU's

Following protests, in early 2024 references to cutting non-carbon dioxide agricultural emissions—including methane and nitrous oxide from animal agriculture—were removed in the final version of the European Commission's communication launching the process for setting 2040 climate goals.[290] Advocacy groups described this "last-minute watering down" as a capitulation.[291]

The Netherlands, Ireland, and Flanders have had active farmer protests relating to climate and animal agriculture. Notably, in each of those countries, while many sectors are facing emissions limitations in order to meet binding climate targets, the outcry has been especially loud from farmers. In the Netherlands, a court order prevented the government from issuing permits for all sorts of projects (not just animal agriculture facilities) that emitted nitrogen.[292] Even though "[o]vernight, 18,000 construction projects, including critical infrastructure and housing development, were mothballed," the loudest response came from the farmers.[293] Downtown Brussels was inundated with hundreds of tractors in 2023, as farmers there protested plans to reduce nitrogen pollution in the Flanders region.[294] And in Ireland, where government plans seek a 50% reduction of emissions from the transport sector, 40% from commercial and public buildings, and only

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Green Deal); Stokstad, *supra* note 220 (discussing farmer protests against nitrogen emissions regulations).

290 According to sources who saw a draft version, the European Commission's climate target plan originally called for the agricultural sector to reduce non-CO2 greenhouse gas emissions by at least 30 percent. Angelo Di Mambro, *Agriculture 'Core Area' for EU's 2040 Climate Targets – Commission Report*, EURACTIV (Jan. 29, 2024), https://www.euractiv.com/section/agriculture-food/news/agriculture-core-area-for-eus-2040-climate-targets-commission-report. However, this language is absent from the final document. *Securing Our Future: Europe's 2040 Climate Target and Path to Climate Neutrality by 2050 Building a Sustainable, Just, and Prosperous Society*, COM (2024) 63 final (Feb. 6, 2024); *see also* Alice Hancock, *EU Backs Down on Agricultural Emissions After Farmers' Protests*, FIN. TIMES (Feb. 5, 2024) https://www.ft.com/content/00b344d9-8ff9-4a71-ae31-a76daecb96ab.

291 Press Release, Eurogroup for Animals, 2040 Climate Target—EU Commission Half-Heartedly Recognises the Role of Shifting Diets (Feb. 6, 2024), https://www.eurogroupforanimals.org/news/2040-climate-target-eu-commission-half-heartedly-recognises-role-shifting-diets; *see also* Andreoni, *supra* note 289 ("Bending to farmers' demands, the European Commission . . . softened its recommendations on cutting agricultural pollution.").

292 Ashoko Mukpo, *How Manure Blew Up the Netherlands*, MONGABAY (Sept. 6, 2023) [hereinafter *How Manure Blew Up the Netherlands*], https://news.mongabay.com/2023/09/how-manure-blew-up-the-netherlands.

293 *Id.*; Monika Pronczuk & Claire Moses, *Labeled Climate Culprits, European Farmers Rebel Over New Standards*, N.Y. TIMES (Aug. 26, 2023), https://www.nytimes.com/2023/08/26/world/europe/europe-farmers-climate-change.html ("The government has also imposed measures in the sectors of construction, mobility, and industry. But the biggest challenge lies with the farmers." (quoting spokesman for Dutch Agriculture Ministry)).

294 Angela Symons, *Hundreds of Dutch Farmers Sign Up to Close Their Livestock Farms Under New Scheme*, EURONEWS (Nov. 30, 2023), https://www.euronews.com/green/2023/11/30/dutch-farmers-could-be-paid-to-close-their-livestock-farms-under-new-scheme.

25% from agriculture—agricultural cuts have generated the most vocal opposition.[295]

The Dutch farmer protests are a particularly instructive example of political peril around environmental animal agriculture policy. As described above,[296] after court judgments found that the Dutch government was not compliant with EU directives requiring the protection of natural areas from nitrogen pollution, the government announced its intention to shrink the national herd by as much as a third.[297] The Dutch Minister for Nitrogen and Nature Policy recognized at the time that the plan did not allow for a "future for all [Dutch] farmers," and the plan itself noted that "this approach will be so radical that it will take a great deal from many to shape it."[298]

In response, tens of thousands of farmers blocked roads with tractors, staged mass protests, and set hay and manure on fire.[299] The farmer protests have, in some instances, become linked to or instrumentalized by far-right parties.[300] Right-wing Dutch leader Geert Wilders and Marine le Pen in France expressed support for the farmers, and former U.S. President Donald Trump warned that "climate fanatics" would come next for U.S. farmers.[301] A Dutch academic expert in social movements observed: "Political scientists call it issue expansion. It's a small issue, but it expands because of vicious circles and before you

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295 Rory Carroll, *Irish Farmers Say They Will Be Forced to Cull Cows to Meet Climate Targets*, GUARDIAN (Aug. 29, 2022), https://www.theguardian.com/world/2022/aug/29/irish-farmers-cull-cows-meet-climate-targets.

296 *See supra* notes 224–229 and accompanying text.

297 Mongabay's series on these events in the Netherlands is a thorough and thought-provoking read. Ashoka Mukpo, *The Dutch Farmers' Protests of 2022: A Mongabay Series*, MONGABAY (Sept. 14, 2023), https://news.mongabay.com/2023/09/the-dutch-nitrogen-crisis-a-mongabay-series.

298 MARIT VAN DER HOEK, U.S. DEP'T OF AGRIC. FOREIGN AGRIC. SERV., GOVERNMENT PRESENTS NATIONAL PROGRAM TO REDUCE NITROGEN GREENHOUSE GAS EMISSIONS IN RURAL AREAS 1, 5 (2022), https://apps.fas.usda.gov/newgainapi/api/Report/DownloadReportByFileName?fileName=Government%20Presents%20National%20Program%20to%20Reduce%20Nitrogen%20Greenhouse%20Gas%20Emissions%20in%20Rural%20Areas%20_The%20Hague_Netherlands_NL2022-0035.pdf.

299 *How Manure Blew Up the Netherlands*, *supra* note 292.

300 *E.g.*, Patrick Smith, *How Dutch Farmers Became the Center of a Global Right-Wing Culture War*, NBC NEWS (Dec. 12, 2022), https://www.nbcnews.com/news/world/dutch-farmers-emissions-global-right-wing-culture-war-rcna60269; *see also* Lili Bayer, *German Vice-Chancellor Warns of Extremism as Far-Right Groups Join Farmers' Protest—As It Happened*, GUARDIAN (Jan. 8, 2024), https://www.theguardian.com/world/live/2024/jan/08/germany-farmers-tractors-block-roads-protests-cuts-agricultural-subsidies-pay-europe-latest-updates (discussing far-right groups' infiltration of protests by German farmers over subsidy reductions); Andreoni, *supra* note 289 ("If policymakers push[] too far on initiatives to protect biodiversity and combat climate change, especially without involving farmers in the decision-making process, it could empower far-right populists who want to reverse such policies."); Dwyer, *supra* note 287 (discussing right-wing political groups using farmer frustration as a political tool).

301 Ashoko Mukpo, *In the Netherlands, Pitchforks Fly for an Empire of Cows*, MONGABAY (Sept. 7, 2023) [hereinafter *In the Netherlands, Pitchforks Fly*], https://news.mongabay.com/2023/09/in-the-netherlands-pitchforks-fly-for-an-empire-of-cows.

know it, it's all about the great reset,"[302] referring to a white nationalist conspiracy theory.[303]

In March 2023, the new Farmer-Citizen Movement (BBB), which had run explicitly against the nitrogen reduction policies, stunningly won a larger share of the vote than any other Dutch party.[304] Far-right leader Geert Wilders and his Freedom Party now have the largest bloc of seats in parliament and ministers from his party were appointed to the cabinet for the first time in summer 2024.[305] Wilders ran an anti-EU campaign including a focus on immigration and climate policy, calling for a withdrawal from international climate obligations.[306]

All of this political turmoil has delayed and endangered the prospects for addressing the pressing environmental issue of nitrogen pollution from animal agriculture.[307] If the country cannot reduce nitrogen pollution in high-value conservation areas in line with EU rules and as directed by the Court of Justice of the European Union, it will face substantial fines.[308] Dutch naturalists fear that the fate of fragile habitats hangs in the balance.[309]

As another example, Ireland may eventually face similar challenges. The European Commission successfully sued Ireland for its failures to limit nitrogen pollution, and later issued a ruling condemning Ireland's continuing noncompliance, noting among other things the challenges of "overgrazing" and "agricultural activities causing nitrogen deposition."[310] Like the Netherlands, Ireland has a large animal agriculture industry, with seven million commercially farmed cows for its five million people.[311] Cows are responsible for about one-fifth of all of Ireland's anthropogenic GHG emissions.[312] As part of meeting its Paris Agreement commitment to reach carbon neutrality by 2050, the Irish government has undertaken to reduce GHG emissions from agriculture by 25% by 2030.[313]

An online kerfuffle originating from Ireland illustrates the potential for dramatic reactions to factual policy discussions of the environmental

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302 Smith, *supra* note 300.

303 Aoife Gallagher & Ciarán O'Connor, *The 'Great Reset'*, INST. FOR STRATEGIC DIALOGUE (Mar. 14, 2023), https://www.isdglobal.org/explainers/the-great-reset.

304 *In the Netherlands, Pitchforks Fly*, *supra* note 301.

305 *Dutch Right-Wing Government Installed as Wilders' Shadow Looms Large*, REUTERS (July 2, 2024), https://www.reuters.com/world/europe/dutch-right-wing-government-installed-wilders-shadow-looms-large-2024-07-02.

306 Cagan Koc & Diederik Baazil, *Dutch Far-Right Leader Wilders Scores Shock Election Victory*, BLOOMBERG (Nov. 23, 2023), https://www.bloomberg.com/news/articles/2023-11-22/far-right-leader-wilders-scores-shock-victory-in-dutch-election.

307 *In the Netherlands, Pitchforks Fly*, *supra* note 301.

308 *Clash over Dutch Farming*, *supra* note 228.

309 *How Manure Blew Up the Netherlands*, *supra* note 292; *In the Netherlands, Pitchforks Fly*, *supra* note 301 ("For those who'd hoped the 2019 court ruling meant that Dutch ecosystems might have a fighting chance to recover, the election was a disaster.").

310 Case C-444/21, Eur. Comm'n v. Ireland, ECLI:EU:C:2023:524, ¶ 117 (June 29, 2023).

311 Dutkiewicz, *Ireland Isn't Culling Cows*, *supra* note 215.

312 *Id.*

313 TEAGASC CLIMATE CTR., *supra* note 265, at 6.

impacts of animal agriculture. A 2022 report from a working group of the Irish Department of Agriculture suggested the possibility of a "voluntary exit/reduction scheme" under which farmers would be paid for removing cows and agree not to replace them for at least five years.[314] A similar idea was described in a government document obtained by a journalist, which stated that removing about ten percent of Ireland's dairy cows would be needed to keep binding emissions targets within reach.[315] Even though no such plan was enacted or even formally proposed or debated, an international media firestorm ensued, surrealistically leading to Elon Musk tweeting: "This really needs to stop. Killing some cows doesn't matter for climate change."[316]

Thus, even the suggestion of an Irish government policy to shrink the herd caused international controversy. But Ireland may not be able to achieve its agricultural emission goals without reducing the number of cattle. A 2023 report by Ireland's Agriculture and Food Development Authority found that "limiting animal number increases" will be necessary to reach emissions targets.[317] In the words of one Irish climate scientist: "Various tried and untried methods have been advanced to suggest compliance with the 25% emissions ceiling," but without success; "[o]nly a reduction in numbers can achieve the targets in the short term."[318]

VI. PATHS FORWARD

> [T]he last four years in the Netherlands have been a warning sign for the global environmental movement. When plans to address biodiversity and climate change—whether through decarbonization, expansion of conservation areas, or agriculture reform—collide with people's livelihoods and sense of place in the world, chaos can and will follow. . . . Already, the Netherlands' political miasma has begun to seep across its borders, a cloud descending onto other parts of Europe like ammonia from a megafarm.
>
> ~In the Clash over Dutch Farming,
> Europe's Future Arrives,
> Ashoka Mukpo[319]

> If there is some kind of main message of the Netherlands towards the world, it would be to act now. The environmental and societal costs will be much higher and more painful if we wait too long, for farmers and citizens alike.

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314 Dutkiewicz, *Ireland Isn't Culling Cows*, *supra* note 215.
315 *Id.*
316 *Id.*
317 TEAGASC CLIMATE CTR., *supra* note 265, at 11.
318 Carroll, *supra* note 295.
319 *Clash over Dutch Farming*, *supra* note 228.

~Kirsten Haanraads,
World Wildlife Fund
Netherlands[320]

Building from the preceding discussion and examples, this Part discusses considerations that could be important in advancing policy to mitigate animal agriculture's climate harms. One clear lesson from the political difficulties in the Netherlands is that earlier action, before the threat of a court judgment and potential fines, may have offered policymakers better options and more opportunity to ease into change. With the benefit of hindsight, the Dutch government seems to have missed an earlier opportunity to "draw[] up long-term plans to reform agricultural production before the situation worsened."[321]

The time-sensitivity and lack of maneuverability in the Dutch situation arose in part from the fact that the policy change was driven by a court decision.[322] Should the conclusion be that litigation is an overly rigid tool for such complicated matters as climate and animal agriculture policy? On the other hand, if environmental advocates had not resorted to litigation, pollution could have continued unchecked, ultimately resulting in an even more difficult situation and more harms to nature and society. Indeed, the Dutch advocates reportedly "begged" for attention from policymakers before resorting to litigation.[323] Even without the catalyst of litigation, the current lack of adequate climate mitigation, if continued, will force urgent changes to food systems.[324] Rather than imperiling our food systems, early mitigation action to curtail emissions from agriculture can be expected to lower long-term food prices, reduce hunger risk, and use less water.[325]

Starting policy change sooner also creates time to build consensus and sequence interventions. The Danish Plant-Based Action Plan provides examples of both. The Plan reportedly grew out of a yearslong process of stakeholder discussions including farmers, industry,

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320 *Id.*

321 *In the Netherlands, Pitchforks Fly*, *supra* note 301.

322 *Supra* notes 224–229 and accompanying text.

323 *How Manure Blew Up the Netherlands*, *supra* note 292; *see also* Daina Bray & Thomas Poston, *The Methane Majors: Climate Change and Animal Agriculture Litigation in U.S. Courts*, 49 COLUM. J. ENV'T L. 145, 247 (2024) ("Well-founded litigation might be uniquely positioned to facilitate action—which likely must include reduced production and consumption of animal products—where gridlocked political processes have failed.").

324 BLINDSPOT, *supra* note 83, at 43 ("If we fail to act now, runaway climate change will force us to adapt our eating habits because of collapsing food-production systems, increasing poverty and inequality. If we act quickly, we can manage the transition to healthier and more nature- and climate-friendly diets that are more just and equitable. This is where our choices and opportunities lie."); *see also* SUTTON ET AL., *supra* note 28, at 1 ("[C]onditions are set to deteriorate even further as the world attempts to feed a global population that will grow by 2 billion by 2050. More food means accelerating food production, land use changes, and related emissions, which exacerbate global heating. In turn, global heating will affect future agricultural yields and food security.").

325 SUTTON ET AL., *supra* note 28, at 8–10, 13.

government, and environmental and animal groups.[326] Another key characteristic of the Danish approach is that the initial measures focus on building demand and opportunity (the carrot); it is not until those efforts are well underway that measures like an agriculture carbon tax (the stick) would be implemented.[327] While carrots will not be sufficient by themselves,[328] the sequencing being tried in Denmark seems promising.

Indeed, the role of building in time for sustained discussion amongst stakeholders, allowing them an opportunity to appreciate each other's positions and challenges, emerges as an important strategy for avoiding the most adversarial of outcomes. In 2020, after farmer protests prompted by environmental regulation, Germany created a "Commission on the Future of Agriculture" bringing together consumers, farmers, environmentalists, and researchers.[329] The German coalition was modeled on a similar coalition that had been created around moving away from coal.[330] The Commission succeeded in arriving at a consensus position, with all participants recognizing that the current food system requires reform to achieve both economic and environmental sustainability.[331] Policy makers can look to prior transitions for lessons on both the adversarial battles that can result without creating space for consensus-building, and the new opportunities that can be created by such discussions.

If we might expect the grim realities of our changing climate and the patent harms of industrial animal agriculture to push stakeholders to a consensus around the need for some level of change, what principles should guide our consideration of policy options? Ensuring international equity and a just transition will be critical. As to the first, not all policy approaches and goals are appropriate in all places.[332] As recognized by the EAT-*Lancet* Commission, some populations depend on animal agriculture, and others face nutrition challenges in contexts where available plant-sourced foods may not be sufficient.[333] Moreover,

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326 Bourke, *supra* note 162.

327 *Id.* ("The world-first Danish strategy to encourage plant-based foods may contain a lesson for other nations looking to cut back on meat: build new demand first.").

328 EU ASSESSMENT REPORT 2024, *supra* note 50, at 173 ("EU policies to encourage sustainable diets focus primarily on information provision and voluntary codes of conduct, but these measures are not sufficient by themselves.").

329 BLINDSPOT, *supra* note 83, at 31; AUBERT, *supra* note 286, at 4 (noting that the German Commission "offer[s] grounds for believing that such a dialogue [amongst stakeholders] is possible").

330 *Id.*

331 *Id.*; ZUKUNFTSKOMMISSION LANDWIRTSCHAFT, THE FUTURE OF AGRICULTURE: A COMMON AGENDA 8 (2021), https://www.bmel.de/SharedDocs/Downloads/EN/Publications/abstract-zukunftskommission-landwirtschaft.pdf?__blob=publicationFile&v=4.

332 *See* SUTTON ET AL., *supra* note 28, at 3 ("[C]ountries have different opportunities to combat climate change through the agrifood system.").

333 EAT, *supra* note 70, at 12 ("[T]he role of animal source foods in people's diets must be carefully considered in each context and within local and regional realities."); FAO ROADMAP, *supra* note 113, at 9 ("Sacrificing food security and nutrition for vulnerable

responsibility for historical emissions, scale of consumption of animal products, and stage of development are highly relevant to discussions of which countries should lead the way on dietary change.[334]

In looking at the various approaches around the world—as well as the political repercussions experienced in the Netherlands and elsewhere—a key grounding principle for a discussion of climate policy for animal agriculture is the need for a just transition for farmers, ranchers, and workers.[335] The International Labour Organization defines a just transition as "greening the economy in a way that is as fair and inclusive as possible to everyone concerned, creating decent work opportunities and leaving no one behind."[336] Most discussions of just transitions in climate policy to date have focused on the shift from fossil fuels to renewable energy, but the applicability and utility of this concept to agricultural climate transitions is now also being discussed.[337] Both the European Green Deal and the Farm-to-Fork strategy recognize the importance of a just transition.[338] In the context of climate reform of the food system, a just transition "means reducing emissions while ensuring jobs, good health, livelihoods, and food security to vulnerable groups and smallholder farmers."[339] A Green Party Member of EU Parliament observed earlier this year that one of the flaws in the Farm to Fork Strategy that may have diminished its chances of success was a lack of economic support, particularly for farmers.[340]

It is an understatement to say that achieving a just transition in animal agriculture will be complex.[341] Dietary choices implicate familial

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populations is not an option; meaning increasing pressure on high-consumption consumers and transitioning toward resource-efficient food choices.").

334 *E.g.*, Mehrabi et al., *supra* note 199, at 162 ("Addressing poverty-limited access versus the demand choices of rich citizens involves balancing very different goals.").

335 Danielle Nierenberg et al., *Devising a Just Transition for Sustainable Livestock Agriculture*, AGRIC. DIVE (Nov. 20, 2023), https://www.agriculturedive.com/news/livestock-emissions-agriculture-cop28-just-transition-oped/700100.

336 *Climate Change and Financing a Just Transition*, INT'L LABOUR ORG. (July 9, 2024), https://www.ilo.org/resource/other/climate-change-and-financing-just-transition.

337 Cleo Verkuijl et al., *A Just Transition in Animal Agriculture Is Necessary for More Effective and Equitable One Health Outcomes*, CABI ONE HEALTH, Oct. 12, 2023, No. ohcs202300021, at 2.

338 FARM TO FORK STRATEGY, *supra* note 75, at 4 ("Ensuring a sustainable livelihood for primary producers, who still lag behind in terms of income, is essential for the success of the [COVID-19 pandemic] recovery and the transition."). In its recent document launching the process to identify steps toward 2040 climate targets, the European Commission observed: "[D]iverse and family-owned farms and those who combine crop and animal production are the backbone of EU farming and should be accompanied in the transition to a climate-neutral land sector, taking into account its social, environmental and economic dimension." *Securing Our Future*, *supra* note 290, at 21–22.

339 SUTTON ET AL., *supra* note 28, at 20.

340 Ruig, *supra* note 286.

341 *See* David De Pue et al., *A Farmer's Perspective on Farm Relocation: Lessons Learnt from Relocated Farmers in Belgium and the Netherlands*, 64 J. ENV'T PLAN. & MGMT. 1474, 1479–92 (2021) (describing, in the parallel context of relocating farmers, the complexity of

and cultural traditions, nutrition, livelihoods, significant industry profits and power, and more.[342] Electoral timeframes are in many ways poorly suited for this challenge. While food system reform may benefit farmers in the medium and long run—by improving resilience in the face of climate change, reducing environmental damage, and creating new income streams—substantial investment will be required to assist those most affected.[343] Delaying the necessary changes can result in a "Pyrrhic victory" for farmers, who may then face more drastic changes and a loss of social support down the road.[344] And given that farmers directly experience the realities of a changing climate, many of them are in favor of adaptation. One Italian farmer criticized the EU Commission's decision to lessen environmental regulation in the Common Agriculture Policy, explaining: "Climate change is there. This is not a political opinion. We are not environmentalists. We are peasants. But we see that it's costly to work against nature."[345]

Engaging with farmers and others who work within the industrial animal agriculture system to ensure a just transition will be essential. One Dutch farmer put it this way: "The farmers are the victims of this whole system. And the agri-industry is earning the money."[346] Tim Benton, director of research on food production and the environment at the Chatham House think tank in London, also encourages a focus on the farmers' perspective:

> The EU's reversal on agriculture-specific climate goals highlights the need for a meticulously-planned 'just transition'—a shift toward climate-friendly farming that doesn't ignore farmers' economic needs. Farmers are increasingly fed up with being seen as the whipping boy of food-systems emissions, in terms of them being told they are bad people and bad

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factors required to promote smooth transitions, both in terms of the farmers' situation and characteristics and the procedural and financial supports provided).

342 *Project: Just Transitions in Animal Agriculture*, STOCKHOLM ENV'T INST., https://www.sei.org/projects/just-transitions-animal-agriculture (last visited Nov. 14, 2024).

343 Kerstine Appunn, *Farming Commission's Proposals Require Next Govt to Undertake Food System Transformation – Merkel*, CLEAN ENERGY WIRE (July 6, 2021, 1:25 PM), https://www.cleanenergywire.org/news/farming-commmissions-proposals-require-next-govt-undertake-food-system-transformation-merkel ("[T]he current food system is neither economically nor ecologically sustainable but that the transformation would be cheaper for society and farmers in the medium term than the current system." (quoting German Environment Minister Svenja Schulze)).

344 Guyomard et al., *supra* note 14, at 10.

345 Win, *supra* note 288.

346 *In the Netherlands, Pitchforks Fly*, *supra* note 301; *see also* Pronczuk & Moses, *supra* note 293 ("Many farmers say they are not resistant to addressing the problem of climate change, and they note that their livelihoods are more directly affected by it than those of many others. But they say the burden should be more evenly spread."); Andreoni, *supra* note 289 ("What the farmers I have spoken to have told me is that the burden and the cost of fighting climate change should be shared more evenly.").

> managers of the land. If we are going to do transitions, then we have to bring people along with us.[347]

Another fundamental question in terms of supporting those most affected by the transition is who should bear the cost. While there is of course a role for government support—which could be achieved in part by reducing or eliminating subsidies for meat[348]—others assert that the agribusinesses that have long benefited from externalizing the costs of their environmental harms should be held accountable,[349] either by policy-driven resource shifts or, where necessary, by litigation.

Whether and how these approaches could be effectively translated to the U.S. context is an urgent question, particularly in light of the scale of the U.S. industry and its emissions. To date, U.S. climate policies have focused on voluntary and incentive-based approaches to animal agriculture.[350] In her insightful article, *Is Meat the New Tobacco?*, Professor Lingxi Chenyang posits that reducing meat demand may actually be easier in some respects than it was to reduce tobacco demand.[351] She recommends two categories of U.S. federal policy reforms as a starting point: (i) removing barriers to information about how industrial meat is produced[352] (such as by repealing ag-gag laws),[353] reforming the federal checkoff programs that collect funds from producers for generic promotion of animal products,[354] reforming federal certification programs to incorporate climate sustainability goals, and (ii) implementing place-based substitutions starting with schools and the National School Lunch Program.[355] While acknowledging that these

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347 Max Graham, *What Europe's Egg-Hurling Farmers Can Teach Us About Climate Progress*, GRIST (Feb. 20, 2024), https://grist.org/agriculture/europe-farmer-protests-eu-climate-progress.

348 *See supra* notes 79, 158 and accompanying text.

349 *Clash over Dutch Farming*, *supra* note 228 ("I think if the government makes clear that behind the nitrogen crisis, there are big corporations that have contributed to it and are still profiting from it, and also show their willingness to hold them accountable for their role and ask them to pay their fair share to finance a just transition, that could be a way out." (quoting Wouter Kolk, campaign leader at environmental group Milieudefensie)).

350 *See, e.g.*, Brown & Hill, *supra* note 8 ("[T]he U.S.' efforts to transform American agriculture are based on 'incentive-driven and market-based' mechanisms.").

351 Lingxi Chenyang, *Is Meat the New Tobacco? Regulating Food in the Age of Climate Change*, 49 ENV'T L. REP. 10344, 10352–57 (2019).

352 *E.g.*, *People Don't See Industrial Meat as a Key Cause of Global Warming—Poll*, MADRE BRAVA (Mar. 17, 2023), https://madrebrava.org/insight/people-don-t-see-industrial-meat-as-a-key-cause-of-global-warming-poll ("[W]hen a simple definition of industrial meat was provided . . . citizens . . . showed concern about the impacts of the industrial meat system.").

353 State "ag-gag" laws seek to criminalize whistleblowing and undercover investigations of food production. Justin Marceau, *Ag Gag Past, Present, and Future*, 38 SEATTLE U. L.R. 1317, 1332 (2015).

354 *See* Chenyang, *supra* note 351, at 10358 ("Mandatory contribution to generic promotional efforts removes incentives for individual producers to differentiate and market their commodity on production attributes like climate sustainability.").

355 *Id.* at 10357–61.

reforms will not by themselves significantly reduce meat consumption, she presents them as "steps in the right direction" to "create a friendlier environment for more drastic regulatory measures."[356] Her approach is thus sensitive to the sequencing of interventions, and similar to the Danish effort in that respect. While the United States doubtless has further to go than even high-producing countries in Europe, starting with more modest legal reforms to help change the atmosphere could be a way in.

VII. CONCLUSION

> We cannot continue doing animal agriculture as we now practice it and is accepted. Let me change that just a bit: if we want to have a healthier population, reduce the incidence of respiratory illnesses and cancer-causing agents, and if we wish to have a healthier environment, with cleaner water, renewable resources, replenishable soil, wildlife habitat, and overall cleaner air to breathe, then we cannot continue doing animal agriculture as we now practice it and is widely accepted.
>
> ~Former U.S. Senator from Iowa Tom Harkin, remarks at *Industrial Farm Animal Production, the Environment, and Public Health* conference at Drake University (2024)[357]

Politicians and policy makers are beginning to acknowledge that the industrial animal agriculture system is not sustainable on its current trajectory.[358] Having surveyed this developing policy landscape, one is left with the impression that progress is not inevitable—far from it, in light of significant political pushback—but that there is an emerging scaffold of both international signaling and national and provincial policy onto which future efforts can be built. Such efforts must be informed by prior clashes between environmental protection and livelihoods, seeking to redirect government support away from large-scale agribusiness and toward ensuring a just transition for communities.

If politicians fall short, private actors will increasingly look for other avenues, through litigation or otherwise.[359] In the first prominent move of its kind, in March 2024 the Dutch supermarket chain Jumbo stopped offering price promotions (i.e., discounts) on fresh beef, pork,

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[356] *Id.* at 10346; *see also id.* at 10351 ("[N]on-price regulatory intervention[s] . . . are generally less expensive to implement than subsidies, and require less political willpower to adopt than taxes.").

[357] Harkin Inst., *Tom Harkin Remarks 2024 09 25*, YOUTUBE (Sept. 25, 2024), https://www.youtube.com/watch?v=HOSsmeBMsg0&t=192s. Senator Harkin's remarks are especially notable because Iowa is ground zero for industrial pork production in the United States. *Iowa Leads States in Hog Production*, U.S. DEP'T OF AGRIC. (Mar. 13, 2024), https://www.ers.usda.gov/data-products/chart-gallery/gallery/chart-detail/?chartId=108733.

[358] MARIT VAN DER HOEK, *supra* note 298, at 7 ("[T]he herd will have to be smaller, there is no escaping that." (quoting position of Dutch political party D66)).

[359] Bray & Poston, *supra* note 323, at 247.

and chicken.[360] The company has also lowered prices of its own-brand meat substitutes to reach price parity, explaining these changes as part of the company's work toward "the protein transition."[361] Perhaps it is not surprising that this innovation would come in the Netherlands, amidst the striking mix of innovation and obstacles that have arisen there. Perhaps the supermarket was inspired by the municipal meat advertising bans in Dutch cities. Or perhaps, in response to the furor of the farmer protests and political turmoil, the company thought it could help support the transition using its own toolbox.

Reining in industrial animal agriculture's emissions, and remedying its many other harms, will require a multitude of actors and solutions. If we are unable to muster the political will to address the harms of animal agriculture before the changing climate further imperils our food systems, we will have missed a critical opportunity to protect our collective future.

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[360] Dayeeta Das, *Jumbo to Cease Price Promotions on Fresh Meat in the Netherlands*, EUR. SUPERMKT. MAG. (Mar. 15, 2024), https://www.esmmagazine.com/retail/jumbo-to-cease-price-promotions-on-fresh-meat-in-the-netherlands-261595; *see also* Toby L.S. Watt et al., *Reducing Consumption of Unhealthy Foods and Beverages Through Banning Price Promotions: What Is the Evidence and Will It Work?*, 23 PUB. HEALTH NUTRITION 2228, 2228 (2020) (concluding that "price promotions increase purchasing of unhealthy food").

[361] Das, *supra* note 360.

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Review

Review on greenhouse gas emissions from pig houses: Production of carbon dioxide, methane and nitrous oxide by animals and manure

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ABSTRACT

The environmental impacts of livestock production are attracting increasing attention, especially the emission of greenhouse gases (GHGs). Currently, pork is the most widely consumed meat product in the world, and its production is expected to grow in the next few decades. This paper deals with the production of carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) by animals and by manure from pig buildings, with a focus on the influence of rearing techniques and nutrition. GHG emissions in piggeries originate from animals through CO_2 exhalation and CH_4 enteric fermentation, and from manure through the release of CO_2, CH_4 and N_2O. The level of the CO_2 exhalation (E-$CO_{2,\ pig}$) depends on the physiological stage, the body weight (BW), the production level and the feed intake of the animals concerned. Enteric CH_4 (E-$CH_{4,\ pig}$) is principally related to dietary fibre intake and the fermentative capacity of the pig's hindgut. Based on a review of the literature, the following equations are proposed in order to estimate E-$CO_{2,\ pig}$ (in kg day^{-1}) and E-$CH_{4,pig}$ (in g day^{-1}) for fattening pigs: E-$CO_{2,\ pig} = 0.136 \times BW^{0.573}$; E-$CH_{4,pig} = 0.012 \times$ dRes; with BW (in kg) and dRes for digestible residues (in g day^{-1}). Numerous pathways are responsible for GHG production in manure. In addition, the microbial, physical and chemical properties of manure interact and modulate the level of emissions. Influencing factors for removal systems for both liquid and solid fractions of manure have been investigated. A large range of parameters showing an impact on the level of GHG production from pig houses has been reported. However, few of these can be considered unquestionably as GHG mitigation techniques because some strategies have shown contradictory effects depending on the gas, the circumstances and the study. Nevertheless, frequent manure removal seems to be an efficient means to reduce concurrently CO_2-, CH_4- and N_2O-emissions from pig buildings for both slatted and bedded floor systems. Manure removal operations may be associated with specific storage conditions and efficient treatment in order to further reduce emissions. Several feeding strategies have been tested to decrease GHG emissions but they seem to be ineffective in reducing emissions both significantly and durably. In general, good management practices that enhance zootechnical performance will have beneficial consequences on GHG emission intensity. Taking into account the results described in the literature regarding CO_2-, CH_4- and N_2O-production from animals and manure in pig houses, we estimate total GHG emissions to 448.3 kg CO_2equiv. per slaughter pig produced or 4.87 kg CO_2equiv. per kg carcass. The fattening period accounts for more than 70% of total emissions, while the gestation, lactation and weaning periods each contribute to about 10% of total emissions. Emissions of CO_2, CH_4 and N_2O contribute to 81, 17 and 2% of total emissions from pig buildings, representing 3.87, 0.83 and 0.11 kg CO_2equiv. per kg carcass, respectively.
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1. Introduction

Globally, livestock production accounts for 18% of anthropogenic emissions of greenhouse gases (GHGs) (Steinfeld et al., 2006). Pork is the most widely consumed meat product in the world, and pig production is the second contributor of GHG emissions from livestock sector, with about 13% of total emissions being related to livestock (Tables 1 and 2; FAO, 2011). By 2050, worldwide pork consumption is expected to increase by almost 40% (FAO, 2011). Most of that increase in consumption will occur in developing countries, owing to demographic growth, changes in food preferences and better access to food due to the intensification of livestock systems close to growing urban populations (FAO, 2011). Presently, industrial farm animal production systems account for over half of pork production, and developing countries contribute to about half of this industrial production (Steinfield et al., 2006). In the future, these shares are expected to grow dramatically. Therefore, the environmental impact of industrial pig production represents a crucial issue for consideration in ensuring sustainability in meat production. Moreover, reducing GHG emissions would mitigate the adverse effects of GHGs on global climate change (increased temperature, higher sea level, drought, soil erosion and loss of global crop productivity) (IPCC, 2007).

Within this context, this paper aims to study the factors that influence the production levels of carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) by animals and manure at pig house level. Emissions associated with feed production, land use and land use change, energy consumption, manure spreading, transportation and food processing are not included in this discussion. Emissions associated with outside manure storage and manure treatments are also outside the scope of this review. These issues will, nevertheless, be briefly touched upon due to the link with emissions released from pig buildings. Direct CO_2 emissions from animals and from manure are usually excluded from GHG assessment because it is assumed that they are compensated by CO_2 consumption through the photosynthesis of plants used as feed. Consequently, CO_2 production by animals and by manure is rarely addressed in the literature. However, these CO_2 emissions at house level are not negligible and may differ from one rearing system to another (Philippe et al., 2007a,b). Moreover, since the synthesis pathways of carbon compounds are interlinked, it seems relevant to consider CO_2 and CH_4 emissions comprehensively. Indeed, a significant reduction in one gas could be compensated by an increase in another. Thus, the choice has been made to include CO_2 emissions in this paper in order to avoid any errors of judgement in assessing the environmental effect of a particular type of GHG mitigation technique.

The paper is organized as follows. Firstly, it describes the processes that are responsible for the production of CO_2, CH_4 and N_2O by animals and by manure at pig house level. Secondly, emission factors reported in the literature are reviewed according to the physiological stages of pig development, and an overall emission factor is proposed for the complete pig production process. Finally, the effects of pig rearing conditions (including dietary factors) on emissions are studied and some mitigation techniques are described.

2. Sources of emissions

2.1. Carbon dioxide

The emissions of CO_2 from pig houses come from two sources: exhalation by pigs and release from manure.

2.1.1. Exhalation by pigs

CO_2 production during respiration is related to the respiratory quotient, defined as the ratio between the volume of CO_2 production and the volume of oxygen consumption. In practice,

Table 1
Projected human population (in billion people) and global meat consumption (in million tons) from 2010 to 2050.
Source: adapted from FAO, 2011.

	2010	2020	2030	2050	Growth 2010–2050
Human population	6.91	7.67	8.31	9.15	+32%
Meat consumption					
Pig meat	102.3 (38%)	115.3 (36%)	129.9 (34%)	140.7 (30%)	+38%
Poultry meat	85.9 (32%)	111.0 (35%)	143.5 (38%)	193.3 (42%)	+125%
Bovine meat	67.3 (25%)	77.3 (24%)	88.9 (23%)	106.3 (23%)	+58%
Sheep/goat meat	13.2 (5%)	15.7 (5%)	18.5 (5%)	23.5 (5%)	+78%
All meat	268.7 (100%)	319.3 (100%)	380.8 (100%)	463.8 (100%)	+73%

Table 2
Contribution of livestock species to global greenhouse gas emissions.
Source: adapted from Steinfeld et al., 2006; FAO, 2013a,b.

Species	Greenhouse gas emissions (million tons CO_2equiv. $year^{-1}$)			
	CO_2 emissions	CH_4 emissions	N_2O emissions	Total emissions
Cattle	1166.2 (61%)	2072.8 (81%)	661.6 (60%)	3900.6 (70%)
Small ruminants	69.9 (4%)	244.5 (10%)	202.6 (18%)	517.0 (9%)
Pigs	338.9 (18%)	237.3 (9%)	131.1 (12%)	707.3 (13%)
Poultry	332.2 (17%)	–	107.3 (10%)	439.5 (8%)
Total	1907.2 (100%)	2554.5 (100%)	1102.6 (100%)	5564.3 (100%)

CO_2equiv.: emissions of CO_2-equivalents, including CO_2, CH_4 and N_2O, taking into account the global warming potential of 25 and 298 for CH_4 and N_2O, respectively.

the respiratory quotients reported in the literature are around 1.10 for growing pigs, around 1.00 for piglets and around 0.90 for reproductive sows (Moehn et al., 2004; Pedersen et al., 2008; Atakora et al., 2011b). CO_2 exhalation can also be derived from animal heat production (HP), which corresponds to the energy used for maintenance, production (growth or milk production) and thermoregulation (Noblet et al., 1989). The International Commission of Agricultural Engineering (CIGR, 2002) stated that HP should be estimated by taking into account the pig's body weight (BW), the production level and the feed energy intake. The production of respiratory CO_2- can be derived from these models, and corresponds to 2.23, 3.68, 0.88 and 1.70 kg CO_2 $head^{-1}$ day^{-1} for gestating sows, lactating sows, weaned piglets and fattening pigs, respectively (CIGR, 2002). Other experiments have been carried out to measure or estimate CO_2 exhalation from practical parameters. Models developed for fattening pigs are presented in Table 3 and illustrated in Fig. 1. In cases of a lack of data, models were simplified to express the CO_2 exhalation function of BW, according to data obtained by Aubry et al. (2004). An aggregation of the models reported in Table 3 gives the following equation proposed to predict CO_2 exhalation (E-$CO_{2,\,pig}$, in kg CO_2 day^{-1}) for pigs of 20–120 kg BW (Fig. 1; $R^2 = 0.91$):

$$E - CO_{2,\,pig} = 0.136\,BW^{0.573} \quad (1)$$

Thus, respiratory CO_2 production can be estimated to about 1.55 kg day^{-1} for a pig of 70 kg BW.

2.1.2. Release from manure

For many years, levels of CO_2 emissions from manure were believed to be negligible (Anderson et al., 1987; van 't Klooster and Heitlager, 1994). According to some recent research, the levels of CO_2 released from manure have been estimated to be 4–5% of the CO_2 exhaled by animals (CIGR, 2002; de Sousa and Pedersen, 2004; Dong et al., 2007). However, some authors have reported CO_2 release accounting for 10–30% of respiratory production (Jeppsson, 2000, 2002; Philippe et al., 2007a,b; Pedersen et al., 2008; Philippe et al., 2012a). During an experiment carried out in a commercial fattening unit, emissions from manure were evaluated to be at around 40% of the tranquil CO_2 exhalation rate (Ni et al., 1999b). The production of CO_2 from manure certainly needs to be taken into account, even though it is not the main source of CO_2 in pig houses.

In manure, CO_2 originates from three sources: (1) the rapid hydrolysis of urea into NH_3 and CO_2 catalysed by the enzyme urease; (2) the anaerobic fermentation of organic matter into intermediate volatile fatty acids (VFAs), CH_4 and CO_2; (3) the aerobic degradation of organic matter (Jeppsson, 2000; Moller et al., 2004; Wolter et al., 2004). For liquid manure, anaerobic processes have been frequently considered as the main source of CO_2 (Ni et al., 1999b). However, this conclusion is contradictory to the results of Moller et al. (2004), who observed under laboratory conditions that aerobic and anaerobic processes are of almost equal importance at a temperature of 20 °C, while a lower temperature (15 °C) favoured the aerobic processes. Moreover, crust formation at the surface of the slurry can also lead to CH_4 oxidation into CO_2 during the passage through the porous areas of the crust.

For solid manure, the principal origin of CO_2 is aerobic production, the so-called composting process, performed by a mesophilic/thermophilic microbial community that converts degradable organic matter (Hellmann et al., 1997; Wolter et al., 2004). The composting process is influenced by several factors, such as temperature, moisture content, carbon/nitrogen ratio, degradability of carbon compounds, pH level and the physical structure of the organic material (Andersson, 1996; Jeppsson, 2000; Paillat et al., 2005).

2.2. Methane

Methane originates from the anaerobic degradation of organic matter performed by bacteria in the digestive tract of the pigs and in the manure.

2.2.1. Enteric fermentation

The level of enteric CH_4 production is mainly determined by the fibre content of the diet and the fermentative capacity of the pig's hindgut. Thus, increased levels of dietary fibre are associated with increased CH_4 production, while fermentative capacity depends on the physiological stage of the pigs, with typically higher CH_4 production for adult pigs (Le Goff et al., 2002a).

Table 3
Equations proposed to estimate CO_2 exhalation by fattening pigs (E-$CO_{2,\,pig}$, in kg day^{-1}) according to body weight (BW, in kg).

References	Equations	Methodology
Müller and Schneider (1985)	$E - CO_{2,\,pig} = 0.114\,BW^{0.588}$	Pigs in metabolic crates (from 20 to 110 kg)
Feddes and DeShazer (1988)	$E - CO_{2,\,pig} = 0.136\,BW^{0.549}$	Data derived from feed intakes
van 't Klooster and Heitlager (1994)	$E - CO_{2,\,pig} = 2.88 \times 10^{-2} \times BW^{0.75} + 8.29 \times 10^{-2} \times BW^{0.549}$	Data derived from feed intakes
Ni et al. (1999a)	$E - CO_{2,\,pig} = 0.224\,BW^{0.46}$	Field measurements in a commercial fattening pig house
Brown-Brandl et al. (2004)	$E - CO_{2,\,pig} = 0.123\,BW^{0.62}$	Literature review
Pedersen et al. (2008)	$E - CO_{2,\,pig} = 0.0998\,BW^{0.646}$	Literature review
This review	$E - CO_{2,\,pig} = 0.136\,BW^{0.573}$	Literature review

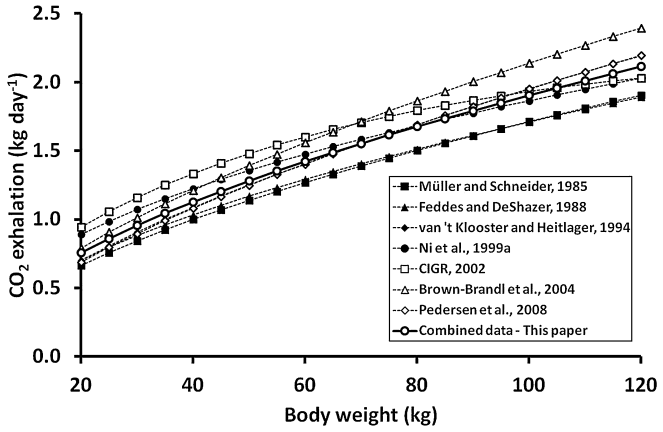


Fig. 1. Carbon dioxide (CO_2) exhalation by pigs estimated according to body weight.

Greater enteric production by sows can be explained by several factors, including increased feeding capacity, better intrinsic ability of bacterial flora to digest fibre, a greater number of bacteria, a reduction in the relative feeding level, and increased transit time (Le Goff et al., 2002a). Fig. 2 illustrates the production of enteric CH_4 for fattening pigs and adult sows reported in the literature according to the level of fibre intake, the so-called digestible residues (dRes), as proposed in INRA-AFZ (2004) and defined as the difference between digested organic matter and digested protein, fat, starch and sugar. By compiling these data, the following equations have been developed to predict the CH_4 enteric production (E-$CH_{4,pig/sow}$, in g CH_4 day^{-1}) from dRes intakes (g day^{-1}) for fattening pigs (Eq. (2)) and for adult sows (Eq. (3)):

$$E - CH_{4,pig} = 0.012 \times dRes (R^2 = 0.77) \quad (2)$$

$$E - CH_{4,sow} = 0.021 \times dRes (R^2 = 0.90) \quad (3)$$

For example, the ingestion of 300 g of dRes is associated with the enteric production of 3.6 g CH_4 by fattening pigs and 6.3 g CH_4 by adult sows. Enteric emissions represent energy losses of 56.65 kJ per g of CH_4 produced, which represents about 0.4–0.5% of digestible energy (DE) for fattening pigs and 1.0–1.5% DE for adult sows. According to the tier 1 methodology from the IPCC guidelines for national inventories (IPCC, 2006), enteric CH_4 is estimated at 1.5 kg per head per year, corresponding to 4.1 g CH_4 day^{-1}, whatever the diet composition and physiological stage. Taking into account conventional diet composition, level of ingestion and/or growth performance Vermorel et al. (2008) estimated for French production daily enteric CH_4 emissions to 0.8, 2.4 and 8.2 g CH_4 $head^{-1}$ for weaned piglets (up to 20 kg), fattening pigs (from 20 kg) and reproductive sows, respectively. Corresponding values for German production were proposed by Dämmgen et al. (2012a) at 0.9, 2.5 and 6.1 g CH_4, respectively.

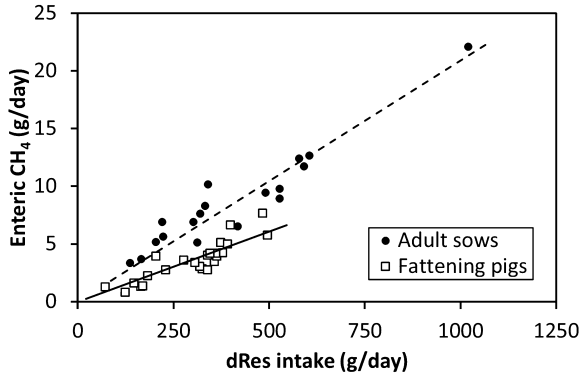


Fig. 2. Estimations of enteric methane (CH_4) production by adult sows and fattening pigs according to the intake of digestive residues (dRes defined as the difference between digested organic matter and digested protein, fat, starch and sugar).Source: adapted from Noblet et al., 1994; Jorgensen et al., 1996; Olesen and Jorgensen, 2001; Le Goff et al., 2002a,b; Ramonet et al., 2000; Galassi et al., 2004, 2005; Jorgensen, 2007; Jorgensen et al., 2007; Serena et al., 2008.

2.2.2. Release from manure

The release of CH_4 from manure originates from the temporal succession of microbial processes (Hellmann et al., 1997; Monteny et al., 2006). Initially, unspecified bacteria convert easily degradable substrates into VFAs, CO_2 and H_2. This extensive microbial activity increases the temperature of the manure and provides suitable conditions for methanogenic bacteria to convert acetate, CO_2 and H_2 into methane under a thermophilic environment. Factors that favour CH_4 production are lack of oxygen, high temperature, a high level of degradable organic matter, high moisture content, a low redox potential, a neutral pH, and a C/N ratio of between 15 and 30 (Moller et al., 2004; Amon et al., 2006; Kebreab et al., 2006).

According to the guidelines for National Greenhouse Gas Inventories (IPCC, 2006), CH_4 emissions from manure (E-$CH_{4,manure}$, in m^3) can be estimated based on the amount of excreted volatile solid (VS) or organic matter (OM), in kg; the ultimate CH_4 potential (B_0), in m^3 CH_4 per kg VS or OM; and the methane conversion factor (MCF), in percentage:

$$E - CH_{4,manure} = VS \times B_0 \times MCF$$

The IPCC (2006) recommends values for VS, B_0 and MCF, depending on the region of the world, the climate, the livestock categories and the type of manure. In Western Europe, the recommended value for VS is 0.30 kg pig^{-1} day^{-1} (IPCC, 2006). In the literature, B_0 values vary from 0.29 to 0.53 m^3 per kg VS or OM (Moller et al., 2004; Chae et al., 2008; Vedrenne et al., 2008; Jarret et al., 2011; Dämmgen et al., 2012b). The B_0 value proposed by the IPCC (2006) is 0.45 m^3 per kg VS. In the literature, extreme MCF values range from 2% to 80% according to manure type, manure management, storage duration, diet composition and temperature (Moller et al., 2004; Jarret et al., 2011; Dämmgen et al., 2012b; Rodhe et al., 2012). In their study, Moller et al. (2004) showed that during long-term storage (90 days), the slurry MCF value increased from 5.3 to 31.3% at temperatures ranging from 15 to 20 °C, respectively. On the other hand, at high temperatures, reducing the storage duration from 90 to 30 days decreased the MCF to 10.9%. Taking into account the proportion of manure management system usage, the emission factor for gas releases from swine manure in temperate Western Europe is estimated to 12 kg CH_4 $head^{-1}$ $year^{-1}$, or 32.9 g CH_4 day^{-1}, including inside and outside storage (IPCC, 2006).

2.3. Nitrous oxide

In pig houses, N_2O originates only from manure. Its formation mainly occurs during incomplete nitrification/denitrification processes performed by micro-organisms that normally convert NH_3 into non-polluting molecular nitrogen (N_2). The main microbial pathways involved in N_2O synthesis are presented in Fig. 3. An abiotic conversion of ammonium under acidic conditions, so-called chemo-denitrification, can also be at the origin of N_2O (Oenema et al., 2005; Petersen and Miller, 2006).

Nitrification, the process that converts ammonia into nitrate (NO_3^-), is usually carried out by autotrophic bacteria that require aerobic conditions with a pH value of above 5 (Kebreab et al., 2006). During nitrification, N_2O is synthesized as a by-product when there is a lack of oxygen and/or a nitrite accumulation. Denitrification is the reduction of NO_3^- into N_2, with many

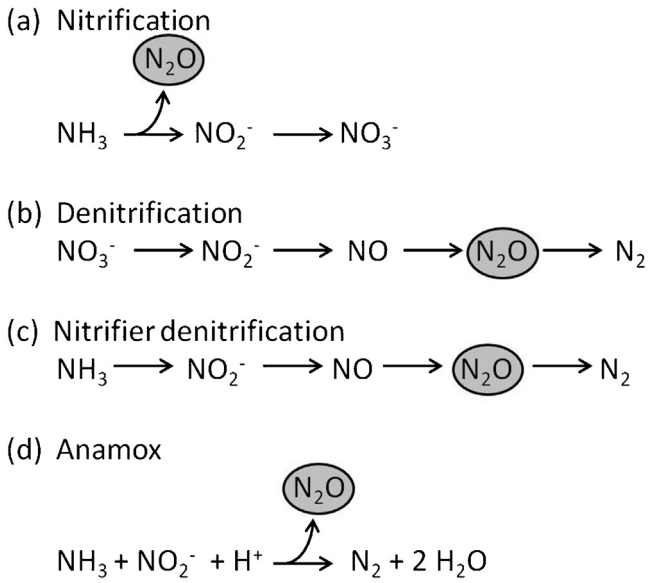


Fig. 3. Microbial pathways involved in N_2O synthesis in manure.

intermediate compounds being produced during the process (NO_2^-, nitric oxide (NO), and N_2O). In manure, denitrification is principally performed by heterotrophic facultative aerobic bacteria. The accumulation of N_2O in manure is favoured in the presence of oxygen and/or low availability of degradable carbohydrates (Poth and Focht, 1985; Driemer and Van den Weghe, 1997). The production of N_2O can also occur during other microbial pathways: the oxidation of ammonium under aerobic or anaerobic conditions, the so-called nitrifier denitrification and anamox processes, respectively. Most nitrifying and denitrifying microorganisms are mesophilic, and thus, the formation of N_2O is generally inhibited by temperatures above 40–50 °C (Hellmann et al., 1997; Kebreab et al., 2006). However, some authors have detected N_2O synthesis under thermophilic conditions (Wolter et al., 2004; Szanto et al., 2007). The relative contribution of these numerous pathways has still to be determined. Nevertheless, N_2O synthesis is known to require a close combination of aerobic and anaerobic areas. These heterogeneous conditions are largely encountered within litter but are rarer in slurry. However, N_2O emissions can occur from slurry when a dry crust is formed on the surface containing a combination of anaerobic and aerobic micro-sites. In any case, N_2O production from manure has a highly stochastic nature, especially due to its numerous sources of emission and environmental controls.

The guidelines for National Greenhouse Gas Inventories (IPCC, 2006) recommend estimating direct N_2O emissions by multiplying N excreted by animals (N_{ex}) by a specific conversion factor for each type of manure management system. For example, this conversion factor is 0.2% N_{ex} for pit storage under animals and 1% N_{ex} for deep bedding. Assuming 40 g N_{ex} pig^{-1} day^{-1}, this represents 0.13 and 0.63 g N_2O pig^{-1} day^{-1}, respectively.

3. Contribution by physiological stage

Several authors have measured GHG emissions from pig houses under practical conditions. Table 4 summarizes results from

Table 4
Emission factors at house level for carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) related to the physiological stage of the pigs (kept on a slatted floor).

Physiological stage	Country	Greenhouse gas emissions (kg CO_2equiv. LU^{-1} day^{-1})			
		CO_2	CH_4	N_2O	Total
Gestating sows					
Lägue et al., 2004	Canada	11.98	2.13	0.00	14.10
Dong et al., 2007	China	5.92	0.24	0.22	6.38
Zhang et al., 2007	USA	8.16	2.39	0.00	10.55
Costa and Guarino, 2009	Italy	8.85	3.30	0.81	12.96
Philippe et al., 2011a	Belgium	5.70	0.60	0.33	6.63
Stinn et al., 2011	USA	8.95	7.07	0.03	16.04
Mean		8.26	2.62	0.23	11.11
Farrowing sows					
Lägue et al., 2004	Canada	21.50	4.56	0.00	26.06
Dong et al., 2007	China	7.49	0.24	0.16	7.89
Zhang et al., 2007	USA	14.08	6.69	0.00	20.77
Stinn et al., 2011	USA	27.86	3.59	0.07	31.53
Mean		17.73	3.77	0.06	21.56
Weaned piglets					
Lägue et al., 2004	Canada	29.85	14.69	0.00	44.54
Dong et al., 2007	China	29.67	1.46	0.38	31.51
Cabaraux et al., 2009	Belgium	10.70	0.74	0.05	11.48
Costa and Guarino, 2009	Italy	6.00	0.61	1.08	7.69
Mean		19.05	4.37	0.38	23.81
Fattening pigs					
Nicks et al., 2005	Belgium	13.86	3.24	0.75	17.85
Dong et al., 2007	China	16.73	0.80	0.26	17.79
Philippe et al., 2007a	Belgium	12.84	3.01	1.19	17.04
Costa and Guarino, 2009	Italy	13.64	4.75	0.97	19.35
Palkovicova et al., 2009	Slovak Republic	14.36	5.76	0.91	21.02
Guingand et al., 2010	France	17.82	1.95	0.47	20.24
Li et al., 2011	USA	16.20	0.53	1.71	18.44
Ngwabie et al., 2011	Sweden	16.38	3.78	0.37	20.53
Mean		15.23	2.98	0.83	19.03

CO_2equiv.: emissions of CO_2-equivalents, including CO_2, CH_4 and N_2O, taking into account the global warming potential of 25 and 298 for CH_4 and N_2O, respectively.
LU: livestock unit, equal to 500 kg BW. In cases of a lack of data, default values for body weight (BW) were estimated to 200, 220, 18 and 70 kg for gestating sows, farrowing sows (including piglets), weaned piglets and fattening pigs, respectively.

research involving the study of CO_2, CH_4 and N_2O together for pigs kept on slatted floors at their different physiological stages. In order to facilitate a comparison between physiological stages and between gases, emissions are expressed in the table as CO_2-equivalents per livestock unit. The CO_2-equivalents (CO_2equiv.) take into account the global warming potential of each gas, which is evaluated to 25 and 298 times that of CO_2 over a 100-year period for CH_4 and N_2O, respectively (IPCC, 2007). The livestock unit (LU) is equal to 500 kg body weight.

The CO_2 emissions related to fattening pigs are quite similar between the studies, while the corresponding values for the other physiological stages shows greater variation, especially for weaned piglets. Similar findings have also been observed by Philippe et al. (2011b) regarding NH_3 emissions. The discrepancy between the results of the studies, as shown in Table 4, may be attributed to differences in housing conditions, ventilation systems, management practices, diet formulation and gas measurement method. Nevertheless, the average emission factors proposed by physiological stage seem consistent between the studies. Indeed, gestating sows present the lowest value (8.26 kg CO_2 LU^{-1} day^{-1}, or 3.3 kg CO_2 sow^{-1} day^{-1}), as influenced by their low feed intake (restricted feeding, low energy density of the diet) and metabolism. Farrowing sows (including piglets) and weaned piglets are associated with the highest emissions (17.73 kg CO_2 LU^{-1} day^{-1}, or 8.87 kg CO_2 sow^{-1} day^{-1}, and 19.05 kg CO_2 LU^{-1} day^{-1}, or 0.69 kg CO_2 pig^{-1} day^{-1}, respectively), as a consequence of ad libitum feeding and intensive productive status (milk production and growth). Emissions related to fattening pigs (15.3 kg CO_2 LU^{-1} day^{-1}, or 2.1 kg CO_2 pig^{-1} day^{-1}) are slightly lower than the latter.

The CH_4 emissions reported in the literature present a large range of variation within each physiological stage. In addition to the variation factors described above for CO_2, the manure removal strategy and the storage duration inside the building seem to play an important role regarding the level of emissions (see below). For the other physiological stages, higher emissions were also observed with a longer duration of indoor manure storage. Table 4 shows that, on average, the mean emission factors expressed per LU do not differ significantly between physiological stages, ranging from 2.62 kg CO_2equiv. LU^{-1} day^{-1} for gestating sows, to 4.37 kg CO_2equiv. LU^{-1} day^{-1} for weaned piglets, with intermediate values for fattening pigs (2.98 kg CO_2equiv. LU^{-1} day^{-1}) and farrowing sows (3.77 kg CO_2equiv. LU^{-1} day^{-1}). Corresponding values expressed per animal are 41.9, 6.3, 16.7 and 78.5 g CH_4 day^{-1}, respectively. The CH_4 emissions associated with gestating sows could be deemed quite low, considering the high fibre content of their diet and their large fermentative capacity. In fact, these effects are counterbalanced by the restricted feeding usually applied at this stage.

As can be seen in Table 4, the N_2O emissions measured from pig houses fitted with a slatted floor were relatively low whatever the pigs' physiological stage. In some experiments (Lägue et al., 2004; Zhang et al., 2007), the production of N_2O emissions was even lower than the detection limit of the measurement equipment, giving small mean values as a result. In this context, important relative differences between studies or physiological stages do not have significant meaning. Thus, it seems more appropriate to consider a generic emission factor for all the stages. Based on the values reported in Table 4, an average emission of 0.40 kg CO_2equiv. LU^{-1} day^{-1} could be proposed.

Also based on these values, total GHG emissions from pig buildings are estimated to 11.11 kg CO_2equiv. $LU^{-1}day^{-1}$ for gestating sows and around 20 kg CO_2equiv. $LU^{-1}day^{-1}$ for lactating sows, weaned piglets and fattening pigs, reflecting the relative metabolism rate of each physiological stage.

The contribution of each physiological stage to GHG emission intensity expressed per unit of product is estimated using the data from Table 4 and is presented in Table 5. Overall, GHG emissions from pig houses are estimated to 448.4 kg CO_2equiv. per slaughter pig produced or 4.87 kg CO_2equiv. per kg carcass. The fattening period accounts for more than 70% of total emissions, while the gestation, lactation and weaning periods each contribute to about 10% of total emissions. Thus, it can be concluded that efforts to reduce emissions should primarily target fattening pigs. Emissions of CO_2, CH_4 and N_2O contribute to 81, 17 and 2% of total emissions from buildings, representing 3.87, 0.83 and 0.17 kg CO_2equiv. per kg carcass, respectively. These figures show the important share of CO_2 in global emissions contributed by pigs and their manure. However, these sources of emission are usually neglected in GHG evaluation. Indeed, several authors have developed life cycle assessment (LCA) studies to estimate the intensity of emissions given off in pig production. These models exclude CO_2 emissions from respiration and manure but include GHG emissions for feed production, manure storage and spreading, and energy consumption. Reported values range from 3.07 to 5.79 kg CO_2equiv. per kg carcass (Vergé et al., 2009; Pelletier et al., 2010; Lesschen et al., 2011; Weiss and Leip, 2012). The discrepancy between these studies comes from the differences in methodology, type of pig production, boundaries of the system, emission categories and allocation.

4. Influencing factors

The GHG emissions from pig houses are principally influenced by floor type, manure management and nutrition of the pigs. The climatic conditions inside the building also impact emission levels.

Table 5
Contribution of the physiological stage of pigs on greenhouse gas emissions per unit of product (assuming no allocation to slaughter by-products).

Physiological stage	Days	Greenhouse gas emissions (kg CO_2equiv.[a])		
		Day^{-1} $animal^{-1}$[b]	Slaughter pig^{-1}[c]	kg $carcass^{-1}$[d]
Dry and gestating sows	125	4.44	55.6	0.60 (12%)
Lactating sows[e]	28	10.78	30.2	0.33 (7%)
Weaned piglets[f]	50	0.86	42.8	0.47 (10%)
Fattening pigs[g]	120	2.67	319.9	3.48 (71%)
Total	323	–	448.4	4.87 (100%)

[a] CO_2equiv.: CO_2-equivalent, including CO_2, CH_4 and N_2O and taking into account the global warming potential of 25 and 298 for CH_4 and N_2O, respectively.
[b] Derived from data presented in Table 4.
[c] Based on 10 slaughtered pigs per litter.
[d] Based on carcass weight of 92 kg (liveweight of 118 kg and dressing percentage of 78%).
[e] Including piglets of up to 8 kg BW.
[f] From 8 to 28 kg BW with 400 g of average daily gain.
[g] From 28 to 118 kg BW with 750 g of average daily gain.

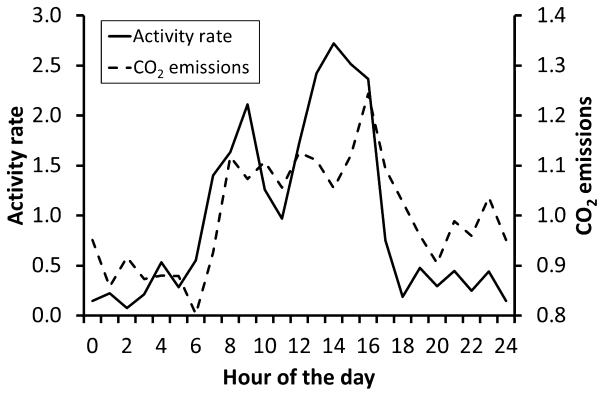


Fig. 4. Nycthemeral evolution around the daily mean (value = 1) of the activity rate of pigs and the carbon dioxide emissions associated with fattening pigs kept on a slatted floor.Source: adapted from Philippe et al., 2013.

4.1. Climatic conditions

Gaseous emissions are positively related to temperature and ventilation rate. An experiment carried out in a commercial pig house emptied of pigs showed that CO_2 emissions from slurry doubled when the manure temperature increased from 15 to 20 °C, and increased from 0.8 to 25.8 g CO_2 h^{-1} per m^2 of slurry when the ventilation rate ranged from 160 to 3350 m^3 h^{-1} (Ni et al., 1999b). Ngwabie et al. (2011) reported that CH_4 emissions doubled when the indoor temperature in a fattening pig unit increased from 16.8 to 22.8 °C. Blanes-Vidal et al. (2008) estimated the correlation between averaged ventilation flow and CH_4 emission to be 0.79 on an hourly basis.

Typically, gaseous emissions from pig houses present a diurnal pattern as a consequence of the comprehensive effects of temperature, ventilation rate and animal activity. The highest emission rates are usually observed during feeding time (Van Milgen et al., 1997; Moehn et al., 2004). For fattening pigs fed ad libitum, a first peak of emission occurs in the morning and a second peak in the afternoon, as illustrated for CO_2 emissions in Fig. 4 (adapted from Philippe et al., 2013). Modification of the feeding schedule can have an impact on the level of daily emissions, as demonstrated by Groenestein et al. (2003) with gestating sows.

The location of the fans in the building also contributes to a modulation of the emission levels. Air inlets or outlets located near the manure surface increase the level of emissions due to greater air flow at the interface (Hayes et al., 2006). In any case, using climate conditions to modulate the release of GHGs seems rather impractical since the ambient parameters must primarily respect the physiological needs of the animals. Nevertheless, optimization of the heating and ventilation in the housing system can have a beneficial effect on emission levels. Good practice includes insulation of the building, adaptation to internal (e.g. density of the pigs and their physiological stage) and external factors (e.g. season and weather), management of air circulation and regular monitoring of the ventilation devices. Regulation of climatic parameters also has an influence on the health, performance, welfare and behaviour of the pigs, thereby causing indirect effects on the level of emissions. In addition, energy saving related to optimal management of climatic factors can be considered environmentally and economically beneficial.

4.2. Floor type and manure management

In pig production, the most frequent housing conditions are based on a slatted floor with a deep pit underneath for the storage of slurry. Alongside this traditional system, bedded systems have met with renewed interest during recent decades, as these systems are related to improved welfare, reduced odour nuisance and a better brand image for livestock production. For both housing systems, a large range of parameters may influence the levels of GHG emissions.

4.2.1. Slatted floor systems

4.2.1.1. Proportion of the slatted area. It is usually assumed that the emission of pollutant gases can be reduced by lowering the slurry emitting surface. With the implementation of a partly slatted floor, some authors have observed a reduction in CO_2 production by 7–13% compared with a fully slatted floor, confirming that slurry is not the main source of emission (Table 6; Sun et al., 2008; Guingand et al., 2010). For CH_4 production, contradictory results have been reported in the literature, with decreased emissions (Lägue et al., 2004; Philippe et al., 2014a) or increased emissions being associated with partly slatted floors (Guingand et al., 2010). The effect of a slatted floor area on N_2O emissions has also shown conflicting results (Fitamant et al., 1999; Lägue et al., 2004; Guingand et al., 2010; Philippe et al., 2014a). In any case, absolute N_2O emissions from slurry have been shown to remain quite low, whatever the type of slatted floor. Cumulative emissions of GHGs (expressed in CO_2-equiv.) have been shown to be reduced by 4–13% by the application of a partly slatted floor compared with a fully slatted floor (Table 6).

Costs associated with partly slatted floors are quite similar to those of fully slatted floors despite a slightly higher labour cost due to pen fouling and the need for additional cleaning (Krieter, 2002). Application of partly slatted floors in existing fully slatted buildings is rather limited. Solid plates can be easily placed on the floor to create a partly slatted floor, but the total surface of the pit will remain unchanged, with no potential effects on emissions.

4.2.1.2. Slurry removal strategy. The increase in the slurry level could favour emissions, since it has been suggested that a smaller space between the slats and the surface of manure increases air turbulence and the release of gases (Ye et al., 2009). However, several authors have reported that a higher slurry depth does not

Table 6
Effect of the proportion of slatted floor (fully or partly slatted floor) on emissions (pig^{-1} day^{-1}) of carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O) and CO_2-equivalent (CO_2equiv., including CO_2, CH_4 and N_2O and taking into account the global warming potential of 25 and 298 for CH_4 and N_2O, respectively) associated with fattening pigs.

References	Fully slatted floor				Partly slatted floor			
	CO_2 (kg)	CH_4 (g)	N_2O (g)	CO_2equiv. (kg)	CO_2 (kg)	CH_4 (g)	N_2O (g)	CO_2equiv. (kg)
Fitamant et al., 1999	–	–	1.10	–	–	–	1.59	–
Lägue et al., 2004	6.00	28.0	0.07	6.72	5.88	15.6	0.00	6.27
Sun et al., 2008	3.38	–	–	–	2.95	–	–	–
Guingand et al., 2010	2.48	9.7	0.19	2.78	2.31	11.2	0.24	2.66
Philippe et al., 2014a	1.45	5.4	0.23	1.64	1.46	4.8	0.21	1.65

promote the release of gases (Lägue et al., 2004; Haeussermann et al., 2006).

Nevertheless, frequent removal of manure has been proposed as a means to diminish the release of emissions from pig buildings. Total emissions within outside storage will also be reduced provided the temperature is lower outside than inside or where specific manure treatments are applied. In their study of CH_4 and N_2O emissions from pig units, Osada et al. (1998) showed that weekly removal of manure reduced the level of these emissions by about 10% compared with the traditional deep-pit system. With the same removal strategy, Guarino et al. (2003) observed a reduction of 19% in CH_4 emissions, but a doubling of N_2O emissions. Yet cumulative emissions (expressed in CO_2-equiv.) were shown to be lowered by 16%. Lavoie et al. (2006) found that when manure was removed three times a week instead of only once, CH_4 emissions were reduced by 16% and N_2O emissions remained insignificant. Results from these three studies regarding CO_2 emissions would suggest that the level of these emissions is not impacted by the removal frequency of manure (Osada et al., 1998; Guarino et al., 2003; Lavoie et al., 2006).

Pit flushing is also an efficient means to mitigate emissions. Sommer et al. (2004) estimated to 35% the reduction potential of cumulative GHGs (CH_4 and N_2O) with daily flushing compared with having a static pit. By combining frequent flushing (six times a day) with a reduced slurry surface, Lagadec et al. (2012) measured a 35% reduction in cumulative emissions (CH_4 and N_2O) with the use of manure gutters and by 55% with the use of a flushing tube, compared with having a static pit. Kroodsma et al. (1993) showed that the frequency, duration and pressure of the flushing water also impacted the efficiency of mitigation. Their results demonstrated that frequent flushing (every 1–2 h) for short periods (2 s) was more effective than prolonged (3–6 s) but less frequent flushing (every 3.5 h). The use of fresh water, as opposed to recycled water, has also been found to further reduce emissions (Kroodsma et al., 1993). This is especially the case for CH_4 because methanogenesis is rapidly initiated in the channel if a small proportion of the slurry remains in the pit after emptying. Without inoculums in the pit, CH_4 formation is low and is initiated after a few days (Sommer et al., 2007).

Accumulated manure can also be removed by scraping. The standard flat scraper system consists of a shallow slurry pit with a horizontal steel scraper under the slatted floor, allowing the manure to be removed from the building every day or several times a week (Groenestein, 1994). With this system, reductions of 15% for CO_2 emissions and of around 50% for CH_4 and N_2O emissions have been obtained under experimental conditions (Godbout et al., 2006; Lagadec et al., 2012). However under practical conditions, this technique has failed to significantly reduce CH_4 emissions (Lagadec et al., 2012).

Other systems have been developed to associate manure removal with under-slat separation of liquid/solid fractions. The V-shaped scraper system involves a channel with two inclined surfaces on each side of a central gutter. The liquid fraction runs off continuously under the force of gravity towards the gutter, and the solid fraction remaining on the inclined surfaces is frequently scraped (Godbout et al., 2006). These authors observed that, when manure was scraped every 2–3 days, although CO_2 emissions remained unchanged, CH_4 emissions reduced by 20%, in comparison with a deep-pit emptied once a week. Furthermore, Lagadec et al. (2012) demonstrated a 50% reduction in N_2O emissions in the case of a scraping frequency of between 3 and 12 times a day, compared with having a static pit. With the V-shaped conveyor belt system, urine constantly flows down in the middle of the belt under the force of gravity, and faeces are removed by the rotation of the belt (de Vries et al., 2013). Results obtained by de Vries et al. (2013) showed that this technique reduced CO_2 emissions by 47% and CH_4 emissions by 90%, but increased N_2O emissions by 250%. Overall, cumulative emissions (CO_2, CH_4 and N_2O) were lowered by 80% (de Vries et al., 2013).

Implementation of elementary frequent manure removal techniques does not seem to be associated with extra cost and could be easily applied in existing buildings. By contrast, flushing strategies (using manure gutters or flushing tubes) require major modifications to be made to existing houses. For new buildings, these systems are economically advantageous due to the reduced requirement to dig a shallow pit and the low operational costs (Guarino et al., 2003). For scraping systems, buildings costs are estimated to be higher than for traditional deep pit systems, i.e. +25 to +35% per animal place (Hamel et al., 2004; Lagadec et al., 2012). Aarnink et al. (2007) estimate the cost for new buildings to be fitted with V-shaped conveyor belts to be 10–15% lower than for traditional systems. However, applicability of these latest techniques in existing houses would appear difficult owing to the required modification of the existing manure outlets.

4.2.1.3. Other techniques. Some other original techniques have been developed to reduce GHG emissions from pig houses. Incorporation of humic acids into slurry has been shown to reduce CH_4 emissions by 34% by improving methanotrophic bacteria, but not to modify CO_2 or N_2O emissions (Shah and Kolar, 2012). The addition of quebracho tannins into slurry has also been shown to reduce CH_4 emissions by up to 95% due to the noxious effects of these compounds on methanogens. Soybean oil sprinkling and misting with essential oils have been shown to decrease CO_2 and CH_4 emissions by about 20% (Ni et al., 2008). By contrast, the addition of clay or zeolite to slurry has been shown to result in increased CH_4 emissions, as a consequence of the neutralization of the toxic effect of ammonia on methanogenic bacteria (Hansen et al., 1999; Kotsopoulos et al., 2008). The use of TiO_2-based paints and coatings has been shown to reduce CH_4 emissions by up to 27% due to the oxidative photocatalytic properties of the chemical (Costa et al., 2012). These findings would need to be confirmed in further studies and, in some cases, the underlying mechanisms require clarification.

4.2.1.4. Outside storage and slurry treatment. The release of gases during the outside storage of slurries is influenced by numerous factors. Seasonal and weather conditions, such as air temperature, relative humidity, wind speed and rainfall, modulate the production of GHGs from slurry (Lägue et al., 2004). Natural or synthetic coverings have been proposed as a means of mitigating emissions by reducing the emitting area, heating and turbulence at the slurry surface. However, some authors have reported increased emissions despite slurry cover (Loyon et al., 2006; Guarino et al., 2006; Van der Zaag et al., 2008). Several slurry treatments have been developed to facilitate the management of emissions and to mitigate their environmental impact. These slurry treatments include, among others, solid–liquid separation, biofiltration, vermifiltration and aerobic or anaerobic treatments (Godbout et al., 2003; Lägue et al., 2004; Loyon et al., 2007; Dinuccio et al., 2008; Lessard et al., 2009; Luth et al., 2011). Generally, strategies that reduce GHG emissions from slurry, preserve its energetic and agronomic values, and favour nutrient uptake for next steps are environmentally efficient. Among the numerous techniques available, anaerobic digestion of slurry with the production of a biogas rich in CO_2 and CH_4 offers an interesting opportunity to significantly reduce GHG emissions due to a lowered release of gases from manure, the production of renewable energy (electricity and heat) and the replacement of fossil fuel consumption. Adoption of an anaerobic digester in a pig farm for 100 fattening places has been estimated to offset a total of 125 t CO_2equiv. per year (Kaparaju and Rintala, 2011). The different

techniques used to treat manure can be combined, and numerous modifications/adaptations have been developed. The level of GHG emissions related to these techniques depends on various parameters such as the type and the duration of treatment, the stage of the process, and the volume and the composition of the manure fraction. Thus, knowledge of the specific conditions for the treatment is essential for precise environmental assessment.

4.2.2. Bedded floor systems

Compared with slatted floor systems, bedded floor systems are usually associated with reduced CH_4 emissions, increased CO_2 emissions, hugely elevated N_2O emissions, and an overall increase in CO_2equiv. emissions (Table 7). The specific environment encountered within the litter, especially the combination of aerobic and anaerobic areas, as opposed to strictly anaerobic slurry, explains these emission factors. Nevertheless, bedded systems combine a wide range of rearing techniques that impact the level of emissions. Indeed, the litter may differ by the bedding material, the amount and frequency of application, the space allowance, the litter management and the removal strategy. These parameters influence the physico-chemical characteristics of the manure, such as density, humidity, temperature, pH and C/N ratio, all of which interact to modulate gas emission levels (Dewes, 1996; Groenestein and Van Faassen, 1996; Misselbrook and Powell, 2005).

Implementation of a bedded system is associated with low building costs due to reduced digging requirements. This technique may also be easily applicable in existing buildings with a concrete solid floor. However, the price of bedding material and the labour involved in litter management induce an increased cost, estimated to be between +5 and 10% compared with slatted floor systems (Krieter, 2002; Philippe et al., 2006b). The availability of substrates may constitute important opportunities or limitations of application, resulting in a different economic balance from area to area.

4.2.2.1. Type of substrate. Several bedding materials have been tested regarding their GHG emissions. The most frequent substrate used is straw, but sawdust, wood shavings or peat may also be used (Jeppsson, 1998; Robin et al., 1999; Nicks, 2004). Results of studies comparing straw litters and sawdust litters show that sawdust litters produce fewer CH_4 emissions but hugely greater N_2O emissions (Table 8). Table 8 shows that, overall, the CO_2equiv. emissions from these studies are higher with the use of sawdust; this is mainly due to the greater contribution of N_2O emissions. Interactions within the litter may explain these results. Indeed, the higher manure density observed with sawdust impairs the composting process, which normally increases the temperature of the manure and amount of air exchange through it (Jeppsson, 2000). Comparing different bedding types under barn conditions, Jeppsson (2000) found manure temperatures of 23.9 and 35.5 °C, respectively, with wood shavings and chopped straw. Lower temperatures favour the activity of nitrifying and denitrifying bacteria, with a higher level of N_2O production as a by-product (Sommer, 2001; Hansen et al., 2006). By contrast, CH_4 production is very heat-dependent, and lower temperatures will significantly diminish these emissions (Hansen et al., 2006). Husted (1994) found that emissions of CH_4 from dung heaps could be divided by a factor ranging from 2.7 to 10.3 when heap temperatures were decreased by 10 °C. Moreover, CH_4 production is also controlled by the rate of its transport throughout the manure and by oxidation (Conrad, 1989). If CH_4 production is reduced and the path of its spread is slow in the presence of oxygen, oxidation is likely to occur and consequently lower CH_4 emissions will be released (Hao and Larney, 2011). Thus, the oxidation of CH_4 into CO_2 could counterbalance the reduction in CO_2 production via the composting process.

4.2.2.2. Amount of substrate and frequency of application. Studies of the effect of the amount of substrate on GHG emissions have shown conflicting results, except for N_2O, for which reductions have been systematically observed with increased amounts of bedding material (Yamulki, 2006; Sommer and Moller, 2000; Guingand and Rugani, 2013; Philippe et al., 2014b). Indeed, Guingand and Rugani (2013) reported that N_2O emissions were lowered by 57% when straw supplies increased from 60 to 90 kg per fattening period. Higher aeration of the litter and/or increased temperatures may explain this finding. For CO_2 and CH_4 production, the underlying mechanisms seem unclear, since contradictions appear in the literature between authors (Jeppsson, 2000; Sommer and Moller, 2000; Yamulki, 2006; Rigolot et al., 2010; Guingand and Rugani, 2013; Philippe et al., 2014b). For instance, Jeppsson (2000) showed that an increase of 25% in straw supply was associated with increased (+72%) CO_2 emissions, while Philippe et al. (2014b) observed unchanged emissions with a straw rate ranging from 50 kg to 100 kg per fattening pig. In practice, interactions between the microbial pathways and the physico-chemical properties of the litter modulate the level of emissions with variable effects according to specific conditions. The main characteristics of manure involved in these processes are dry matter content, C/N ratio, availability of carbohydrates, aeration and temperature. Regarding CH_4, on the one hand, extra substrate may inhibit gas production because of greater aeration (Rigolot et al., 2010; Yamulki, 2006; Sommer and

Table 7
Effect of floor type (bedded or slatted floor) on emissions (pig^{-1} day^{-1}) of carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O) and CO_2-equivalent (CO_2equiv., including CO_2, CH_4 and N_2O and taking into account the global warming potential of 25 and 298 for CH_4 and N_2O, respectively).

	Bedded floor					Slatted floor			
	Litter type	CO_2 (kg)	CH_4 (g)	N_2O (g)	CO_2equiv. (kg)	CO_2 (kg)	CH_4 (g)	N_2O (g)	CO_2equiv. (kg)
Weaned piglets									
Cabaraux et al., 2009	Straw	0.33	0.75	0.03	0.36	0.30	0.91	0.00	0.32
Cabaraux et al., 2009	Sawdust	0.43	0.52	0.32	0.54	0.34	0.86	0.01	0.36
Fattening pigs									
Robin et al., 1999	Sawdust	–	–	4.72	–	–	–	0.79	–
Ahlgrimm and Breford, 1998	Straw	–	2.74	–	–	–	6.16	–	–
Kermarrec and Robin, 2002	Sawdust	–	–	5.53	–	–	–	–	–
Philippe et al., 2007a	Straw	1.97	16.03	1.11	2.70	1.74	16.32	0.54	2.31
Philippe et al., 2007b	Straw	1.77	8.88	0.68	2.19	1.61	15.20	0.67	2.19
Gestating sows									
Philippe et al., 2011a	Straw	2.83	9.20	2.27	3.74	2.41	10.12	0.47	2.80

Table 8
Effect of the type of substrate on emissions (pig^{-1} day^{-1}) of carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O) and CO_2-equivalent (CO_2equiv., including CO_2, CH_4 and N_2O and taking into account the global warming potential of 25 and 298 for CH_4 and N_2O, respectively) associated with a bedded system.

	Straw-based deep litter				Sawdust-based deep litter			
	CO_2 (kg)	CH_4 (g)	N_2O (g)	CO_2equiv. (kg)	CO_2 (kg)	CH_4 (g)	N_2O (g)	CO_2equiv. (kg)
Weaned piglets								
Nicks et al., 2003	0.46	1.58	0.36	0.61	0.48	0.77	1.39	0.91
Cabaraux et al., 2009	0.33	0.75	0.03	0.36	0.43	0.52	0.32	0.54
Fattening pigs								
Nicks et al., 2004	1.30	7.39	0.03	1.49	1.32	4.96	2.09	2.07

Moller, 2000). On the other hand, extra substrate may promote emissions by providing degradable carbohydrates for methanogenic bacteria (Guingand and Rugani, 2013; Philippe et al., 2014b).

The effect of the frequency of straw application has been addressed by Guingand and Rugani (2013). The authors observed increased emissions of CH_4 (+40%) and N_2O (+167%) when straw was supplied every week compared with every 2 weeks, although the total amount of straw was similar for both frequencies.

4.2.2.3. Surface area of the bedded area. Some studies have examined the impact on emissions of the surface area of the bedded area. Based on experimental data, Hassouna et al. (2005) proposed two emission factors for N_2O emissions related to animal density: 4–12% N_{ex} with less than 2 m^2 fattening pig^{-1} and 2–8% N_{ex} with more than 2 m^2 fattening pig^{-1}. With gestating sows, Philippe et al. (2010) measured a reduction in CO_2-, CH_4- and N_2O-emissions by 12, 33 and 28%, respectively, when the available bedded area was increased from 2.5 to 3.0 m^2 per animal.

4.2.2.4. Litter removal strategy. As in the case of slurry systems, manure removal strategies have been proposed to reduce pollutant emissions from bedded systems.

The height of a manure pile influences the level of GHG emissions. Under laboratory conditions, Dong et al. (2011) increased manure height from 10 to 40 cm by increasing the amount of manure from 6.6 to 22.8 kg. The authors obtained a lowering of CO_2- and N_2O-emissions by 53 and 11%, respectively, but a doubling of CH_4 emissions, resulting from an increase in anaerobic conditions. With straw-based deep litters, GHG emissions increase regularly over the course of time throughout the same fattening period, principally due to the accumulation of dejection (Philippe et al., 2007a; Philippe et al., 2010; Philippe et al., 2012a). In their study, Nicks et al. (2004) found that the rearing of three successive batches of pigs on the same litter did not increase the CO_2 and N_2O emissions from one fattening period to another, but that it did significantly increase CH_4 emissions from 3.3 to 12.7 g CH_4 pig^{-1} day^{-1} between the first and the third batch. Thus, frequent manure removal has been suggested as a means to mitigate emissions, and straw flow systems have been developed in response (Bruce, 1990). In this system, straw is supplied at the top of a sloped lying area. It travels down the slope with the aid of pig motion, is mixed with dung and then goes out of the pen into a passage from which manure is regularly scraped and removed. This kind of manure management is efficient in diminishing GHG emissions, as observed by Philippe et al. (2012a), who measured a reduction by 10, 46 and 55% for CO_2-, CH_4- and N_2O-emissions, respectively, compared with deep-litter. Overall, these authors found that CO_2equiv. emissions (including CO_2, CH_4 and N_2O) were reduced by 50%.

During the outside storage of solid manure, air temperature seems not to significantly influence the level of emissions, in contrast with wind speed or rainfall episodes (Wolter et al., 2004). Manure operations such as turning, stacking or covering impact on GHG emissions, but there have been some contradictory findings between studies (Hellmann et al., 1997; Paillat et al., 2005; Szanto et al., 2007; Jiang et al., 2013). Interlinked relationships between biological, physical and chemical factors inside the manure heap may explain these discrepancies. Whatever the storage conditions and treatment of manure, it is imperative that these conserve the energetic and agronomic value of the manure.

4.3. Nutrition

The main dietary strategy proposed for the abatement of pollutant gas emissions is the manipulation of the levels of crude protein and fibre content in the diet. Some dietary additives have also been studied for their impact on GHG emissions.

Evaluation of the cost-effectiveness of dietary manipulation is made difficult principally due to the large fluctuation in raw material prices depending on market conditions. For instance, the economic impact of the level of crude protein in the diet is greatly affected by the cost of soybean meal, on the one hand, and synthetic amino acids on the other hand. For the 2004–2008 period, Pineiro et al. (2009) found that the cost difference between reduced crude protein diet supplemented with amino acids and the standard diet fluctuated from +5 to 6€ per pig produced. Feedstuffs rich in dietary fibre are quite inexpensive since they are usually by-products of the feed, food or biofuel industries (e.g.: sugar beet pulp, wheat bran and distiller's grain). However, the price of high fibre diets greatly depends on local opportunities and the availability of such ingredients. Dietary manipulations are mitigation methods that are easy for farmers to apply and that can be adapted according to the circumstances.

4.3.1. Crude protein content

Diets reduced in crude protein content (CPC) but supplemented with amino acids have been given to pigs to match the protein supply with their growth potential and so to improve the efficiency of protein utilization, with similar zootechnical performance but with resulting reduced N excretion and NH_3 production (Philippe et al., 2011b). Thus, it has been suggested that a lower CPC could also reduce N_2O emissions, since NH_3 is the precursor of the formation of N_2O (Misselbrook et al., 1998). However, experiments have failed to corroborate this hypothesis (Table 9). Indeed, laboratory-scale experiments based on slurry samples have resulted in similar levels of N_2O emissions despite CPC being reduced by 15–20% (Clark et al., 2005; Le et al., 2009; Osada et al., 2011). Under barn conditions with fattening pigs on litter, Philippe et al. (2006a) reported a doubling of N_2O emissions (1.02 vs. 0.52 g N_2O pig^{-1} day^{-1}) with CPC reduced by 18%. It has also been assumed that a lower CPC would reduce CO_2- and CH_4-emissions due to improved nutrient utilization, but contradictory findings have also been observed for these gases (Table 9). In studies

Table 9
Effects of a reduction in dietary crude protein content (CPC) on emissions of carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O) and CO_2-equivalents (CO_2equiv., including CO_2, CH_4 and N_2O and taking into account the global warming potential of 25 and 298 for CH_4 and N_2O, respectively).

References	CO_2	CH_4	N_2O	CO_2equiv.	Context
Quiniou et al., 1995	+7%	–	–	–	Respiratory chambers, fattening pigs, 17.7 vs. 24.3% CPC
Atakora et al., 2002	−5%	–	–	–	Respiratory chambers, gestating sows, 14.8 vs. 19.3% CPC
Atakora et al., 2002	−7%	–	–	–	Respiratory chambers, lactating sows, 12.0 vs. 16.3% CPC
Atakora et al., 2003	NS	−60%	–	–	Respiratory chambers, non-pregnant sows, 11.% vs. 14.6% CPC
Atakora et al., 2005	NS	NS	–	–	Respiratory chambers, fattening pigs, 11.2 vs. 16.8% CPC
Atakora et al., 2011a	NS	−27%	–	–	Respiratory chambers, fattening pigs, 12.0 vs. 19.5% CPC
Atakora et al., 2011b	NS	−19%	–	–	Respiratory chambers, fattening pigs, 16.2 vs. 19.0% CPC
Clark et al., 2005	+10%	+10%	NS	+10%	Slurry samples, fattening pigs, 13.9 vs. 16.8% CPC
Velthof et al., 2005	–	−21%	–	–	Slurry samples, fattening pigs, 14.2 vs. 18.0% CPC
Le et al., 2009	NS	NS	NS	NS	Slurry samples, fattening pigs, 12.0 vs. 15.0% CPC
Osada et al., 2011	–	NS	NS	–	Slurry samples, fattening pigs, 14.5 vs. 17.0% CPC
Philippe et al., 2006a	NS	−13%	+96%	+7%	Pens with fattening pigs on straw litter, 14.4 vs. 17.6% CPC

involving respiratory chambers, most results have shown a non-significant difference in CO_2-exhalation despite a CPC reduction of up to 45% (Atakora et al., 2003, 2005, 2011a,b). Quiniou et al. (1995) measured an increase of 7% in respiratory CO_2 production with fattening pigs, while Atakora et al. (2002) noted a decreased production of 5–7% with reproductive sows. Regarding CH_4 emissions, some authors have reported reductions ranging from 13% under field conditions (Philippe et al., 2006a) to 60% in respiratory chambers (Atakora et al., 2002). Reduced VFA production with a low CPC diet could explain these results, since VFAs are precursors of CH_4 (Velthof et al., 2005). However, non-significant differences or increases in CH_4 production have also been obtained by some authors in cases of reduced CPC (Atakora et al., 2005; Clark et al., 2005; Le et al., 2009; Osada et al., 2011). Philippe et al. (2006a) reported a 7% increase in cumulative GHG emissions (including CO_2, CH_4 and N_2O) with pigs on litter consuming a reduced CPC diet. This was due to a higher contribution of N_2O despite lower CH_4 emissions.

4.3.2. Dietary fibre

Several studies have dealt with the impact of dietary fibre on GHG emissions (Table 10). It has been established that diets rich in fibre increase CH_4 production from both sources – animal and manure. Linear relationships were given in Section 2.2.1 for predicting enteric CH_4 production from ingested dietary fibre. But digestive production can also be modulated by parameters such as the botanical origin, the solubility and the fermentability of the fibre (Philippe et al., 2008). An experiment on sows fed different diets with a similar dietary fibre content but different sources of fibre showed a higher CH_4 production in cases where maize bran was incorporated compared with wheat bran (7.6 vs. 5.1 g CH_4 sow^{-1} day^{-1}; Le Goff et al., 2002b). Indeed, soluble fibres, as found in maize bran, sugar beet pulp or potato pulp, have a higher digestibility and fermentability than insoluble fibres, as found in wheat bran, pea hulls or seed residues (Jorgensen et al., 2007).

Higher CH_4 releases from slurry in cases of a fibrous diet have been reported under laboratory conditions by some authors (Clark et al., 2005; Velthof et al., 2005; Jarret et al., 2012). Jarret et al. (2012) compared CH_4 production from the slurries of fattening pigs fed a conventional diet (11% NDF) or a fibrous diet with 20% dried distiller's grain with solubles (DDGS; 14% NDF) and they obtained higher emissions (+76%) with the fibrous diet. The authors explained this result in terms of the lower digestibility of high fibre diets and thus the higher quantity of excreted OM (0.32 vs. 0.19 kg pig^{-1} day^{-1}). The B_0 of excreta, on the other hand, did not differ significantly between treatments (around 0.38 m^3 per kg OM). By contrast to these results, Clark et al. (2005) did not observe a significant difference in CH_4 emissions under in vitro conditions, whatever the fibre content. At house level, CH_4 emissions have been shown to increase by 13–52% with fibrous diets as much with a slatted floor as with a bedded floor (Philippe et al., 2009, 2012a,b, 2013; Pepple et al., 2011).

Regarding CO_2 production, conflicting results have been reported depending on the study and the source of emissions (Table 10). Schrama et al. (1998) measured a 25% lowering of CO_2 exhalation as a consequence of a reduction in pig activity. At house level, Philippe et al. (2009) observed an increase of 24% in emissions with a diet based on sugar beet pulp (48% NSP) compared with a conventional diet based on cereals (26% NSP). The reduced feed efficiency observed with a fibrous diet could explain this result.

N_2O emissions from slurry-based systems are unaffected by dietary fibre content (Clark et al., 2005; Pepple et al., 2011; Philippe et al., 2012b), in contrast to bedded systems, for which emissions have been shown to reduce with a high-fibre diet (Philippe et al., 2009, 2012b). In fact, with a fibrous diet, the pig's motivation to

Table 10
Effects of dietary fibre content on emissions of carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O) and CO_2-equivalents (CO_2equiv., including CO_2, CH_4 and N_2O and taking into account the global warming potential of 25 and 298 for CH_4 and N_2O, respectively).

References	CO_2	CH_4	N_2O	CO_2equiv.	Context
Schrama et al., 1998	−25%	+96%	–	–	Respiratory chambers, fattening pigs, 12 vs. 18% NSP (0 vs. 17% SBP)
Wang et al., 2004	+6%	+153%	–	–	Respiratory chambers, fattening pigs, 4 vs. 11.6% NSP (0 vs. 12% SBP)
Li et al. 2011	−7%	+93%	–	–	Environmentally controlled pens, fattening pigs, 32 vs. 40% NDF (0 vs. 20% DDGS)
Clark et al., 2005	−17%	NS	NS	−5%	Slurry samples from fattening pigs, 0 vs. 20% SBP
Velthof et al., 2005	–	+74%	–		Slurry samples from fattening pigs, 13 vs. 25% NSP
Jarret et al., 2012	–	+76%	–		Slurry samples from fattening pigs, 11 vs. 14% NDF (0 vs. 13% DDGS)
Philippe et al., 2009	+24%	+13%	−61%	+5%	Pens with gestating sows on straw litter, 26 vs. 48% NSP (7 vs. 42% SBP)
Pepple et al., 2011	−13%	+45%	NS	+28%	Buildings with fattening pigs on a slatted floor, 0 vs. 20% DDGS
Philippe et al., 2013	−9%	+33%	NS	−6%	Pen with fattening pigs on a slatted floor, 18 vs. 30% NSP (0 vs. 23% SBP)
Philippe et al., 2012b	NS	+44%	NS	+6%	Pen with gestating sows on a slatted floor, 25 vs. 44% NSP (0 vs. 37% SBP)
Philippe et al., 2012b	+14%	+52%	−40%	+9%	Pen with gestating sows on straw litter, 25 vs. 44% NSP (0 vs. 37% SBP)

NSP: non-starch polysaccharides; SBP: sugar beet pulp; NDF: neutral detergent fibre, DDGS: dried distiller's grain with solubles.

manipulate and to chew the straw is reduced, as a sign of greater satiety (Philippe et al., 2008). Thus, the litter is more aerated with longer wisps of straw, which limits N_2O production.

Overall, cumulative GHG emissions (combining CO_2, CH_4 and N_2O) seem to be little influenced by the presence of dietary fibre. This can be seen in reports by authors regarding emissions within a context of pigs receiving increased dietary fibre. Emission levels at house level ranged from −6 to +9% compared with emissions produced by pigs consuming a conventional diet (Philippe et al., 2009, 2012a,b). An exception to this finding can be seen in the study of Pepple et al. (2011), who observed that CO_2equiv. emissions increased by 28% where pigs received a high fibre diet. The authors explained this result in terms of the large contribution of CH_4 in their experimental conditions due to a long storage duration of slurries inside the building.

4.3.3. Feed additives

Several feed additives have been studied for their influence on environmental factors, especially on ammonia emissions, but few experiments have dealt with greenhouse gas emissions resulting from these additives.

Most studies have argued that feed supplementations that improve nutrient digestibility and growth performance in pigs potentially reduce pollutant gas emissions on an absolute scale and per product unit (Moehn et al., 2007). However, this statement has rarely been experimentally tested and validated.

Cellulases and hemicellulases have been added to animal diets in order to counterbalance the anti-nutritional effects of fermentable fibres and to improve animal performance (O'Shea et al., 2010). A further beneficial effect of these enzymes may be a reduction in CH_4 production by enteric bacteria, which are linearly related to fibre ingestion. However, Moehn et al. (2007) observed a tendency for increased CH_4 emissions despite xylanase supplementation.

Dietary inclusion of acidifying salts has also been suggested as a means to modify GHG production. Yet Aarnink et al. (2008) did not observe a significant difference in CH_4 and N_2O emissions despite the addition of 1% benzoic acid in the diet of fattening pigs. Eriksen et al. (2010) showed that a diet supplemented with 2% benzoic acid resulted in a transient reduction in CH_4-emissions from slurries stored under laboratory conditions (from day 20 to 34 of storage). The authors explained this result in terms of the inhibition of methanogenic bacteria, possibly due to a reduction in manure pH, the toxic effect of sulphides or the direct impact of benzoic acid. The temporality of the reduction could reflect the adaptation of the bacteria to slurry acidification.

Yucca extract inclusion has been proposed as a means to inhibit urease activity and to chemically convert or bind NH_3 (Duffy and Brooks, 1998), leading to an improvement in the performance and health status of pigs (Colina et al., 2001). However, Amon et al. (1995) measured an increase in CO_2 production with the dietary addition of *Yucca shidigera* extract. The effects on CH_4 and N_2O emissions of the inclusion of *Yucca* extract in the diet of pigs are still unknown.

The addition of phytase, primarily used to reduce phosphorus excretion, has been shown to increase feed efficiency and protein deposition, and this could possibly lead to a decrease in emissions (Ball and Möhn, 2003). However, to the best of our knowledge, the addition of phytase has not been studied for its effect on GHG emissions.

Probiotic agents are believed to improve the microbial environment in the gut, leading to better digestibility, performance and health status as a result (Fuller, 1989; Tsukahara et al., 2001). Under laboratory conditions, Tsukahara et al. (2001) measured emissions from the intestinal content of piglets fed a diet supplemented with a mixture of live lactic acid bacteria (*Lactobacillus acidophilus*,*Bifidobacterium bifidum* and *Enterococcus faecalis*). The authors obtained reductions of approximately 50 and 35% for CO_2- and CH_4-emissions, respectively, explained by the fact that lactic acid bacteria are stoichiometrically less favourable to gas production (Stanier et al., 1986). Barn experiments would need to be carried out to confirm these findings on a larger scale.

5. Conclusion

This review has reported and analysed the results of studies in the literature regarding GHG emissions produced by animals and manure in pig houses. Taking into account the results regarding CO_2-, CH_4- and N_2O-production, cumulative emissions of GHGs produced by pigs and manure at pig house level are estimated to approximately 4.87 kg CO_2equiv. per kg of carcass. Although CO_2 is the main contributor of these emissions (accounting for about 81%), this gas is usually not included in the calculation of overall GHG production because it is assumed that CO_2 emitted by livestock is compensated during photosynthesis by plants used as feed. In addition in the past, CO_2 emissions from manure were often erroneously considered negligible, while they can represent up to 40% of respiratory production.

The production levels of CO_2, as for CH_4 and N_2O, can be altered by several factors, such as housing conditions, manure management and diet composition. For instance, comparisons between slatted and bedded floor systems show higher CO_2equiv. emissions from bedded floor systems due to greater CO_2 emissions but mainly due to high N_2O emissions that are not counterbalanced by the eventual reduction in CH_4 emissions. While litter systems are usually associated with a better brand image and are commonly required for environmental labelling, the data reported in this review show that the environmental benefits are not always so obvious for all aspects of the production process. Moreover, GHG emissions from bedded systems greatly depend on the type, the amount and the frequency of substrate supply. These parameters may interact, with variable impacts, on emission levels. Further studies need to be carried out in order to understand more precisely the underlying phenomena and interactions that modulate GHG production from litter.

Whatever the floor type, frequent manure removal is an efficient means used to diminish GHG emissions from pig buildings on the condition that emissions from outside storage operations are prevented. This is particularly true for CH_4 production, which increases greatly over the course of time and in ambient temperatures. Frequent manure removal seems particularly advantageous since manure treatments can be associated with the removal. In this sense, separation of the solid and liquid fractions of the slurry provides interesting opportunities. Indeed, this separation reduces storage requirements and transportation costs, and offers more homogenous materials for land spreading, recycling or other specific treatments in order to enhance the agronomic, energetic and environmental profitability of the processes.

Regarding dietary strategies, inclusion of fibre impacts on GHG production by increasing CH_4 emissions from the digestive tract and from the manure. For gestating sows fed with a high fibre diet and kept on a straw based deep litter, concurrent reductions in N_2O emissions have been observed, resulting in a limited effect on CO_2equiv. emissions. A reduction in dietary CPC, which is well-known to reduce N excretion, has been shown to fail to limit the release of N_2O from manure. Other feeding strategies have also been used to investigate the assumption that improved nutrient utilization can lower GHG emissions. However, this statement has not been systematically proven in experiments, since diets supplemented with feed additives such as acidifying salts, *Yucca*

extracts or probiotics seem ineffective in significantly reducing the intensity of GHG emissions. Nevertheless, innovative nutritional options could be examined in the future, as they appear to be efficient in reducing emissions. Recycling of the co-products from the feed-, food- or biofuel-processing industry into animal feed requires further investigation, as this could provide economical and ecological advantages due to the allocation of the cost and the impacts. Overall, feeding strategies offer the advantage of being easy to implement and quick to adapt according to the availability and cost of raw materials, which fluctuate temporally.

Good management practices that respect the physiological requirements of the animals and that promote their zootechnical potential will have beneficial consequences on performance and indirectly on the intensity of GHG emissions. In light of this, factors such as the design of the building, the regulation of bioclimatic parameters, the sanitary status of the herd and genetic selection may modulate the level of GHG production.

The choice of rearing technique is also guided by other elements, such as animal welfare, the agronomical value of manure, investment and operating costs. Specific field conditions lead to decisions in favour of mitigation techniques. Options presented in this review may contribute to a reduction in the intensity of emissions generated by pig production. However, in order to be universally efficient, these strategies would need to be integrated on a larger scale taking into account supplementary emissions associated with pre-, on- and post-farm processing, such as feed production, energy consumption, manure spreading and the transportation of animal and products.

References

Aarnink, A.J.A., Huis in 't Veld, J., Hol, J.M.G., Vermeij, I., 2007. Kempfarm Housing System for Growing-finishing Pigs: Environmental Emissions and Investment Costs. In Animal Sciences Group, Report 67. Wageningen University and Research Centre, Lelystad, The Netherlands.

Aarnink, A.J.A., Hol, A., Nijeboer, G.M., 2008. Ammonia Emission Factor for Using Benzoic Acid (1% Vevovitall®) in the Diet of Growing-Finishing Pigs. In Animal Sciences Group, Report 133. Wageningen University and Research Centre, Wageningen, The Netherlands p. 21.

Ahlgrimm, H., Breford, J., 1998. Methanemissionen aus der schweinemast. Landbauforschung Volkenrode 1, 26–34.

Amon, B., Kryvoruchko, V., Amon, T., Zechmeister-Boltenstern, S., 2006. Methane: nitrous oxide and ammonia emissions during storage and after application of dairy cattle slurry and influence of slurry treatment. Agric. Ecosyst. Environ. 112, 153–162.

Amon, M., Dobeic, M., Misselbrook, T.H., Pain, B.F., Phillips, V.R., Sneath, R.W., 1995. A farm scale study on the use of de-odorase(R) for reducing odor and ammonia emissions from intensive fattening piggeries. Bioresour. Technol. 51, 163–169.

Anderson, G.A., Smith, R.J., Bundy, D.S., Hammond, E.G., 1987. Model to predict gaseous contaminants in swine confinement buildings. J. Agric. Eng. Res. 37, 235–253.

Andersson, M., 1996. Performance of bedding materials in affecting ammonia emissions from pig manure. J. Agric. Eng. Res. 65, 213–222.

Atakora, J.K., Moehn, S., Sands, J.S., Ball, R.O., 2011a. Effects of dietary crude protein and phytase–xylanase supplementation of wheat grain based diets on energy metabolism and enteric methane in growing finishing pigs. Anim. Feed Sci. Technol. 166, 422–429.

Atakora, J.K.A., McMillan, D.J., Moehn, S., Ball, R.O., 2002. Low protein diet for sows: effects on production of carbon dioxide and heat. Adv. Pork Prod. 13, Abstract #14.

Atakora, J.K.A., Moehn, S., Ball, R.O., 2003. Low protein diets for sows reduce greenhouse gas production. Adv. Pork Prod. 14, Abstract #16.

Atakora, J.K.A., Moehn, S., Ball, R.O., 2005. Performance and greenhouse gas emission in finisher pigs fed very low protein diet. Adv. Pork Prod. 16, Abstract #14.

Atakora, J.K.A., Moehn, S., Ball, R.O., 2011b. Enteric methane produced by finisher pigs is affected by dietary crude protein content of barley grain based, but not by corn based, diets. Anim. Feed Sci. Technol. 166–167, 412–421.

Aubry, A., Quiniou, N., Cozler, Y.L., Querne, M., 2004. New standardized criteria for GTE performances. Techni-Porc. 27, 37–41.

Ball, R.O., Möhn, S., 2003. Feeding strategies to reduce greenhouse gas emissions from pigs. Adv. Pork Prod. 14, 301–311.

Blanes-Vidal, V., Hansen, M.N., Pedersen, S., Rom, H.B., 2008. Emissions of ammonia, methane and nitrous oxide from pig houses and slurry: effects of rooting material, animal activity and ventilation flow. Agric. Ecosyst. Environ. 124, 237–244.

Brown-Brandl, T.M., Nienaber, J.A., Xin, H., Gates, R.S., 2004. A literature review of swine heat production. Trans. ASAE 47, 259.

Bruce, J.M., 1990. Straw-flow – a high welfare system for pigs. Farm Build. Prog. 102, 9–13.

Cabaraux, J.F., Philippe, F.X., Laitat, M., Canart, B., Vandenheede, M., Nicks, B., 2009. Gaseous emissions from weaned pigs raised on different floor systems. Agric. Ecosyst. Environ. 130, 86–92.

Chae, K., Jang, A., Yim, S., Kim, I.S., 2008. The effects of digestion temperature and temperature shock on the biogas yields from the mesophilic anaerobic digestion of swine manure. Bioresour. Technol. 99, 1–6.

CIGR, 2002. Fourth Report of Working Group on Climatization of Animal Houses. Heat and Moisture Production at Animal and House Levels. Danish Institute of Agricultural Sciences, Horsens, Denmark, pp. 45.

Clark, O.G., Moehn, S., Edeogu, I., Price, J., Leonard, J., 2005. Manipulation of dietary protein and nonstarch polysaccharide to control swine manure emissions. J. Environ. Qual. 34, 1461–1466.

Colina, J.J., Lewis, A.J., Miller, P.S., Fischer, R.L., 2001. Dietary manipulation to reduce aerial ammonia concentrations in nursery pig facilities. J. Anim. Sci. 79, 3096–3103.

Conrad, R., 1989. Control of methane production in terrestrial ecosystems. In: Andreae, M., Schimel, D. (Eds.), Exchange of Trace Gases Between Terrestrial Ecosystems and the Atmosphere. John Wiley & Sons Ltd., Chichester, England, pp. 39–58.

Costa, A., Chiarello, G.L., Selli, E., Guarino, M., 2012. Effects of TiO_2 based photocatalytic paint on concentrations and emissions of pollutants and on animal performance in a swine weaning unit. J. Environ. Manage. 96, 86–90.

Costa, A., Guarino, M., 2009. Definition of yearly emission factor of dust and greenhouse gases through continuous measurements in swine husbandry. Atmos. Environ. 43, 1548–1556.

Dämmgen, U., Amon, B., Hutchings, N.J., Haenel, H.D., Rösemann, C., 2012a. Data sets to assess methane emissions from untreated cattle and pig slurry and solid manure storage systems in the German and Austrian emission inventories. Landbauforschung Volkenrode 62, 1–19.

Dämmgen, U., Schulz, J., Klausing, H.K., Hutchings, N.J., Haenel, H.D., Rösemann, C., 2012b. Enteric methane emissions from German pigs. Landbauforschung Volkenrode 62, 83–96.

de Sousa, P., Pedersen, S., 2004. Ammonia emission from fattening pig houses in relation to animal activity and carbon dioxide production. Agricultural Engineering International: CIGR Ejournal VI, Manuscript BC04 003.

de Vries, J.W., Aarnink, A.J.A., Groot Koerkamp, P.W.G., De Boer, I.J.M., 2013. Life cycle assessment of segregating fattening pig urine and feces compared to conventional liquid manure management. Environ. Sci. Technol. 47, 1589–1597.

Dewes, T., 1996. Effect of pH, temperature, amount of litter and storage density on ammonia emissions from stable manure. J. Agric. Sci. 127, 501–509.

Dinuccio, E., Berg, W., Balsari, P., 2008. Gaseous emissions from the storage of untreated slurries and the fractions obtained after mechanical separation. Atmos. Environ. 42, 2448–2459.

Dong, H., Zhu, Z., Shang, B., Kang, G., Zhu, H., Xin, H., 2007. Greenhouse gas emissions from swine barns of various production stages in suburban Beijing, China. Atmos. Environ. 41, 2391–2399.

Dong, H., Zhu, Z., Zhou, Z., Xin, H., Chen, Y., 2011. Greenhouse gas emissions from swine manure stored at different stack heights. Anim. Feed Sci. Technol. 166, 557–561.

Driemer, J., Van den Weghe, H., 1997. Nitrous oxide emissions during nitrification and denitrification of pig manure. In: Voermans, J.A.M., Monteny, G.J. (Eds.), Proceedings of the International Symposium on Ammonia and Odour Control from Animal Production Facilities, Dutch Society of Agricultural Engineering, Wageningen, The Netherlands, Vinkeloord, The Netherlands, pp. 389–396.

Duffy, C., Brooks, P., 1998. Using *Yucca* schidigera in pig diets: effects on nitrogen metabolism. In: Lyons, T.P., Jacques, K.A. (Eds.), Biotechnology in the Feed Industry. Alltach, Nicholasville, Kentucky, USA, pp. 61.

Eriksen, J., Adamsen, A.P.S., Norgaard, J.V., Poulsen, H.D., Jensen, B.B., Petersen, S.O., 2010. Emissions of sulfur-containing odorants, ammonia, and methane from pig slurry: effects of dietary methionine and benzoic acid. J. Environ. Qual. 39, 1097–1107.

FAO, 2011. World Livestock 2011– Livestock in Food Security. FAO, Rome, Italy.

FAO, 2013a. Greenhouse Gas Emissions From Pig and Chicken Supply Chains – A Global Life Cycle Assessment. FAO, Roma, Italy.

FAO, 2013b. Greenhouse Gas Emissions From Ruminant Supply Chains – A Global Life Cycle Assessment. FAO, Roma, Italy.

Feddes, J.J.R., DeShazer, J.A., 1988. Feed consumption as a parameter for establishing minimum ventilation rates. Trans. ASAE 31, 571–575.

Fitamant, D., Quillien, J.P., Callarec, J., Morvan, J., Lemasle, M., Laplanche, A., 1999. Nitrogen distribution and net flow in the form of gas and liquid from a piggery. Journées Rech. Porcine 31, 99–104.

Fuller, R., 1989. Probiotics in man and animals. J. Appl. Microbiol. 66, 365–378.

Galassi, G., Crovetto, G.M., Rapetti, L., Tamburini, A., 2004. Energy and nitrogen balance in heavy pigs fed different fibre sources. Livest. Prod. Sci. 85, 253–262.

Galassi, G., Crovetto, G.M., Rapetti, L., 2005. Trend of energy and nitrogen utilization of high fibre diets in pigs from 100 to 160 kg bodyweight. Ital. J. Anim. Sci. 4, 149–157.

Godbout, S., Lague, C., Lemay, S.P., Marquis, A., Fonstad, T.A., 2003. Greenhouse gas and odour emissions from swine operations under liquid manure management in Canada. In: Commission Internationale de Génie Rural (Ed.), Proceedings of the International Symposium on Gaseous and Odour Emissions from Animal

Production Facilities, Danish Institute for Agricultural Sciences, Foulum, Denmark, pp. 426–443.
Godbout, S., Lemay, S.P., Marquis, A., Pouliot, F., Larouche, J.P., Hamel, D., Lachance, I., Belzile, M., Dufour, V., Turgeon, N., 2006. Évaluation Technico-économique D'un Système De Séparation Liquide/solide Des Déjections À La Source Dans Un Bâtiment Porcin Et Les Impacts Sur L'environnement. Institut de Recherche et de Développement en Agro-environnement, Quebec, Canada.
Groenestein, C.M., 1994. Ammonia emission from pig houses after frequent removal of slurry with scrapers. Proceedings of the XII World Congress on Agricultural Engineering. CIGR, Merelbeke, Belgium, pp. 543–550.
Groenestein, C.M., Hendriks, M., den Hartog, L.A., 2003. Effect of feeding schedule on ammonia emission from individual and group-housing systems for sows. Biosyst. Eng. 85, 79–85.
Groenestein, C.M., Van Faassen, H.G., 1996. Volatilization of ammonia, nitrous oxide and nitric oxide in deep-litter systems for fattening pigs. J. Agric. Eng. Res. 65, 269–274.
Guarino, A., Fabbri, C., Brambilla, M., Valli, L., Navarotto, P., 2006. Evaluation of simplified covering systems to reduce gaseous emissions from livestock manure storage. T. ASABE 49, 737–747.
Guarino, M., Fabbri, C., Navarotto, P., Valli, L., Mascatelli, G., Rossetti, M., Mazzotta, V., 2003. Ammonia, methane and nitrous oxide emissions and particulate matter concentrations in two different buildings for fattening pig. In: Commission Internationale de Génie Rural (Ed.), Proceedings of the International Symposium on Gaseous and Odour Emissions from Animal Production Facilities, Danish Institute for Agricultural Sciences Foulum, Denmark, pp. 140–149.
Guingand, N., Quiniou, N., Courboulay, V., 2010. Comparison of ammonia and greenhouse gas emissions from fattening pigs kept either on partially slatted floor in cold conditions or on fully slatted floor in thermoneutral conditions. Journées Rech. Porcine 42, 277–284.
Guingand, N., Rugani, A., 2013. Incidence de la réduction de la quantité de paille et de la fréquence des apports sur les émissions d'ammoniac: de GES et d'odeurs chez les porcs en engraissement. Journées Rech. Porcine 45, 141–142.
Haeussermann, A., Hartung, E., Gallmann, E., Jungbluth, T., 2006. Influence of season ventilation strategy, and slurry removal on methane emissions from pig houses. Agric. Ecosyst. Environ. 112, 115–121.
Hamel, D., Pouliot, F., Leblanc, R., Godbout, S., Von Bermuth, R.D., Hill, J., 2004. Évaluation Technico-économique D'un Système De Séparation Liquide-solide Des Déjections À La Source Dans Un Bâtiment Porcin Et Les Impacts Sur L'environnement. Centre de développement du porc du Québec, Ste Foy Québec, Canada.
Hansen, K.H., Angelidaki, I., Ahring, B.K., 1999. Improving thermophilic anaerobic digestion of swine manure. Water Res. 33, 1805–1810.
Hansen, M.N., Henriksen, K., Sommer, S.G., 2006. Observations of production and emission of greenhouse gases and ammonia during storage of solids separated from pig slurry: effects of covering. Atmos. Environ. 40, 4172–4181.
Hao, X., Larney, F.J., 2011. Reducing greenhouse gas emissions from animal manure. Manure Manage. Update 37–45.
Hassouna, M., Robin, P., Texier, C., Ramonet, Y., 2005. NH_3, N_2O, CH_4 emissions from pig-on-litter systems. Proceedings of the International Workshop on Green Pork Production, Paris, France pp. 121–122.
Hayes, E.T., Curran, T.P., Dodd, V.A., 2006. Odour and ammonia emissions from intensive pig units in Ireland. Bioresour. Technol. 97, 940–948.
Hellmann, B., Zelles, L., Palojarvi, A., Bai, Q.Y., 1997. Emission of climate-relevant trace gases and succession of microbial communities during open-window composting. Appl. Environ. Microbiol. 63, 1011–1018.
Husted, S., 1994. Seasonal variation in methane emission from stored slurry and solid manures. J. Environ. Qual. 23, 585–592.
INRA-AFZ, 2004. Tables De Composition Et De Valeur Nutritive Des Matières Premières Destinées Aux Animaux D'élevage. INRA Editions, Paris France.
IPCC, 2006. IPPC Guidelines for National Greenhouse Gas Inventories. Institute for Global Environmental Strategies, Hayama, Japan.
IPCC, 2007. Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.
Jarret, G., Cerisuelo, A., Peu, P., Martinez, J., Dourmad, J.-Y., 2012. Impact of pig diets with different fibre contents on the composition of excreta and their gaseous emissions and anaerobic digestion. Agric. Ecosyst. Environ. 160, 51–58.
Jarret, G., Martinez, J., Dourmad, J.-Y., 2011. Pig feeding strategy coupled with effluent management – fresh or stored slurry: solid phase separation – on methane potential and methane conversion factors during storage. Atmos. Environ. 45, 6204–6209.
Jeppsson, K.H., 1998. Ammonia emission from different deep-litter materials for growing-finishing pigs. Swed. J. Agric. Res. 28, 197–206.
Jeppsson, K.H., 2000. Carbon dioxide emission and water evaporation from deep litter systems. J. Agric. Eng. Res. 77, 429–440.
Jeppsson, K.H., 2002. Diurnal variation in ammonia, carbon dioxide and water vapour emission from an uninsulated: deep litter building for growing/finishing pigs. Biosyst. Eng. 81, 213–223.
Jiang, T., Schuchardt, F., Li, G.X., Guo, R., Luo, Y.M., 2013. Gaseous emission during the composting of pig feces from Chinese Ganqinfen system. Chemosphere 90, 1545–1551.
Jorgensen, H., Zhao, X.Q., Eggum, B.O., 1996. The influence of dietary fibre and environmental temperature on the development of the gastrointestinal tract digestibility, degree of fermentation in the hind-gut and energy metabolism in pigs. Br. J. Nutr. 75, 365–378.
Jorgensen, H., 2007. Methane emission by growing pigs and adult sows as influenced by fermentation. Livestock Sci. 109, 216–219.
Jorgensen, H., Serena, A., Hedemann, M.S., Knudsen, K.E.B., 2007. The fermentative capacity of growing pigs and adult sows fed diets with contrasting type and level of dietary fibre. Livestock Sci. 109, 111–114.
Kaparaju, P., Rintala, J., 2011. Mitigation of greenhouse gas emissions by adopting anaerobic digestion technology on dairy: sow and pig farms in Finland. Renewable Energy 36, 31–41.
Kebreab, E., Clark, K., Wagner-Riddle, C., France, J., 2006. Methane and nitrous oxide emissions from Canadian animal agriculture: a review. Can. J. Anim. Sci. 86, 135–158.
Kermarrec, C., Robin, P., 2002. Nitrogenous gas emissions during the rearing of pigs on sawdust litter. Journées Rech. Porcine 34, 155–160.
Kotsopoulos, T.A., Karamanlis, X., Dotas, D., Martzopoulos, G.G., 2008. The impact of different natural zeolite concentrations on the methane production in thermophilic anaerobic digestion of pig waste. Biosyst. Eng. 99, 105–111.
Krieter, J., 2002. Evaluation of different pig production systems including economic, welfare and environmental aspects. Archiv fur Tierzucht 45, 223–236.
Kroodsma, W., Tveld, J., Scholtens, R., 1993. Ammonia emission and its reduction from cubicle houses by flushing. Livestock Prod. Sci. 35, 293–302.
Lagadec, S., Landrain, B., Landrain, P., Hassouna, M., Robin, P., 2012. Systèmes d'évacuations fréquentes des déjections Rapport d'étude, Chambres d'agriculture de Bretagne, p. 10.
Lägue, C., Marquis, A., Godbout, S., Legace, R., Fonstad, T.A., Lemay, S.P., Joncas, R., Jaulin, L., 2004. Greenhouse Gas Emissions from Swine Operations in Québec and Saskatchewan: Benchmark Assessments. University of Saskatchewan, Saskatchewan, Canada.
Lavoie, J., Beaudet, Y., Létourneau, C., Godbout, S., Lemay, S., Belzile, M., Lachance, I., Pouliot, F., 2006. Evaluation de la qualité de l'air dans les porcheries équipées d'un système de séparation liquide-solide des déjections, Report R-460; IRSST, Montréal, QC, Canada.
Le Goff, G., Dubois, S., Van Milgen, J., Noblet, J., 2002a. Influence of dietary fibre level on digestive and metabolic utilisation of energy in growing and finishing pigs. Anim. Res. 51, 245–260.
Le Goff, G., Le Groumellec, L., van Milgen, J., Dubois, S., Noblet, J., 2002b. Digestibility and metabolic utilisation of dietary energy in adult sows: influence of addition and origin of dietary fibre. Br. J. Nutr. 87, 325–335.
Le, P.D., Aarnink, A.J.A., Jongbloed, A.W., 2009. Odour and ammonia emission from pig manure as affected by dietary crude protein level. Livestock Sci. 121, 267–274.
Lessard, P., Bourgault, C., LeBihan, Y., Turgeon, N., Aubry, G., Buelna, G., 2009. Treatment of pig slurry by a process of biofiltration: study of formation of methane. Can. J. Civil Eng. 36, 1958–1962.
Lesschen, J.P., van den Berg, M., Westhoek, H.J., Witzke, H.P., Oenema, O., 2011. Greenhouse gas emission profiles of European livestock sectors. Anim. Feed Sci. Technol. 166–167, 16–28.
Li, W., Powers, W., Hill, G.M., 2011. Feeding distillers dried grains with solubles and organic trace mineral sources to swine and the resulting effect on gaseous emissions. J. Anim. Sci. 89, 3286–3299.
Loyon, L., Guiziou, F., Beline, E., Peu, P., 2007. Gaseous emissions (NH_3 N_2O, CH_4 and CO_2) from the aerobic treatment of piggery slurry – comparison with a conventional storage system. Biosyst. Eng. 97, 472–480.
Loyon, L., Guiziou, F., Picard, S., Saint-Cast, P., 2006. Impact of peat and polystyrene ball covers on the ammonia emissions from the storage and spreading of pig slurry: a farm-scale study. DIAS Report, Plant Production, 129–131.
Luth, R.P., Germain, P., Lecomte, M., Landrain, B., Li, Y., Cluzeau, D., 2011. Earthworm effects on gaseous emissions during vermifiltration of pig fresh slurry. Bioresour. Technol. 102, 3679–3686.
Misselbrook, T.H., Chadwick, D.R., Pain, B.F., Headon, D.M., 1998. Dietary manipulation as a means of decreasing N losses and methane emissions and improving herbage N uptake following application of pig slurry to grassland. J. Agric. Sci. 130, 183–191.
Misselbrook, T.H., Powell, J.M., 2005. Influence of bedding material on ammonia emissions from cattle excreta. J. Dairy Sci. 88, 4304–4312.
Moehn, S., Atakora, J., Sands, J., Ball, R., 2007. Effect of phytase–xylanase supplementation to wheat-based diets on energy metabolism in growing–finishing pigs fed ad libitum. Livestock Sci. 109, 271–274.
Moehn, S., Bertolo, R., Pencharz, P., Ball, R., 2004. Pattern of carbon dioxide production and retention is similar in adult pigs when fed hourly, but not when fed a single meal. BMC Physiol. 4, 11.
Moller, H.B., Sommer, S.G., Ahring, B.K., 2004. Biological degradation and greenhouse gas emissions during pre-storage of liquid animal manure. J. Environ. Qual. 33, 27–36.
Monteny, G.J., Bannink, A., Chadwick, D., 2006. Greenhouse gas abatement strategies for animal husbandry. Agric. Ecosyst. Environ. 112, 163–170.
Müller, W., Schneider, B., 1985. Heat: water vapour and CO_2 production in dairy cattle and pig housing. Part 1. Provisional planning data for the use of heat exchangers and heat pumps in livestock housing. Tierärztliche Umschau 40, 274–280.
Ngwabie, N.M., Jeppsson, K.H., Nimmermark, S., Gustafsson, G., 2011. Effects of animal and climate parameters on gas emissions from a barn for fattening pigs. Appl. Eng. Agric. 27, 1027–1037.
Ni, J.Q., Hendriks, J., Coenegrachts, J., Vinckier, C., 1999a. Production of carbon dioxide in a fattening pig house under field conditions I. Exhalation by pigs. Atmos. Environ. 33, 3691–3696.

Ni, J.Q., Vinckier, C., Coenegrachts, J., Hendriks, J., 1999b. Effect of manure on ammonia emission from a fattening pig house with partly slatted floor. Livestock Prod. Sci. 59, 25–31.
Ni, J.-Q., Heber, A.J., Lim, T.T., Tao, P.C., Schmidt, A.M., 2008. Methane and carbon dioxide emission from two pig finishing barns. J. Environ. Qual. 37, 2001–2011.
Nicks, B., 2004. Technical characteristics and environmental aspects of breeding fattening pigs and weaned piglets on accumulated litters. Ann. Méd. Vét. 148, 31–38.
Nicks, B., Laitat, M., Farnir, F., Vandenheede, M., Desiron, A., Verhaeghe, C., Canart, B., 2004. Gaseous emissions from deep-litter pens with straw or sawdust for fattening pigs. Anim. Sci. 78, 99–107.
Nicks, B., Laitat, M., Vandenheede, M., Desiron, A., Verhaeghe, C., Canart, B., 2003. Emissions of ammonia, nitrous oxide, methane, carbon dioxide and water vapor in the raising of weaned pigs on straw-based and sawdust-based deep litters. Anim. Res. 52, 299–308.
Nicks, B., Philippe, F.X., Laitat, M., Farnir, F., Canart, B., Vandenheede, M., 2005. Gaseous emissions in the raising of fattening pigs on fully slatted-floor or on straw-based deep litter. In: Krynski, A., Wrzesien, R. (Eds.), Animal and Environment. ISAH, Warsaw, Poland, pp. 373–377.
Noblet, J., Fortune, H., Shi, X., Dubois, S., 1994. Prediction of net energy value of feeds for growing pigs. J. Anim. Sci. 72, 344–354.
Noblet, J., Dourmad, J.Y., Le Dividich, J., Dubois, S., 1989. Effect of ambient temperature and addition of straw or alfalfa in the diet on energy metabolism in pregnant sows. Livestock Prod. Sci. 21, 309–324.
O'Shea, C.J., Sweeney, T., Lynch, M.B., Gahan, D.A., Callan, J.J., O'Doherty, J.V., 2010. Effect of beta-glucans contained in barley- and oat-based diets and exogenous enzyme supplementation on gastrointestinal fermentation of finisher pigs and subsequent manureodor and ammonia emissions. J. Anim. Sci. 88, 1411–1420.
Oenema, O., Wrage, N., Velthof, G., Groenigen, J.W., Dolfing, J., Kuikman, P., 2005. Trends in global nitrous oxide emissions from animal production systems. Nutr. Cycling Agroecosyst. 72, 51–65.
Olesen, C.S., Jorgensen, H., 2001. Effect of dietary fibre on digestibility and energy metabolism in pregnant sows. Acta Agric. Scand. Sect. A: Anim. Sci. 51, 200–207.
Osada, T., Rom, H.B., Dahl, P., 1998. Continuous measurement of nitrous oxide and methane emission in pig units by infrared photoacoustic detection. Trans. ASAE 41, 1109–1114.
Osada, T., Takada, R., Shinzato, I., 2011. Potential reduction of greenhouse gas emission from swine manure by using a low-protein diet supplemented with synthetic amino acids. Anim. Feed Sci. Technol. 166, 562–574.
Paillat, J.-M., Robin, P., Hassouna, M., Leterme, P., 2005. Predicting ammonia and carbon dioxide emissions from carbon and nitrogen biodegradability during animal waste composting. Atmos. Environ. 39, 6833–6842.
Palkovicova, Z., Knizatova, M., Mihina, S., Broucek, J., Hanus, A., 2009. Emissions of greenhouse gases and ammonia from intensive pig breeding. Folia Vet. 53, 168–170.
Pedersen, S., Blanes-Vidal, V., Jørgensen, H., Chwalibog, A., Haeussermann, A., Heetkamp, M., Aarnink, A., 2008. Carbon dioxide production in animal houses: a literature review. Manuscript BC 08 008.
Pelletier, N., Lammers, P., Stender, D., Pirog, R., 2010. Life cycle assessment of high- and low-profitability commodity and deep-bedded niche swine production systems in the Upper Midwestern United States. Agric. Syst. 103, 599–608.
Pepple, L., Burns, R., Xin H., Li, H., Patience, J., 2011. Ammonia, hydrogen sulfide, and greenhouse gas emissions from wean-to-finish swine barns fed diets with or without DDGS. Agric. Biosyst. Eng. Conference Papers, Posters and Presentations. Paper 138.
Petersen, S.O., Miller, D.N., 2006. Greenhouse gas mitigation by covers on livestock slurry tanks and lagoons. J. Sci. Food Agric. 86, 1407–1411.
Philippe, F.X., Cabaraux, J.F., Laitat, M., Stilmant, D., Wavreille, J., Nicks, B., 2013. Les Impacts Environnementaux Du Choix Des Modalités D'hébergement Des Porcs Charcutiers. University of Liège, Liège, Belgium, and Walloon Agricultural Research Centre, Gembloux, Belgium.
Philippe, F.X., Cabaraux, J.F., Nicks, B., 2011a. Ammonia emissions from pig houses: influencing factors and mitigation techniques. Agric. Ecosyst. Environ. 141, 245–260.
Philippe, F.X., Canart, B., Laitat, M., Wavreille, J., Bartiaux-Thill, N., Nicks, B., Cabaraux, J.F., 2010. Effects of available surface on gaseous emissions from group-housed gestating sows kept on deep litter. Animal 4, 1716–1724.
Philippe, F.X., Canart, B., Laitat, M., Wavreille, J., Vandenheede, M., Bartiaux-Thill, N., Nicks, B., Cabaraux, J.F., 2009. Gaseous emissions from group-housed gestating sows kept on deep litter and offered an ad libitum high-fibre diet. Agric. Ecosyst. Environ. 132, 66–73.
Philippe, F.X., Laitat, M., Canart, B., Farnir, F., Massart, L., Vandenheede, M., Nicks, B., 2006a. Effects of a reduction of diet crude protein content on gaseous emissions from deep-litter pens for fattening pigs. Anim. Res. 55, 397–407.
Philippe, F.X., Laitat, M., Canart, B., Vandenheede, M., Nicks, B., 2007a. Comparison of ammonia and greenhouse gas emissions during the fattening of pigs: kept either on fully slatted floor or on deep litter. Livestock Sci. 111, 144–152.
Philippe, F.X., Laitat, M., Canart, B., Vandenheede, M., Nicks, B., 2007b. Gaseous emissions during the fattening of pigs kept either on fully slatted floors or on straw flow. Animal 1, 1515–1523.
Philippe, F.X., Laitat, M., Nicks, B., Cabaraux, J.F., 2012a. Ammonia and greenhouse gas emissions during the fattening of pigs kept on two types of straw floor. Agric. Ecosyst. Environ. 150, 45–53.
Philippe, F.X., Laitat, M., Vandenheede, M., Canart, B., Nicks, B., 2006b. Comparison of zootechnical performances and nitrogen contents of effluent for fattening pigs kept either on slatted floor or on straw-based deep litter. Ann. Méd. Vét. 150, 137–144.
Philippe, F.X., Laitat, M., Wavreille, J., Bartiaux-Thill, N., Nicks, B., Cabaraux, J.F., 2011b. Ammonia and greenhouse gas emission from group-housed gestating sows depends on floor type. Agric. Ecosyst. Environ. 140, 498–505.
Philippe, F.X., Laitat, M., Wavreille, J., Bartiaux-Thill, N., Nicks, B., Cabaraux, J.F., 2012b. Effets des fibres et du type de sol sur les émissions de gaz à effet de serre et d'ammoniac associées à l'élevage de truies. Journées Rech. Porcine 44, 133–134.
Philippe, F.X., Laitat, M., Wavreille, J., Nicks, B., Cabaraux, J.F., 2014a. Ammonia and greenhouse gases emissions associated to fattening pigs kept either on fully or partly slatted floor. Journées Rech. Porcine 46, 211–212.
Philippe, F.X., Laitat, M., Wavreille, J., Nicks, B., Cabaraux, J.F., 2014b. Effects of the amount of straw on ammonia and greenhouse gases emissions associated to fattening pigs kept on deep litter. Journées Rech. Porcine 46, 213–214.
Philippe, F.X., Remience, V., Dourmad, J.Y., Cabaraux, J.F., Vandenheede, M., Nicks, B., 2008. Food fibers in gestating sows: effects on nutrition behaviour, performances and waste in the environment. INRA Prod. Anim. 21, 277–290.
Pineiro, C., Montalvo, G., Garcia, M.A., Bigeriego, M., 2009. Influence of Soya Bean Meal and Synthetics Amino Acids Prices in the Cost of Nutritional Best Available Techniques in Spain. In: Book of Abstracts of the 60th Annual Meeting of the European Association for Animal Production. Wageningen Academic Publishers, Wageningen, The Netherlands p. 327.
Poth, M., Focht, D.D., 1985. N-15 kinetic-analysis of N_2O production by nitrosomonas-europaea – an examination of nitrifier denitrification. Appl. Environ. Microbiol. 49, 1134–1141.
Quiniou, N., Dubois, S., Noblet, J., 1995. Effect of dietary crude protein level on protein and energy balances in growing pigs: comparison of two measurement methods. Livestock Prod. Sci. 41, 51–61.
Ramonet, Y., van Milgen, J., Dourmad, J.Y., Dubois, S., Meunier-Salaun, M.C., Noblet, J., 2000. The effect of dietary fibre on energy utilisation and partitioning of heat production over pregnancy in sows. Brit. J. Nutr. 84, 85–94.
Rigolot, C., Espagnol, S., Robin, P., Hassouna, M., Beline, F., Paillat, J.M., Dourmad, J.Y., 2010. Modelling of manure production by pigs and NH_3 N_2O and CH_4 emissions. Part II: effect of animal housing, manure storage and treatment practices. Animal 4, 1413–1424.
Robin, P., de Oliveira, P.A., Kermarrec, C., 1999. Ammonia: nitrous oxide and water emissions from pigs housed on several types of litter during the growing period. Journées Rech. Porcine 31, 111–115.
Rodhe, L.K.K., Abubaker, J., Ascue, J., Pell, M., Nordberg, T., 2012. Greenhouse gas emissions from pig slurry during storage and after field application in northern European conditions. Biosyst. Eng. 113, 379–394.
Schrama, J.W., Bosch, M.W., Verstegen, M.W.A., Vorselaars, A., Haaksma, J., Heetkamp, M.J.W., 1998. The energetic value of nonstarch polysaccharides in relation to physical activity in group-housed, growing pigs. J. Anim. Sci. 76, 3016–3023.
Serena, A., Jorgensen, H., Bach Knudsen, K.E., 2008. Digestion of carbohydrates and utilization of energy in sows fed diets with contrasting levels and physico-chemical properties of dietary fiber. J. Anim. Sci. 86, 2208–2216.
Shah, S.B., Kolar, P., 2012. Evaluation of additive for reducing gaseous emissions from swine waste. Agric. Eng. Int.: CIGR J. 14, 10–20.
Sommer, S.G., 2001. Effect of composting on nutrient loss and nitrogen availability of cattle deep litter. Eur. J. Agron. 14, 123–133.
Sommer, S.G., Moller, H.B., 2000. Emission of greenhouse gases during composting of deep litter from pig production – effect of straw content. J. Agric. Sci. 134, 327–335.
Sommer, S.G., Petersen, S.O., Moller, H.B., 2004. Algorithms for calculating methane and nitrous oxide emissions from manure management. Nutr. Cycling Agroecosyst. 69, 143–154.
Sommer, S.G., Petersen, S.O., Sorensen, P., Poulsen, H.D., Moller, H.B., 2007. Methane and carbon dioxide emissions and nitrogen turnover during liquid manure storage. Nutr. Cycling Agroecosyst. 78, 27–36.
Stanier, R.Y., Ingraham, J.L., Wheelis, M.L., Painter, P.R., 1986. The Microbial World, fifth ed. Prentice-Hall, New Jersey.
Steinfeld, H., Gerber, P., Wassenaar, T., Castel, V., Rosales, C., de Haan, C., 2006. Livestock's Long Shadow: Environmental Issues and Options. Food and Agriculture Organization of the United Nations, Rome, Italy.
Stinn, J.P., Xin H., Li, H., Shepherd, T., Burns, R., 2011. Quantification of greenhouse gas and ammonia emissions from a Midwestern swine breeding/gestation/farrowing facility. Agric. Biosyst. Eng. Conference Papers, Posters and Presentations. Paper 203.
Sun, G., Guo, H.Q., Peterson, J., Predicala, B., Lague, C., 2008. Diurnal odor, ammonia, hydrogen sulfide, and carbon dioxide emission profiles of confined swine grower/finisher rooms. J. Air Waste Manage. Assoc. 58, 1434–1448.
Szanto, G.L., Hamelers, H.M., Rulkens, W.H., Veeken, A.H.M., 2007. NH_3: N_2O and CH_4 emissions during passively aerated composting of straw-rich pig manure. Bioresour. Technol. 98, 2659–2670.
Tsukahara, T., Azuma, Y., Ushida, K., 2001. The effect of a mixture of live lactic acid bacteria on intestinal gas production in pigs. Microb. Ecol. Health D 13, 105–110.
Van Milgen, J., Noblet, J., Dubois, S., Bernier, J.F., 1997. Dynamic aspects of oxygen consumption and carbon dioxide production in swine. Br. J. Nutr. 78, 397–410.
Van der Zaag, A.C., Gordon, R.J., Glass, V.M., Jamieson, R.C., 2008. Floating cover to reduce gas emissions from liquid manure storage: a review. Appl. Eng. Agric. 24, 657–671.
van 't Klooster, C., Heitlager, B., 1994. Determination of minimum ventilation rate in pig houses with natural ventilation based on carbon dioxide balance. J. Agric. Eng. Res. 57, 279–287.

Vedrenne, F., Béline, F., Dabert, P., Bernet, N., 2008. The effect of incubation conditions on the laboratory measurement of the methane producing capacity of livestock wastes. Bioresour. Technol. 99, 146–155.
Velthof, G.L., Nelemans, J.A., Oenema, O., Kuikman, P.I., 2005. Gaseous nitrogen and carbon losses from pig manure derived from different diets. J. Environ. Qual. 34, 698–706.
Vergé, X.P.C., Dyer, J.A., Desjardins, R.L., Worth, D., 2009. Greenhouse gas emissions from the Canadian pork industry. Livestock Sci. 121, 92–101.
Vermorel, M., Jouany, J.P., Eugène, M., Sauvant, D., Noblet, J., Dourmad, J.Y., 2008. Evaluation quantitative des émissions de méthane entérique par les animaux d'élevage en 2007 en France. INRA Prod. Anim. 21, 403–418.
Wang, J., Zhu, Y., Li, D., Jørgensen, H., Jensen, B., 2004. The influence of different fiber and starch types on nutrient balance and energy metabolism in growing pigs. Asian-Aust. J. Anim. Sci. 17, 263–270.
Weiss, F., Leip, A., 2012. Greenhouse gas emissions from the EU livestock sector: A life cycle assessment carried out with the CAPRI model. Agric. Ecosyst. Environ. 149, 124–134.
Wolter, M., Prayitno, S., Schuchardt, F., 2004. Greenhouse gas emission during storage of pig manure on a pilot scale. Bioresour. Technol. 95, 235–244.
Yamulki, S., 2006. Effect of straw addition on nitrous oxide and methane emissions from stored farmyard manures. Agric. Ecosyst. Environ. 112, 140–145.
Ye, Z., Zhang, G., Seo, I.H., Kai, P., Saha, C.K., Wang, C., Li, B., 2009. Airflow characteristics at the surface of manure in a storage pit affected by ventilation rate floor slat opening, and headspace height. Biosyst. Eng. 104, 97–105.
Zhang, Q., Zhou, X.J., Cicek, N., Tenuta, M., 2007. Measurement of odour and greenhouse gas emissions in two swine farrowing operations. Can. Biosyst. Eng. 49, 6.13–6.20.

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Review

Climate Change and Livestock Production: A Literature Review

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Abstract: Globally, the climate is changing, and this has implications for livestock. Climate affects livestock growth rates, milk and egg production, reproductive performance, morbidity, and mortality, along with feed supply. Simultaneously, livestock is a climate change driver, generating 14.5% of total anthropogenic Greenhouse Gas (GHG) emissions. Herein, we review the literature addressing climate change and livestock, covering impacts, emissions, adaptation possibilities, and mitigation strategies. While the existing literature principally focuses on ruminants, we extended the scope to include non-ruminants. We found that livestock are affected by climate change and do enhance climate change through emissions but that there are adaptation and mitigation actions that can limit the effects of climate change. We also suggest some research directions and especially find the need for work in developing country settings. In the context of climate change, adaptation measures are pivotal to sustaining the growing demand for livestock products, but often their relevance depends on local conditions. Furthermore, mitigation is key to limiting the future extent of climate change and there are a number of possible strategies.

Keywords: livestock production; adaptation; mitigation

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1. Introduction

Livestock products and services play an important role for humans. Globally, livestock occupy about 26% of the ice-free land with one-third of the cropland being used for feed production [1]. Livestock production generates nearly 40% of global agricultural gross domestic product (GDP). Livestock provide 33% of the global protein and 17% of the global calories consumed. Production creates substantial employment opportunities for rural households [2,3]. Additionally, livestock are a major provider of food, nutritional security, livelihood, and income in developing countries [4].

Driven by population and income growth plus urbanization, the demand for livestock products is growing rapidly. Simultaneously, livestock production is facing increasing pressure from climate change effects, such as increasing temperatures, more variable precipitation patterns, more frequent extreme events, and increasing carbon dioxide concentrations [5]. Such changes have been found to impact livestock performance across many regions and are projected to have growing impacts. Predictive models broadly indicate the impact will be negative [6]. Meanwhile, livestock are a direct source of both methane and nitrous oxide and an indirect source of those gases and carbon through land use and feed production. Globally, the livestock emissions share is an estimated 14.5% of total anthropogenic emissions [7].

The interaction between ongoing climate change and demands for increasing livestock production makes it challenging to increase production while lowering climate impacts and Greenhouse Gas (GHG) emissions. Addressing such challenges requires an understanding of climate change effects on livestock production, as well as the effect of both adaptation and mitigation actions. This paper overviews climate change impacts on livestock production, livestock emissions, and possible adaptation and mitigation actions. In constructing this

review, we relied on material from 157 references, with the papers classified as shown in Table 1.

Table 1. Counts of papers used in the review by category.

Category	Sub-Category	Number of Papers Cited
By topic	Climate change impacts and adaptation	95
	Livestock emissions and mitigation	27
	Comprehensive treatment	31
By year	Before 2000	12
	2000 to 2010	39
	2011 to 2021	102
By region	North America	42
	Europe	14
	Asia	8
	Africa and Australia	8
	Region not specified	40
	Multi-region/global	41
By livestock species	Ruminants	41
	Hogs	15
	Poultry	18
	Not livestock	32
	Multiple livestock	47

2. Impact of Climate Change on Livestock Production

The climate is changing, exhibiting higher temperatures, increasing precipitation variation, and more frequent extremes. This is driven by increasing carbon dioxide (CO_2) concentrations. Such changes have been found to alter livestock and associated feed production. We will follow Collier [8] and broadly divide the impacts into direct and indirect effects: Direct effects refer to climate and CO_2 impacts on livestock thermoregulation, metabolism, immune system function, and production. Indirect effects derive from the influence of climate on feed production, water availability, and pest/pathogen populations. A brief summary of the impacts appears in Table 2. In addition, the impacts are elaborated below.

Table 2. Climate change impacts on livestock production.

Impact Type	Observed Impacts	Major Influential Factors
Direct Impact	Reduced feed intake	Increased temperature (heat stress)
	Decline in animal milk and meat production	
	Decreased reproductive performance	
	Negatively affected immune functions	
	Increased mortality	
Indirect Impact	Changes in feedstuff crop yields	Elevated CO_2 level
	Changes in pasture composition and forage production	
	Changes in forage quality	Increased temperature and elevated CO_2 level
	Shrinking water availability and increasing water use	Increased temperature
	Larger seasonal variation in resource availability	More frequent extreme climate events
	Increased disease, pest, and parasite stress	Increased temperature and changes in the precipitation pattern

2.1. Direct Effects

The thermal environment is the major climatic factor that affects animal production. This involves a combination of air temperature, humidity, and air movement [9]. The relationship describing the best conditions of these is often referred to as the thermal comfort zone. In this zone, animals exhibit optimum performance and minimal energy expenditure [10]. When conditions rise above this zone, extra energy is required to maintain thermoregulation and production processes become less effective [11]. Animals suffer from thermal stress when the environmental temperature deviates outside the thermal comfort zone. The phenotypic response of animals to an individual source of stress can be called acclimation [12,13]. Heat stress is more problematic and has a greater effect than cold stress [14,15]. Climate change is also almost certainly increasing temperatures and, in association, increasing heat stress and lowering cold stress. Therefore, heat stress has been the dominant topic within the discussion of thermal stress.

Heat stress has been found to have negative effects on livestock. The estimated annual U.S. livestock industry loss caused by heat stress falls between $1.7 and $2.4 billion [16]. Heat stress occurs when animals are not able to dissipate sufficient heat to keep homeothermy [17]. This has been found to lead to increased respiration, pulse, and heart rate, along with increased body temperatures [18]. In turn, this can result in reduced feed intake, milk production, and reproduction efficiency, as well as changes in mortality and immune system function. Below, we discuss these impacts in more detail, with emphasis on animal performance rather than underlying biological mechanisms.

2.1.1. Feed Intake

Reduced feed intake is one response to high environmental temperatures. Ruminants experience reduced appetite, gut motility, and rumination under increased heat stress [19,20]. Lactating dairy cows exhibit a reduction in feed intake as ambient temperatures rise above 25–26 °C and show more rapid declines above 30 °C [21]. Goats are less susceptible to heat stress than other ruminants. However, their voluntary feed intake declines when the ambient temperature is more than 10 °C above their thermal comfort zone [22].

Hogs exposed to heat stress exhibit increased body temperature, and their feed intake decreases by 10.9% when temperatures increase from 20 to 35 °C [23]. Such impacts persist beyond the period when the hogs are exposed to heat stress. Hence it is suggested that feeding in early morning hours could help avoid reduced feed intake [24].

Poultry animals also exhibit reduced feed intake when exposed to high temperatures. An increase in ambient temperature from 21.1 to 32.2 °C has been found to lead to a 9.5% drop in feed intake for birds from the post-hatch period to 6 weeks of age [25]. The reduction in feed intake causes decreased feed conversion efficiency and daily weight gain [26–29].

More generally, across all the livestock types, heat-stress-related decreased feed intake leads to decreased milk, meat, and egg production, which in turn leads to further sectoral losses.

2.1.2. Animal Production: Milk and Others

Studies indicate that the dairy industry suffers greater heat-stress-related economic loss than does the other U.S. livestock sectors [16]. Under heat stress, dairy cows reduce feed dry matter intake and this explains approximately 35% of the decrease in milk production [30]. Meanwhile, as high-producing dairy cows are larger and emit more metabolic heat than lower-producing breeds, the most productive breeds exhibit more sensitivity to heat stress [3]. As a consequence, milk production declines as heat-stress-caused metabolic heat production increases [21]. In addition to milk production, hot and humid environments also affect milk composition. Ravagnolo et al. [31] and Gorniak [32] have indicated that lactating cows start to suffer from heat stress at a temperature–humidity index of 72 and above this level, milk protein and milk fat content declines as the index increases.

Similar changes in milk composition have been found for dairy goats [33] and buffaloes [34] but have only been narrowly studied.

Meat production has been found to be affected by heat stress for all major commercial livestock types [35]. Heat-stressed ruminants exhibit reduced body size, carcass weight, and fat thickness and lower meat quality [10,36,37]. Small ruminants, such as goats and sheep, have been found to be more adapted to a hot and humid environment [38]. However, feedlot cattle have been found to be more vulnerable due to their being raised with greater exposure to rough radiant surfaces and fed high-energy diets [35,39].

Similar to ruminants, hogs exhibit reduced carcass weight and meat quality when exposed to a high temperature [40]. Under high ambient temperature, they have also been found to exhibit reduced average daily gain of 9.8% when compared to thermoneutral animals [41].

Chickens exposed to heat stress increase energy expenditure to maintain thermoneutral conditions at the expense of growth [42]. Heat-stressed broilers exhibit reduced weight gain, feed conversion rates, protein concentration, and breast muscle weight [43–45]. For laying hens, egg shell strength, daily feed intake, egg mass, and egg production are more sensitive to heat stress compared to other traits [46]. In addition, significant declines in egg shell quality and egg production are observed in breeders [47]. The reduction in egg quality and production caused by heat stress can be mediated by alterations in dietary calcium [48].

2.1.3. Reproduction

Heat stress affects reproduction for both sexes. For females, heat stress reduces estrous period and fertility while increasing the incidence of anestrous and embryonic death. For males, there are declines in semen quality, testicular volume, and quantity of fertile sperm. Significant seasonal differences in reproductive performance in both sexes have been reported [49].

Although poultry reproduction is also affected by heat stress, birds may exhibit a difference in performance compared to mammals. Male broilers are reported to be more sensitive to heat-related infertility than female broilers [50]. For layers, environmental stress could delay the process of ovulation, reduce yolk quality, and affect hatchability [51].

2.1.4. Disease and Parasite Stress

Many factors, including species, breed, geographical location, disease characteristics, and animal susceptibility, contribute to the effects of climate change on livestock health [52]. In terms of animals themselves, the immune system is their major body defense that protects them from environmental stressors and other noxious insults [53]. Heat stress can negatively affect immune functions via cell-mediated and humoral immune responses [54]. As a result, periods of hot weather can cause livestock to be more vulnerable to diseases and raise the incidence of certain diseases (such as mastitis), leading to an increased potential of morbidity and death [55–57].

In addition, heat stress could affect the health condition of livestock through other functional pathways. For example, growing hogs may suffer from intestinal injuries if exposed to acute heat for several hours [28]. Broilers and laying hens are also reported to experience intestinal microbiota alterations under heat stress [58,59].

Simultaneously, increased temperature and altered precipitation may accelerate the incidence of pathogens and parasites. Although the effect of pathogens and parasites on livestock is generally regarded as an indirect effect, it is covered in this section since it is usually discussed in conjunction with animal health. This would affect the distribution and abundance of vector-borne pests and introduce new diseases [52,60]. These may increase the potential for morbidity/mortality and associated economic loss [61]. Compared to other impacts, climate change effect on livestock disease is more difficult to estimate and predict due to the nature of disease and climate-change-driven alterations to livestock. Such impact assessment is even more challenging in developing countries [52,61].

2.1.5. Mortality

Mortality is an important heat stress impact that has significant associated economic loss. Studies on dairy cows and hogs show that added heat stress increases mortality rates [62–64]. Hot and humid weather has been found to be more life threatening to cows and hogs compared to hot but dry conditions, and a temperature higher than 37.7 °C with over 50% humidity was shown to be detrimental [65].

For poultry, the body temperature of birds is usually higher and more variable than that of mammals and they are more sensitive to rising temperature. Chickens can function normally up to ambient temperature of 27 °C or a body temperature of 41 °C, but an increase of 4 °C in body temperature would be lethal to them [66].

2.2. Indirect Effects

Livestock feed is mostly composed of forages and grain/oilseed crop product. Production of those items is affected by climate, as are water supplies, both through irrigation and soil moisture. Thus climate change indirectly imposes effects, mainly through its impacts on feed supply and water. There exists a huge body of literature focusing on climate change impacts on crop production, and herein we are not trying to cover the details of this research area (for a review, see Reilly et al. [67], Shukla et al. [68], and IPCC [69]). In terms of solely livestock production, crops and forages provide feedstocks consumed by livestock. In this regard, climate change affects the supply of livestock feed but the magnitude of this impact on livestock production while commonly discussed has not been separately evaluated. We discuss the general aspects of this discussion in the remainder of this section.

First, let us introduce some terminology. The International Forage and Grazing Terminology Committee [70] defines forage as "edible parts of plants that can provide feed for grazing animals or that can be harvested for feeding." Forage plants can be roughly divided into two large groups: grasses and legumes. Besides these two groups, forage plants include others, such as woody species. As they are usually not considered as major feed for domestic animals and the impacts of climate change on woody species feed have not been well investigated, we will not cover them in this review. Two relevant studies to refer to are Papanastasis et al. [71] and Hejcman et al. [72]. Legumes can be grouped into cool season (C3) and warm season categories (C4) based on leaf anatomy [73]. Increases in atmospheric CO_2 and temperature are alter forage quantity and quality, with the magnitude dependent on the livestock system [74], location, and species. Precipitation patterns and extreme climate events are also influential, with the main impacts being production variation. Other influential factors include water supplies, which will be discussed in more detail below.

CO_2 contributes to crop growth [75]. C3 crop (soybeans, cotton, and wheat) yields increase under increased CO_2 concentrations, while yields of C4 crops (corn and sorghum) do not directly respond to the elevated CO_2 but may indirectly benefit under drought. Other climatic factors that affect livestock feed supply quantity are precipitation; temperature; and extreme events, such as drought. Increased precipitation is beneficial to corn, sorghum, rice, and soybean [76,77]. As for temperature, C4 species enjoy greater effects from temperature rise, but such effects depend on location, plant species, and production system [52,78]. Drought causes significant crop yield reductions, especially in hot regions [79,80]. A recent study in Europe found that drought stress is the main driver of losses for corn and winter wheat, especially in low-yielding years [81]. These climatic factors are often confounded, and their effects on vegetation growth are not easy to isolate. For example, higher temperatures at lower latitudes may be associated with higher water stress, while higher temperatures at higher latitudes may increase suitability for cropping and expand the length of the growing season.

Grass forage supplies are also affected by climate change. In terms of grassland and pasture, increases in average temperature bring significant changes in pasture composition, patterns, and biome distribution. Changes in precipitation patterns and more frequent droughts may lead to shorter pasture growing periods. Some research has indicated

that changes in temperature, CO_2 levels, and nitrogen deposition decrease the primary production in pasture [82], while some argue that higher temperatures favor grasses over forbs and legumes.

2.2.1. Forage Quality

Adequate nutrition is critical to weight gain, production, and reproduction, and forage is an important nutrition component for ruminants. As forage quality varies greatly within and between forage crops and nutritional needs vary among animal species, providing suitable feed to animals requires a balance. Most forage-quality studies have focused on digestibility, nutritive value, voluntary intake, and effects of anti-quality factors [83]. Forages of higher digestibility supply more energy per unit dry matter (DM) consumed. Nutritive values reported by forage analysis usually include neutral detergent fiber (NDF); acid detergent fiber (ADF); crude protein (CP); and minerals, such as calcium (Ca), phosphorus (P), magnesium (Mg), and potassium (K) [84]. Quality can be affected by climate through increased temperatures and dry conditions, which cause variations in concentrations of water-soluble carbohydrates and nitrogen [82]. Forage quality may also increase due to an increase in nonstructural carbohydrates resulting from elevated CO_2 level [85]. However, quality may also decrease since rising temperatures can increase lignin within plant tissues and therefore reduce digestibility [86]. Lee et al. [87] suggest that increasing temperature reduces forage nutritive values and correspondingly may lead to higher methane production.

2.2.2. Water

Water is scarce worldwide, and the magnitude of water scarcity depends on the supply relative to the demand. Agriculture is the single largest global water user, accounting for 69% of fresh water withdrawals [88]. As human populations, incomes, and livestock product demand increase, water scarcity will likely grow in importance as a constraint on production agriculture. The livestock sector uses water for consumption by animals, growing feed crops, and product processing [52]. It accounts for about 22% of the total evapotranspiration (ET) from global agricultural land and 41% of total consumptive water use [89].

Climate change is projected to change water availability [69,90] and water usage in animal production [3]. Rising temperatures are likely to increase per animal and per land area animal water consumption and irrigation water use [91,92]. Water salination caused by sea-level rise is another concern [93,94]. Competition for water between livestock, crops, and nonagricultural uses will increase in the coming decades, and it requires more efficient production systems to address water scarcity issue [95].

2.2.3. Seasonal Variation and Extreme Climate Events

Climate change may alter the seasonal pattern and variability of resource availability and crop yield [96,97], imposing further impacts on livestock production. As the frequency and duration of heat waves increase, animals will suffer from additional heat stress [62]. Knee et al. [98] found significant seasonal differences in cattle muscle glycogen and also that conditions with nutritious and abundant pastures coincide with better beef quality in spring and that worse pastures coincide with worse beef quality in summer. Moreover, changes in seasonal patterns of forage availability could bring additional challenges for grazing management and livestock management [99]. Increasing risk of extreme drought threatens forage quantity, and adaptation strategies are required to cope with such extreme events [100]. In addition, changes in snow melt timing alter water availability patterns during the year, which affects feed supplies [96,101].

3. Impact of Livestock Production on GHG Emissions

Livestock is a substantial contributor to global GHGs, with emissions estimated at 8.1 gigatons of CO_2-eq per annum or 14.5% of total anthropogenic emissions [7]. The three

main GHGs emitted by livestock are methane (CH_4), nitrous oxide (N_2O), and carbon dioxide (CO_2). Their relative incidence has been explored using the FAO Global Livestock Environmental Assessment Model (GLEAM) [102] and are converted to CO_2 equivalents using 100-year global warming potentials from IPCC (2014) (298 for N_2O and 34 for CH_4).

The GLEAM results indicate that emissions from livestock supply chains consist of 50% methane (CH_4), 24% nitrous oxide (N_2O), and 26% carbon dioxide (CO_2), with emissions by category shown in Figure 1. In terms of species, cattle are the major contributor, with about 62% of total livestock emissions. Other species (hogs, poultry, buffaloes, and small ruminants) each represent between 7 and 11% of the sector's emissions. Within cattle, beef and dairy animals generate similar amounts of total emissions. Figure 2 shows the global estimates of livestock emissions by species.

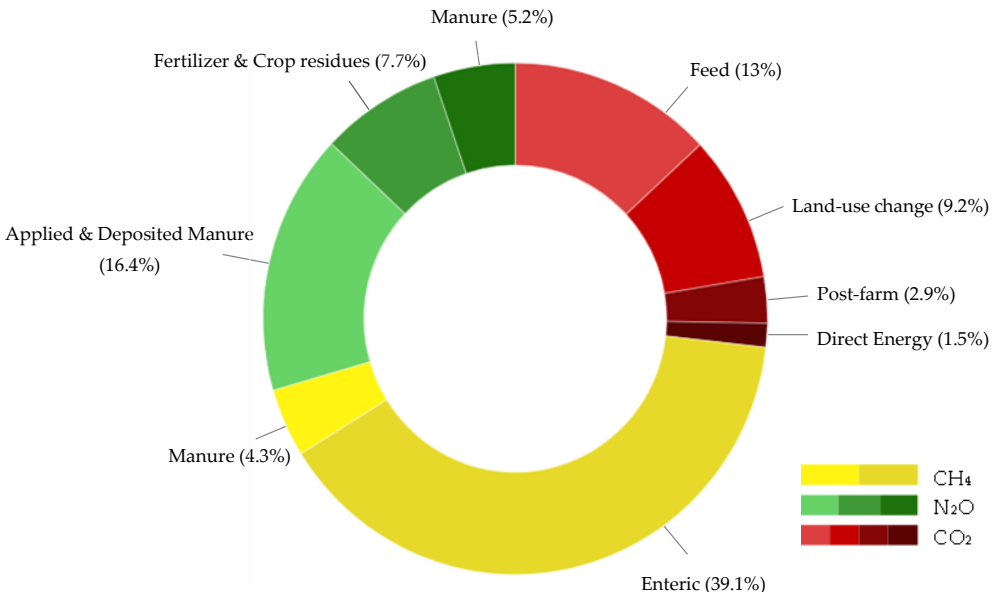


Figure 1. Emissions from livestock (by category), where methane (CH_4) emissions are portrayed in yellow, nitrous oxide (N_2O) in green, and carbon dioxide (CO_2) in red. Figure drawn by authors with data source from [7].

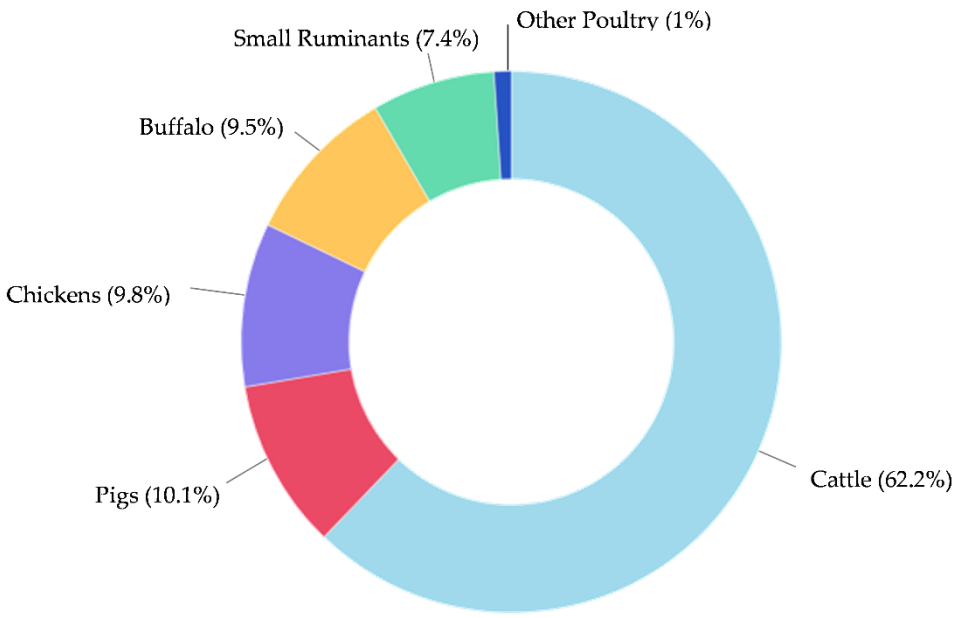


Figure 2. Emissions from livestock (by species). Figure drawn by authors with data source from [102].

Livestock GHG emissions arise directly through raising animals, including enteric fermentation, manure, and associated energy consumption. Indirect emissions mainly come from feed production and related land use change. Some studies indicate that indirect emissions exceed direct emissions, while others show the opposite [103,104].

3.1. Direct Effects: Enteric Fermentation and Manure Management

Enteric fermentation occurs mainly within ruminant animals' digestive systems, where microbes break down coarse plant materials and, in the process, produce methane, which is emitted by exhaling, belching, and other means. This is the largest ruminant emission source [105]. Non-ruminants also produce methane during digestion but in much smaller amounts. A variety of factors affect ruminant emission quantity, such as feed characteristics, use of feed additives, and animal health condition. The most influential ones are feed quality and feed intake. Higher feed digestibility leads to lower enteric methane emission and higher animal production. Increased feed intake leads to more methane being produced. The rate of conversion from feed energy intake to methane depends on species, production systems, and regional characteristics [7].

Manure also contributes to emissions in the form of methane and nitrous oxide (N_2O) emissions. The anaerobic decomposition of organic material releases methane, and nitrous oxide is released mainly from ammonia decomposition. Organic matter and nitrogen content in manure are the two chemical components that can lead to N_2O emissions during storage and processing [104]. Hogs and dairy cows are the largest source of manure-related methane emissions [106]. The largest manure-related N_2O emissions come from soil emissions associated with manure application [103]. The manure storage and handling process greatly affects resultant emissions, particularly when manure is handled in ponds or lagoons [106]. Other factors that affect manure emissions include air temperature, moisture, duration of waste management, and animal diet. If manure is handled through solid systems (e.g., deposited on pastures), N_2O emissions will be higher than methane since the generation of N_2O requires both aerobic and anaerobic conditions. Methane emissions are higher when manure is treated in liquid systems using lagoons or ponds.

3.2. Indirect Effects: Feed Production and Land Use Change

3.2.1. Feed Production

Emissions related to feed production, processing, and transport constitute about 45% of livestock-related emissions. Of all these feed-related emissions, N_2O from fertilization of feed crops and CH_4 from manure application to pasture generate about 50%, while related land use change generates about 25% [7]. Emissions from feed production consists of CO_2, N_2O, and CH_4. CO_2 emission arises from the production of fertilizers and pesticides for feed crops, feed transportation and processing, fuel used in production, and associated land use change. N_2O emissions are mainly from fertilizer use and manure application, with a small portion coming from the cultivation of leguminous feed crops (e.g., rice, soybeans, peas, alfalfa, and clover). The amount of feed-related CH_4 emissions is much smaller than that of feed-related CO_2 and N_2O emissions.

3.2.2. Land Use Change

Land use change is another indirect source of livestock-related GHG emissions. Gerber et al. [7] calculated that land use change contributes 9.2% of total livestock GHG emissions. This occurs through land use change to produce pasture (6%) and feed crops (3.2%). Agricultural land occupies 38% of the global land surface, with about two-thirds of this for livestock [107]. Driven by population growth, urbanization, and growing incomes, the demand for livestock and livestock products is expected to increase, inducing more livestock production. By 2050 compared to 2005/2007, world meat production is projected to increase by 76% and milk by 63% [108]. Associated with this, grazing intensities are projected to increase by about 70%, with feed demand almost doubled [109].

Historically, increased production of livestock and livestock feed has significantly impacted land use, which affects the natural carbon cycle [3]. Plants take CO_2 from the atmosphere and nitrogen (N) from the soil and store them in above- and below-ground biomass. Forest lands sequester more carbon in soil and vegetation than croplands and pastures, and thus when forest land is converted to cropland and pasture, much of the sequestered carbon is released into the atmosphere.

There is debate on appropriate procedures for accounting for emissions from land-use change, and there is no current shared consensus. Different scale and land-use change factors result in significantly different results. [110]. Steinfeld et al. [103] estimated that deforestation due to the expansion of pasture and feed crops is responsible for 8% of total anthropogenic CO_2 emissions. Hong et al. [111] estimated that land-use emissions accounted for 27% of global total anthropogenic GHG emissions during the 1970—2017 period.

3.2.3. Energy Consumption

Energy consumption is another source of CO_2 emissions, mainly related to fossil fuel use. For livestock, energy-related emissions occur across the supply chain spanning from production of fertilizers, use of machinery, and transport of feed and livestock. On-the farm animal-related energy includes that used for heating/cooling, ventilation, illumination, and milking. Upstream feed production uses energy in production, drying, and commodity transport. Downstream energy is used in processing livestock commodities and packing and transporting final products to retailers. The total energy consumption along the livestock supply chain contributes about 25% of total emissions in the livestock sector [7].

4. Adaptation

Climate change adaptation refers to adjustment in ecological, social, or economic systems to reduce the negative or enhance the positive impacts of climate change. In an agricultural setting, adaptation can occur through ecological change or human action. For livestock, natural adaptation results from different mechanisms through which animals adapt to climatic conditions. Human adaptation involves actions and practices that could help animals adapt to climate change and enhance the livestock performance. In a livestock context, adaptation actions can be divided into three broad classifications: animal responses, management actions, and resource [112].

4.1. Animal Responses

Animals can adapt through physiological, biochemical, immunological, anatomical, and behavioral responses [113]. Herein, we focus on behavioral responses. For details on other animal adaption mechanisms, see Gaughan et al. [112].

Commonly observed responses to heat stress include reduced feed intake, shade seeking, increased sweating and panting, increased water intake and drinking frequency, increased standing time and decreased lying time, and reduced defecation and urination frequency.

It is noteworthy that domestic animals are rarely exposed to a single stress. Besides heat stress, under feeding, lack of water, and poor nutrition may occur together. The cumulative effects of multiple stressors may be multiplicative rather than additive [112]. Animals may not be able to fully adapt to climate stressors by themselves, and thus producers may need to help in order to sustain livestock production and profitability. However, one should note that climate change can be so large that it may not be possible overcome an effect and in such cases, more extreme actions, such as changes in land use, species, or abandonment, may be in order [114].

4.2. Human Adaptation Strategies

Human adaptation strategies involve breeding, production/management system modifications, and institutional and policy changes. Table 3 presents a brief summary of livestock management adaptation strategies, and a detailed discussion follows.

Table 3. Summary of human adaptation strategies.

Animal Genetics
•Choose species that are more heat-tolerant •Genetic selection to changed conditions
Physical modification
•Provide shade and sprinklers for outdoor animals •Improve/supply cooling systems indoors
Feed and pest management
•Modify diet composition and feeding time •Supplemental feeding •Adoption of integrated pest management
Livestock system
•Diversify livestock species •Adjust stocking rate •Integrate livestock system with forestry or crops

4.2.1. Animal Genetics

Breed selection has traditionally been used to improve livestock production efficiency and has facilitated a massive increase in livestock production. However, current species selected for higher production in some cases have higher metabolic heat production and hence can be more susceptible to heat stress [115]. As future climate is predicted to be hotter, with more frequent heat extremes, breeding techniques and breed type selection can also be an adaptation action. Genetic variation in heat stress response in livestock species has been observed and measured [116,117]. Some breeds are less affected by heat stress, such as smaller, lighter-colored animals [118], or breeds can show great physical and physiological adaptation to heat stress. If such trait is heritable, selective breeding for heat tolerance could be used to improve animal adaptation to climatic stress [119,120]. Producers can switch breeds, for example, using more Bos indicus cattle [121,122].

4.2.2. Physical Modification

Physical modification of the environment can also be undertaken and can be broadly divided into two groups: outdoor and indoor.

For animals kept outdoors on grasslands or pasture, one cost-effective adaptation method is shade provision. This lowers exposure to solar radiation and reduces heat stress [39,123]. Sprinklers and misters could also help to decrease body temperatures [124], and they are more effective in drier weather. Huynh [125] suggested the use of a combination of different methods as there exist interaction effects. For example, the combination of sprinkling and a covered pen without an outdoor yard leads to higher daily gain for hogs than the provision of sprinkling alone.

For livestock kept indoors, in buildings, physical modification options can involve use or addition of (1) ventilation systems, (2) heat reducing building materials (e.g., insulation and orientation), and (3) forced air velocity, fogging, misting, sprinkling, and pad cooling [126]. Air conditioning and pad cooling have been found to have the best performance

in terms of lowering heat stress [126], but the high initial investment and operating expense might make them impractical [127].

4.2.3. Feed and Pest Management

Feeding practices can be used to improve animal performance under heat stress. These involve modification of diet composition, changes in feeding time and/or frequency, and water management [120]. These practices help alleviate heat stress through increasing energy content, increasing nutrient and electrolytes or certain minerals intake, and maintaining water balance. Feeding modifications in cattle [128,129], hogs [130–132], and poultry [66,133,134] have all been investigated, and the general effect is positive.

Pest management has not been fully discussed as livestock adaptation, although researchers have noticed that future changes in precipitation patterns may affect the spread and quantity of some vector-borne pests [52]. There are several concerns related to livestock pest management. First, some pests will develop resistance to insecticides and drugs in a short time, which would limit the effectiveness of insecticides or drugs. Thus, in practice, it is suggested to use the rotation of insecticides with different modes of action [135]. Second, high-density or confined systems can encourage pests and disease outbreak, with poultry in particular suffering a lot from pest problems [136]. Third, drug residues in animal products due to inappropriate use of pesticides may be a potential threat to public health [137]. As a result of these considerations, integrated pest management is needed [138], as well as improved techniques in pesticides.

4.2.4. Livestock Management System

Livestock management adaptations can involve one or more of the following strategies:

(1) Diversification of livestock species: Multi-species farming enhances the producer's ability to cope with a changing climate and the associated change in rangeland conditions and can also improve the sustainability of livestock farms [139,140].
(2) Adjustment in stocking rates: Díaz-Solís et al. [141] found that adjusting stocking rate can be used to reduce the effect of drought on cow-calf in Mexican state of Coahuila. Mu et al. [142] found that in the U.S., the stocking rate of cattle decreases as THI increases and precipitation increases in summer.
(3) Integration of livestock system with forestry or crops: Because of their positive synergistic effects on soil properties and nutrient cycling, mixed crop–livestock or forestry–livestock can help with soil degradation, reduce chemical use, and generate economies of scale at the farm level [143,144].

5. Mitigation

There are mitigation measures that reduce livestock GHG emissions. Gerber et al. [7] indicated that livestock emission intensities vary greatly between production systems and regions and the mitigation potential lies in the gap between the management techniques that result in the lowest and highest emission intensities. They estimated that the emissions from the livestock sector can be reduced by 18% if producers in a given system, region, and climate adopt the practices currently applied by the top 25% of producers with the lowest emission intensity and 30% if using techniques employed by the top 10%. We summarize many potential mitigation options in Table 4 and discuss them below.

5.1. Land Resource Management

Substantial livestock mitigation lies in livestock management and land use. Thornton et al. [145] estimated that the maximum mitigation potential from livestock and pasture management is approximately 7% of the global agriculture mitigation potential to 2030. Possible strategies involve adoption of improved pastures, intensification of ruminant diets, changes in ruminant breeds, reductions in stocking rate, and lowering grazing intensity. Havlík et al. [146] indicated that significant emission reduction could be achieved through transitions to more efficient and less land-demanding livestock systems. They also found

that mitigation policies targeting land-use-change-related emissions are 5–10 times more efficient than policies targeting emissions from livestock only.

Table 4. Summary of mitigation strategies.

Land resource management
•Improve grazing management •Alter grazing intensity and or manure use to enhance Carbon sequestration
Enteric fermentation management
•Modify diet and nutrition for livestock • Genetic selection
Manure management
•Alter storage practices •Modify diet and nutrition for livestock
Fertilizer management
•Increase nitrogen efficiency •Offest commerial nitrogen use by using manure

Another land-use-related mitigation category deals with carbon sequestration, which mainly relates to feed crop production. Carbon sequestering actions include using conservation tillage, selecting to produce higher yielding crops, reducing deforestation, converting cropland to grassland, and improving grass species [3,103].

5.2. Enteric Fermentation Management

As discussed above, enteric fermentation is the main source of ruminant methane emissions. This emission source can be reduced through dietary management and genetics. Knapp et al. [147] found that nutrition and feeding strategies such as improving forage digestibility can reduce enteric methane emission by 2.5–15% per unit of milk produced and that more significant reductions can be achieved if combined with genetic and management approaches. Feed additives and supplements, such as antibiotics, lipids, grain, and ionophores, have also been shown to decrease enteric methane emissions [105,148].

5.3. Manure Management

Livestock manure generates both N_2O and CH_4 emissions, and most of these are related to storage and handling methods [3]. Altered manure storage practices can reduce manure GHG emissions. These include shortened storage duration, lowered storage temperature, solid–liquid separation, and less use of water [149,150]. Anaerobic digestion processes, in which microorganisms break down manure in the absence of oxygen, produce a mixture of biogas (mainly CH_4 and CO_2) and digestate that can be captured and used as bioenergy to generate heat or electricity. This also indirectly reduces GHG emissions by replacing emission-intensive fossil energy and by changing the composition of emissions from the traditional combination of N_2O and CH_4 into a combination of CO_2 and CH_4 [151]. Anaerobic digestion can lead to an over 30% reduction in GHG emissions compared to traditional manure treatment [152]. Dietary adjustment for animals can also be used to reduce manure emission as it could change the volume and composition of the manure.

5.4. Fertilizer Management

Fertilizer application in feed crop production contributes N_2O emissions attributable to the livestock sector. Associated mitigation strategies aim at increasing nitrogen application efficiency. Possible measures include the use of time-released nitrogen, precision application, organic fertilizers, plant breeding, genetic modifications, and changes in plant species [153,154]. However, it is complex to calculate the mitigation potential of increasing fertilizer efficiency on animal feed production, and this leaves a gap for future studies to discover.

Another possible practice related to reducing emission from feed production involves shifts in types of livestock feed. Pikaar et al. [155] analyzed the potential of using microbial proteins (MP) as a feed replacement, finding that it can replace 10–19% of conventional crop-based animal feed protein demand, which leads to a reduction by 7% in agricultural greenhouse gas emission.

6. Discussion

On the one hand, climate change can affect livestock production directly through increased heat stress and indirectly through impacts on the quantity and quality of forage and crop-based feeds, as well as land and water availability. Associated adaptation strategies could target direct animal responses, by adjusting their living environment and feed, or focus on the modification of production and management systems.

On the other hand, livestock production influences climate change by contributing to 14.5% of the global anthropogenic GHG emissions. Mitigation strategies from the livestock side could help address enteric emissions and improve manure management, along with more emission efficient feed production through reduced use of N-fertilizer and land carbon sequestration. Figure 3 provides an overview of the major impacts, emission types, and actions covered in this review.

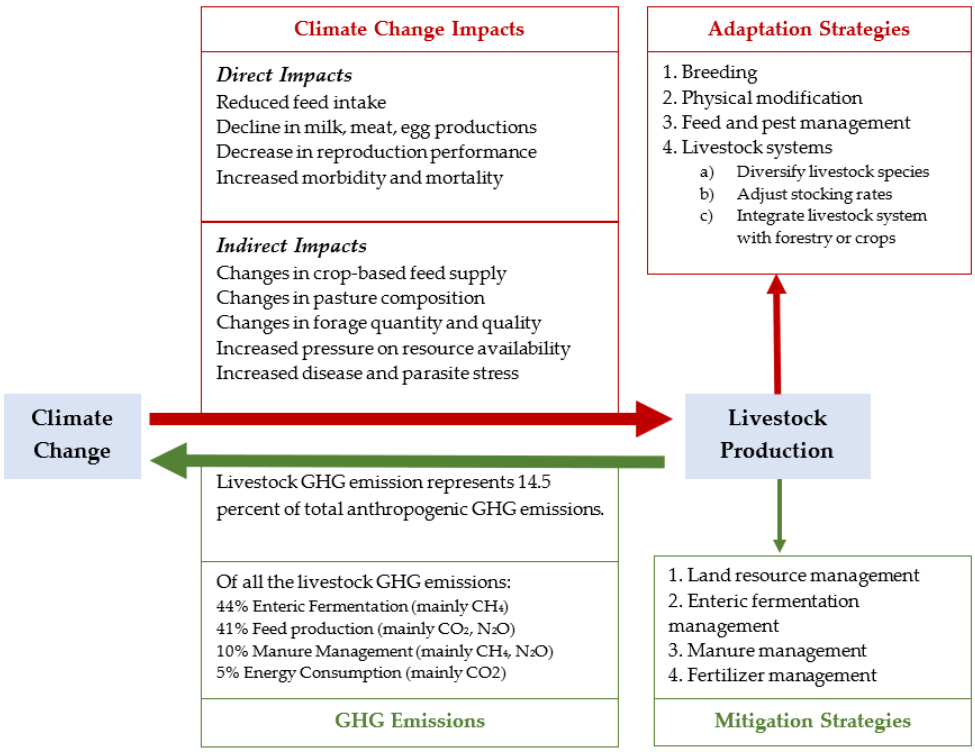


Figure 3. An overview of the relationship between climate change and livestock production.

Despite the numerous studies carried out in this field, there remain a number of research gaps. First, the literature mainly focuses on ruminants, with less coverage of other

species, such as hogs and poultry. These animals are also affected, and their productivity may even be more affected than that of ruminants [13]. Considering emissions on the basis of the per-unit protein produced, chicken meat, eggs, and pork have lower emission intensities compared to beef meat, and this could be exploited as a mitigation strategy [102]. Thus, research on non-ruminants is needed. Second, current publications have a strong focus on grassland-based livestock systems, while a mixed crop–livestock system produces half of the world's food and supports a large number of households in developing regions [156]. This additional research is needed on livestock in such production systems. Third, adaptation and mitigation strategies are not universally applicable, being place, species, and context specific. In addition, some options are too costly or resource intensive to be applied in a number of settings and the strategy potential is limited by the dietary needs for milk, meat, and eggs and by local conditions in terms of income, awareness of climate change impacts, experience, loan terms, and many other factors [157]. Research is needed to identify locally appropriate mitigation and adaptation strategies, especially in the context of developing countries, as well as policy approach for encouraging and implementing adoption. For doing this, better data, methods, and coverage are needed.

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References

1. Food and Agriculture Organization of the United Nations (FAO). Livestock and Landscapes: Sustainability Pathways. *Food and Agriculture Organizations of the United Nations*. Available online: https://www.fao.org/3/ar591e/ar591e.pdf (accessed on 3 November 2021).
2. Thornton, P.K. Livestock production: Recent trends, future prospects. *Philos. Trans. R. Soc. B Biol. Sci.* **2010**, *365*, 2853–2867. [CrossRef] [PubMed]
3. Rojas-Downing, M.M.; Nejadhashemi, A.P.; Harrigan, T.; Woznicki, S.A. Climate change and livestock: Impacts, adaptation, and mitigation. *Clim. Risk Manag.* **2017**, *16*, 145–163. [CrossRef]
4. Swanepoel, F.J.C.; Stroebel, A.; Moyo, S. The Role of Livestock in Developing Communities: Enhancing Multifunctionality. University of the Free State and CTA. 2010. Available online: https://cgspace.cgiar.org/handle/10568/3003 (accessed on 9 August 2021).
5. Intergovernmental Panel on Climate Change. *Climate Change 2014: Mitigation of Climate Change*; Cambridge University Press: New York, NY, USA, 2014.
6. Escarcha, J.; Lassa, J.; Zander, K. Livestock under climate change: A systematic review of impacts and adaptation. *Climate* **2018**, *6*, 54. [CrossRef]
7. Gerber, P.J.; Steinfeld, H.; Henderson, B.; Mottet, A.; Opio, C.; Dijkman, J.; Falcucci, A.; Tempio, G. Tackling Climate Change through Livestock: A Global Assessment of Emissions and Mitigation Opportunities. 2013. Available online: https://www.cabdirect.org/cabdirect/abstract/20133417883 (accessed on 5 August 2021).
8. Collier, R.J.; Baumgard, L.H.; Zimbelman, R.B.; Xiao, Y. Heat stress: Physiology of acclimation and adaptation. *Anim. Front.* **2019**, *9*, 12–19. [CrossRef]
9. Ames, D. Thermal Environment Affects Production Efficiency of Livestock. *BioScience* **1980**, *30*, 457–460. [CrossRef]
10. Nardone, A.; Ronchi, B.; Lacetera, N.; Bernabucci, U. Climatic Effects on Productive Traits in Livestock. *Vet. Res. Commun.* **2006**, *30*, 75–81. [CrossRef]
11. Bianca, W. The signifiance of meteorology in animal production. *Int. J. Biometeorol.* **1976**, *20*, 139–156. [CrossRef]
12. Fregly, M.J. Adaptations: Some General Characteristics. In *Comprehensive Physiology*; American Cancer Society: Atlanta, GA, USA, 2011; pp. 3–15. Available online: https://onlinelibrary.wiley.com/doi/abs/10.1002/cphy.cp040101 (accessed on 1 September 2021).
13. Nardone, A.; Ronchi, B.; Lacetera, N.; Ranieri, M.S.; Bernabucci, U. Effects of climate changes on animal production and sustainability of livestock systems. *Livest. Sci.* **2010**, *130*, 57–69. [CrossRef]
14. Collier, R.J.; Beede, D.K.; Thatcher, W.W.; Israel, L.A.; Wilcox, C.J. Influences of Environment and Its Modification on Dairy Animal Health and Production. *J. Dairy Sci.* **1982**, *65*, 2213–2227. [CrossRef]

15. Maibam, U.; Hooda, O.K.; Sharma, P.S.; Upadhyay, R.C.; Mohanty, A.K. Differential level of oxidative stress markers in skin tissue of zebu and crossbreed cattle during thermal stress. *Livest. Sci.* **2018**, *207*, 45–50. [CrossRef]
16. St-Pierre, N.R.; Cobanov, B.; Schnitkey, G. Economic losses from heat stress by US livestock industries. *J. Dairy Sci.* **2003**, *86*, E52–E77. [CrossRef]
17. Daramola, J.O.; Abioja, M.O.; Onagbesan, O.M. Heat Stress Impact on Livestock Production. In *Environmental Stress and Amelioration in Livestock Production*; Sejian, V., Naqvi, S.M.K., Ezeji, T., Lakritz, J., Lal, R., Eds.; Springer: Berlin/Heidelberg, Germany, 2012; pp. 53–73. [CrossRef]
18. Rashamol, V.P.; Sejian, V.; Bagath, M.; Krishnan, G.; Archana, P.R.; Bhatta, R. Physiological Adaptability of Livestock to Heat Stress: An Updated Review. Periodikos. 2018. Available online: http://www.jabbnet.com/journal/jabbnet/article/doi/10.31893/2318-1265jabb.v6n3p62-71 (accessed on 20 July 2021).
19. Baile, C.A.; Forbes, J.M. Control of feed intake and regulation of energy balance in ruminants. *Physiol. Rev.* **1974**, *54*, 160–214. [CrossRef]
20. Yadav, B.; Singh, G.; Verma, A.K.; Dutta, N.; Sejian, V. Impact of heat stress on rumen functions. *Vet. World* **2013**, *6*, 992–996. [CrossRef]
21. Kadzere, C.T.; Murphy, M.R.; Silanikove, N.; Maltz, E. Heat stress in lactating dairy cows: A review. *Livest. Prod. Sci.* **2002**, *77*, 59–91. [CrossRef]
22. Lu, C.D. Effects of heat stress on goat production. *Small Rumin. Res.* **1989**, *2*, 151–162. [CrossRef]
23. Lopez, J.; Jesse, G.W.; Becker, B.A.; Ellersieck, M.R. Effects of temperature on the performance of finishing swine: I. Effects of a hot, diurnal temperature on average daily gain, feed intake, and feed efficiency. *J. Anim. Sci.* **1991**, *69*, 1843–1849. [CrossRef]
24. Cervantes, M.; Antoine, D.; Valle, J.A.; Vásquez, N.; Camacho, R.L.; Bernal, H.; Morales, A. Effect of feed intake level on the body temperature of pigs exposed to heat stress conditions. *J. Therm. Biol.* **2018**, *76*, 1–7. [CrossRef]
25. Syafwan, S.; Kwakkel, R.P.; Verstegen, M.W.A. Heat stress and feeding strategies in meat-type chickens. *World's Poult. Sci. J.* **2011**, *67*, 653–674. [CrossRef]
26. Lacetera, N.; Bernabucci, U.; Ronchi, B.; Nardone, A. Physiological and productive consequences of heat stress. The case of dairy ruminants. In Proceedings of the Symposium on interaction between Climate and Animal Production: EAAP Technical Series, Viterbo, Italy, 4 September 2003; pp. 45–60.
27. Parkhurst, C.; Mountney, G.J. *Poultry Meat and Egg Production*; Springer Science & Business Media: Berlin/Heidelberg, Germany, 2012; 307p.
28. Pearce, S.C.; Sanz-Fernandez, M.V.; Hollis, J.H.; Baumgard, L.H.; Gabler, N.K. Short-term exposure to heat stress attenuates appetite and intestinal integrity in growing pigs. *J. Anim. Sci.* **2014**, *92*, 5444–5454. [CrossRef]
29. Herbut, P.; Angrecka, S.; Godyń, D.; Hoffmann, G. The physiological and productivity effetcts of heat stress in cattle—A review. *Ann. Anim. Sci.* **2019**, *19*, 579–594. [CrossRef]
30. Rhoads, M.; Rhoads, R.; VanBaale, M.J.; Collier, R.; Sanders, S.R.; Weber, W.J.; Crooker, B.A.; Baumgard, L.H. Effects of heat stress and plane of nutrition on lactating Holstein cows: I. Production, metabolism, and aspects of circulating somatotropin. *J. Dairy Sci.* **2009**, *92*, 1986–1997. [CrossRef]
31. Ravagnolo, O.; Misztal, I.; Hoogenboom, G. Genetic component of heat stress in dairy cattle, development of heat index function. *J. Dairy Sci.* **2000**, *83*, 2120–2125. [CrossRef]
32. Gorniak, T.; Meyer, U.; Südekum, K.-H.; Dänicke, S. Impact of mild heat stress on dry matter intake, milk yield and milk composition in mid-lactation Holstein dairy cows in a temperate climate. *Arch. Anim. Nutr.* **2014**, *68*, 358–369. [CrossRef]
33. Salama, A.A.K.; Contreras-Jodar, A.; Love, S.; Mehaba, N.; Such, X.; Caja, G. Milk yield, milk composition, and milk metabolomics of dairy goats intramammary-challenged with lipopolysaccharide under heat stress conditions. *Sci. Rep.* **2020**, *10*, 5055. [CrossRef]
34. Seerapu, S.R.; Kancharana, A.R.; Chappidi, V.S.; Bandi, E.R. Effect of microclimate alteration on milk production and composition in Murrah buffaloes. *Vet World* **2015**, *8*, 1444–1452. [CrossRef] [PubMed]
35. Gonzalez-Rivas, P.A.; Chauhan, S.S.; Ha, M.; Fegan, N.; Dunshea, F.R.; Warner, R.D. Effects of heat stress on animal physiology, metabolism, and meat quality: A review. *Meat Sci.* **2020**, *162*, 108025. [CrossRef]
36. Elam, N.A.; Vasconcelos, J.T.; Hilton, G.; VanOverbeke, D.L.; Lawrence, T.E.; Montgomery, T.H.; Montgomery, T.H.; Nichols, W.T.; Streeter, M.N.; Hutcheson, J.P.; et al. Effect of zilpaterol hydrochloride duration of feeding on performance and carcass characteristics of feedlot cattle1. *J. Anim. Sci.* **2009**, *87*, 2133–2141. [CrossRef] [PubMed]
37. Summer, A.; Lora, I.; Formaggioni, P.; Gottardo, F. Impact of heat stress on milk and meat production. *Anim. Front.* **2019**, *9*, 39–46. [CrossRef] [PubMed]
38. Berihulay, H.; Abied, A.; He, X.; Jiang, L.; Ma, Y. Adaptation Mechanisms of Small Ruminants to Environmental Heat Stress. *Animals* **2019**, *9*, 75. [CrossRef]
39. Silanikove, N. Effects of heat stress on the welfare of extensively managed domestic ruminants. *Livest. Prod. Sci.* **2000**, *67*, 1–18. [CrossRef]
40. Pearce, S.C.; Gabler, N.K.; Ross, J.W.; Escobar, J.; Patience, J.F.; Rhoads, R.P.; Baumgard, L.H. The effects of heat stress and plane of nutrition on metabolism in growing pigs. *J. Anim. Sci.* **2013**, *91*, 2108–2118. [CrossRef]
41. da Fonseca de Oliveira, A.C.; Vanelli, K.; Sotomaior, C.S.; Weber, S.H.; Costa, L.B. Impacts on performance of growing-finishing pigs under heat stress conditions: A meta-analysis. *Vet. Res. Commun.* **2019**, *43*, 37–43. [CrossRef]

42. Zaboli, G.; Huang, X.; Feng, X.; Ahn, D.U. How can heat stress affect chicken meat quality?—A review. *Poult. Sci.* **2019**, *98*, 1551–1556. [CrossRef]
43. Song, D.J.; King, A.J. Effects of heat stress on broiler meat quality. *World's Poult. Sci. J.* **2015**, *71*, 701–709. [CrossRef]
44. Zhang, Z.Y.; Jia, G.Q.; Zuo, J.J.; Zhang, Y.; Lei, J.; Ren, L.; Feng, D.Y. Effects of constant and cyclic heat stress on muscle metabolism and meat quality of broiler breast fillet and thigh meat. *Poult. Sci.* **2012**, *91*, 2931–2937. [CrossRef]
45. Shakeri, M.; Cottrell, J.J.; Wilkinson, S.; Ringuet, M.; Furness, J.B.; Dunshea, F.R. Betaine and Antioxidants Improve Growth Performance, Breast Muscle Development and Ameliorate Thermoregulatory Responses to Cyclic Heat Exposure in Broiler Chickens. *Animals* **2018**, *8*, 162. [CrossRef]
46. Mignon-Grasteau, S.; Moreri, U.; Narcy, A.; Rousseau, X.; Rodenburg, T.B.; Tixier-Boichard, M.; Zerjal, T. Robustness to chronic heat stress in laying hens: A meta-analysis. *Poult. Sci.* **2015**, *94*, 586–600. [CrossRef]
47. Oguntunji, A.O.; Alabi, O.M. Influence of high environmental temperature on egg production and shell quality: A review. *World's Poult. Sci. J.* **2010**, *66*, 739–750. [CrossRef]
48. He, S.P.; Arowolo, M.A.; Medrano, R.F.; Li, S.; Yu, Q.F.; Chen, J.Y.; He, J. Impact of heat stress and nutritional interventions on poultry production. *World's Poult. Sci. J.* **2018**, *74*, 647–664. [CrossRef]
49. Ross, J.W.; Hale, B.J.; Seibert, J.T.; Romoser, M.R.; Adur, M.K.; Keating, A.F.; Baumgard, L.H. Physiological mechanisms through which heat stress compromises reproduction in pigs. *Mol. Reprod. Dev.* **2017**, *84*, 934–945. [CrossRef]
50. Nawab, A.; Ibtisham, F.; Li, G.; Kieser, B.; Wu, J.; Liu, W.; Zhao, Y.; Nawab, Y.; Li, K.; Xiao, M.; et al. Heat stress in poultry production: Mitigation strategies to overcome the future challenges facing the global poultry industry. *J. Therm. Biol.* **2018**, *78*, 131–139. [CrossRef]
51. Ayo, J.O.; Obidi, J.A.; Rekwot, P.I. Effects of Heat Stress on the Well-Being, Fertility, and Hatchability of Chickens in the Northern Guinea Savannah Zone of Nigeria: A Review. *ISRN Vet. Sci.* **2011**, *14*, 838606. [CrossRef]
52. Thornton, P.K.; Van de Steeg, J.; Notenbaert, A.; Herrero, M. The impacts of climate change on livestock and livestock systems in developing countries: A review of what we know and what we need to know. *Agric. Syst.* **2009**, *101*, 113–127. [CrossRef]
53. Thompson-Crispi, K.A.; Mallard, B.A. Type 1 and type 2 immune response profiles of commercial dairy cows in 4 regions across Canada. *Can. J. Vet. Res.* **2012**, *76*, 120–128.
54. Bagath, M.; Krishnan, G.; Devaraj, C.; Rashamol, V.P.; Pragna, P.; Lees, A.M.; Sejian, V. The impact of heat stress on the immune system in dairy cattle: A review. *Res. Vet. Sci.* **2019**, *126*, 94–102. [CrossRef]
55. Chirico, J.; Jonsson, P.; Kjellberg, S.; Thomas, G. Summer mastitis experimentally induced by *Hydrotaea irritans* exposed to bacteria. *Med. Vet. Entomol.* **1997**, *11*, 187–192. [CrossRef]
56. Mashaly, M.M.; Hendricks, G.L.; Kalama, M.A.; Gehad, A.E.; Abbas, A.O.; Patterson, P.H. Effect of Heat Stress on Production Parameters and Immune Responses of Commercial Laying Hens. *Poult. Sci.* **2004**, *83*, 889–894. [CrossRef]
57. Dahl, G.E.; Tao, S.; Laporta, J. Heat Stress Impacts Immune Status in Cows Across the Life Cycle. *Front. Vet. Sci.* **2020**, *7*, 116. [CrossRef] [PubMed]
58. Wang, X.J.; Feng, J.H.; Zhang, M.H.; Li, X.M.; Ma, D.D.; Chang, S.S. Effects of high ambient temperature on the community structure and composition of ileal microbiome of broilers. *Poult. Sci.* **2018**, *97*, 2153–2158. [CrossRef] [PubMed]
59. Zhu, L.; Liao, R.; Wu, N.; Zhu, G.; Yang, C. Heat stress mediates changes in fecal microbiome and functional pathways of laying hens. *Appl. Microbiol. Biotechnol.* **2019**, *103*, 461–472. [CrossRef] [PubMed]
60. Paull, S.H.; Raffel, T.R.; LaFonte, B.E.; Johnson, P.T.J. How temperature shifts affect parasite production: Testing the roles of thermal stress and acclimation. *Funct. Ecol.* **2015**, *29*, 941–950. [CrossRef]
61. Grace, D.; Bett, B.K.; Lindahl, J.F.; Robinson, T.P. Climate and Livestock Disease: Assessing the Vulnerability of Agricultural Systems to Livestock Pests under Climate Change Scenarios. 2015. Available online: https://cgspace.cgiar.org/handle/10568/66595 (accessed on 4 September 2021).
62. Vitali, A.; Felici, A.; Esposito, S.; Bernabucci, U.; Bertocchi, L.; Maresca, C.; Nardone, A.; Lacetera, N. The effect of heat waves on dairy cow mortality. *J. Dairy Sci.* **2015**, *98*, 4572–4579. [CrossRef]
63. Bishop-Williams, K.E.; Berke, O.; Pearl, D.L.; Hand, K.; Kelton, D.F. Heat stress related dairy cow mortality during heat waves and control periods in rural Southern Ontario from 2010–2012. *BMC Vet. Res.* **2015**, *11*, 291. [CrossRef]
64. Ross, J.; Hale, B.; Gabler, N.; Rhoads, R.; Keating, A.; Baumgard, L. Physiological consequences of heat stress in pigs. *Anim. Prod. Sci.* **2015**, *1*, 55. [CrossRef]
65. Jeffrey, F.; Keown, R.J.G. How to Reduce Heat Stress in Dairy Cattle. University of Missouri Extension. Available online: https://extension.missouri.edu/publications/g3620 (accessed on 3 November 2021).
66. Saeed, M.; Abbas, G.; Alagawany, M.; Kamboh, A.A.; Abd El-Hack, M.E.; Khafaga, A.F.; Chao, S. Heat stress management in poultry farms: A comprehensive overview. *J. Therm. Biol.* **2019**, *84*, 414–425. [CrossRef]
67. Reilly, J.M.; Hrubovcak, J.; Graham, J.; Abler, D.G.; Darwin, R.; Hollinger, S.E.; Izaurralde, R.C.; Jagtap, S.; Jones, J.W.; Kimble, J.; et al. Changing Climate and Changing Agriculture: Report of the Agricultural Sector Assessment Team, US National Assessment. In *Prepared as Part of USGCRP National Assessment of Climate Variability*; Cambridge University Press: New York, NY, USA, 2002.
68. Shukla, P.R.; Skea, J.; Calvo Buendia, E.; Masson-Delmotte, V.; Pörtner, H.O.; Roberts, D.C.; Zhai, P.; Slade, R.; Connors, R.; Van Diemen, R. *IPCC, 2019: Climate Change and Land: An IPCC Special Report on Climate Change, Desertification, Land Degradation, Sustainable Land Management, Food Security, and Greenhouse Gas Fluxes in Terrestrial Ecosystems*; Intergovernmental Panel on Climate Change (IPCC): Geneva, Switzerland, 2019.

69. Intergovernmental Panel on Climate Change. *Climate Change 2014: Impacts, Adaptation, and Vulnerability—Part B: Regional Aspects—Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*; Barros, V.R., Field, C.B., Dokken, D.J., Mastrandrea, M.D., Mach, K.J., Bilir, T.E., Chatterjee, M., Ebi, K.L., Estrada, Y.O., Genova, R.C., et al., Eds.; Cambridge University Press: Cambridge, UK; New York, NY, USA, 2014; 688p. [CrossRef]
70. Allen, V.G.; Batello, C.; Berretta, E.J.; Hodgson, J.; Kothmann, M.; Li, X.; McIvor, J.; Milne, J.; Morris, C.; Peeters, A.; et al. An international terminology for grazing lands and grazing animals. *Grass Forage Sci.* **2011**, *66*, 2–28. [CrossRef]
71. Papanastasis, V.P.; Yiakoulaki, M.D.; Decandia, M.; Dini-Papanastasi, O. Integrating woody species into livestock feeding in the Mediterranean areas of Europe. *Anim. Feed Sci. Technol.* **2008**, *140*, 1–17. [CrossRef]
72. Hejcman, M.; Hejcmanová, P.; Pavlů, V.; Thorhallsdottir, A.G. Forage quality of leaf fodder from the main woody species in Iceland and its potential use for livestock in the past and present. *Grass Forage Sci.* **2016**, *71*, 649–658. [CrossRef]
73. Pearcy, R.W.; Ehleringer, J. Comparative ecophysiology of C3 and C4 plants. *Plant Cell Environ.* **1984**, *7*, 1–13. [CrossRef]
74. Rust, J.M. The impact of climate change on extensive and intensive livestock production systems. *Anim. Front.* **2019**, *9*, 20–25. [CrossRef]
75. Hatfield, J.L.; Boote, K.J.; Kimball, B.A.; Ziska, L.H.; Izaurralde, R.C.; Ort, D.; Thomson, A.M.; Wolfe, D. Climate Impacts on Agriculture: Implications for Crop Production. *Agron. J.* **2011**, *103*, 351–370. [CrossRef]
76. Cho, S.J.; McCarl, B.A. Climate change influences on crop mix shifts in the United States. *Sci. Rep.* **2017**, *7*, 40845. [CrossRef] [PubMed]
77. Kukal, M.S.; Irmak, S. Climate-Driven Crop Yield and Yield Variability and Climate Change Impacts on the, U.S. Great Plains Agricultural Production. *Sci. Rep.* **2018**, *8*, 3450. [CrossRef] [PubMed]
78. Hadi, A.; Naz, N.; Ur Rehman, F.; Kalsoom, M.; Tahir, R.; Adnan, M.; Saeed, M.S.; Khan, A.U.; Mehta, J. Impact of Climate Change Drivers on C4 Plants: A Review. *Curr. Res. Agric. Farming* **2020**, *1*, 13–18. [CrossRef]
79. Hummel, M.; Hallahan, B.F.; Brychkova, G.; Ramirez-Villegas, J.; Guwela, V.; Chataika, B.; Curley, E.; McKeown, P.C.; Morrison, L.; Talsma, E.F.; et al. Reduction in nutritional quality and growing area suitability of common bean under climate change induced drought stress in Africa. *Sci. Rep.* **2018**, *8*, 16187. [CrossRef]
80. Ray, R.L.; Fares, A.; Risch, E. Effects of Drought on Crop Production and Cropping Areas in Texas. *Agric. Environ. Lett.* **2018**, *3*, 170037. [CrossRef]
81. Webber, H.; Ewert, F.; Olesen, J.E.; Müller, C.; Fronzek, S.; Ruane, A.C.; Bourgault, M.; Martre, P.; Ababaei, B.; Bindi, M.; et al. Diverging importance of drought stress for maize and winter wheat in Europe. *Nat. Commun.* **2018**, *9*, 4249. [CrossRef]
82. Hopkins, A.; Prado, A.D. Implications of climate change for grassland in Europe: Impacts, adaptations and mitigation options: A review. *Grass Forage Sci.* **2007**, *62*, 118–126. [CrossRef]
83. Ball, D.M.; Collins, M.; Lacefield, G.; Martin, N.; Mertens, D.; Olson, K.; Putnam, D.; Undersander, D.; Wolf, M. Understanding Forage Quality. American Farm Bureau Federation Publication. 2001. Available online: http://pss.uvm.edu/pdpforage/Materials/ForageQuality/Understanding_Forage_Quality_Ball.pdf (accessed on 3 November 2021).
84. Collins, M.; Nelson, C.J.; Moore, K.J.; Barnes, R.F. *Forages, Volume 1: An Introduction to Grassland Agriculture*; John Wiley & Sons: Hoboken, NJ, USA, 2017; 432p.
85. Dumont, B.; Andueza, D.; Niderkorn, V.; Lüscher, A.; Porqueddu, C.; Picon-Cochard, C. A meta-analysis of climate change effects on forage quality in grasslands: Specificities of mountain and Mediterranean areas. *Grass Forage Sci.* **2015**, *70*, 239–254. [CrossRef]
86. Polley, H.W.; Briske, D.D.; Morgan, J.A.; Wolter, K.; Bailey, D.W.; Brown, J.R. Climate change and North American rangelands: Trends, projections, and implications. *Rangel. Ecol. Manag.* **2013**, *66*, 493–511. [CrossRef]
87. Lee, M.A.; Davis, A.P.; Chagunda, M.G.G.; Manning, P. Forage quality declines with rising temperatures, with implications for livestock production and methane emissions. *Biogeosciences* **2017**, *14*, 1403–1417. [CrossRef]
88. Food and Agriculture Organization of the United Nations. AQUASTAT Website. 2016. Available online: https://www.fao.org/aquastat/en/overview/methodology/water-use (accessed on 3 November 2021).
89. Heinke, J.; Lannerstad, M.; Gerten, D.; Havlík, P.; Herrero, M.; Notenbaert, A.M.O.; Hoff, H.; Müller, C. Water Use in Global Livestock Production—Opportunities and Constraints for Increasing Water Productivity. *Water Resour. Res.* **2020**, *56*, e2019WR026995. [CrossRef]
90. Intergovernmental Panel on Climate Change. *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*; Masson-Delmotte, V., Zhai, P., Pirani, A., Connors, S., Péan, C., Berger, S., Caud, N., Chen, Y., Goldfarb, L., Gomis, M., et al., Eds.; Cambridge University Press: New York, NY, USA, 2021.
91. Fader, M.; Shi, S.; von Bloh, W.; Bondeau, A.; Cramer, W. Mediterranean irrigation under climate change: More efficient irrigation needed to compensate for increases in irrigation water requirements. *Hydrol. Earth Syst. Sci.* **2016**, *20*, 953–973. [CrossRef]
92. Gerten, D.; Heinke, J.; Hoff, H.; Biemans, H.; Fader, M.; Waha, K. Global Water Availability and Requirements for Future Food Production. *J. Hydrometeorol.* **2011**, *12*, 885–899. [CrossRef]
93. Watson, R.T.; Zinyowera, M.C.; Moss, R.H.; Dokken, D.J. *The Regional Impacts of Climate Change: An Assessment of Vulnerability*; Cambridge University Press: New York, NY, USA, 1998.
94. Tully, K.; Gedan, K.; Epanchin-Niell, R.; Strong, A.; Bernhardt, E.S.; BenDor, T.; Mitchell, M.; Kominoski, J.; Jordan, T.E.; Neubauer, S.C.; et al. The invisible flood: The chemistry, ecology, and social implications of coastal saltwater intrusion. *BioScience* **2019**, *69*, 368–378. [CrossRef]

95. Reynolds, C.; Crompton, L.; Mills, J. Livestock and Climate Change Impacts in the Developing World. *Outlook Agric.* **2010**, *39*, 245–248. [CrossRef]
96. Konapala, G.; Mishra, A.K.; Wada, Y.; Mann, M.E. Climate change will affect global water availability through compounding changes in seasonal precipitation and evaporation. *Nat. Commun.* **2020**, *11*, 3044. [CrossRef]
97. McCarl, B.A.; Villavicencio, X.; Wu, X.M. Climate Change and Future Analysis: Is Stationarity Dying? *Am. J. Agric. Econ.* **2008**, *90*, 1241–1247. [CrossRef]
98. Knee, B.W.; Cummins, L.J.; Walker, P.; Warner, R. Seasonal variation in muscle glycogen in beef steers. *Aust. J. Exp. Agric.* **2004**, *44*, 729–734. [CrossRef]
99. Hidosa, D.; Guyo, M. Climate change effects on livestock feed resources: A review. *J. Fish. Livest. Prod.* **2017**, *5*, 259.
100. Bai, Y.; Deng, X.; Zhang, Y.; Wang, C.; Liu, Y. Does climate adaptation of vulnerable households to extreme events benefit livestock production? *J. Clean. Prod.* **2019**, *210*, 358–365. [CrossRef]
101. Hajek, I.L.; Knapp, A.K. Shifting seasonal patterns of water availability: Ecosystem responses to an unappreciated dimension of climate change. *N. Phytol.* **2021**, *233*, 119–125. [CrossRef]
102. Food and Agriculture Organization of the United Nations (FAO). Global Livestock Environmental Assessment Model (GLEAM). Available online: https://www.fao.org/gleam/results/en/ (accessed on 3 November 2021).
103. Steinfeld, H.; Gerber, P.; Wassenaar, T.; Castel, V.; Rosales, M.; de Haan, C. Livestock's Long Shadow. 2006. Available online: http://www.fao.org/docrep/010/a0701e/a0701e00.HTM (accessed on 24 August 2017).
104. Grossi, G.; Goglio, P.; Vitali, A.; Williams, A.G. Livestock and climate change: Impact of livestock on climate and mitigation strategies. *Anim. Front.* **2019**, *9*, 69–76. [CrossRef]
105. Beauchemin, K.A. Dietary Mitigation of Enteric Methane from Cattle. *CAB Rev.* **2009**, *4*. Available online: http://www.cabi.org/cabreviews/review/20093276253 (accessed on 9 September 2021). [CrossRef]
106. Johnson, D.E.; Ward, G.M. Estimates of animal methane emissions. *Environ. Monit. Assess.* **1996**, *42*, 133–141. [CrossRef]
107. Food and Agriculture Organization of the United Nations (FAO). Sustainable Food and Agriculture. Available online: http://www.fao.org/sustainability/news/detail/en/c/1274219/ (accessed on 3 November 2021).
108. Alexandratos, N.; Bruinsma, J. (Eds.) *World Agriculture towards 2030/2050: The 2012 Revision*; ESA Working Papers 12-03; ESA: Paris, France, 2012.
109. Yitbarek, M.B. Livestock and livestock product trends by 2050: Review. *Int. J. Anim. Res.* **2019**, *4*, 30.
110. Flysjö, A.; Cederberg, C.; Henriksson, M.; Ledgard, S. The interaction between milk and beef production and emissions from land use change—Critical considerations in life cycle assessment and carbon footprint studies of milk. *J. Clean. Prod.* **2012**, *28*, 134–142. [CrossRef]
111. Hong, C.; Burney, J.A.; Pongratz, J.; Nabel, J.E.M.S.; Mueller, N.D.; Jackson, R.B.; Davis, S.J. Global and regional drivers of land-use emissions in 1961–2017. *Nature* **2021**, *589*, 554–561. [CrossRef]
112. Gaughan, J.B.; Sejian, V.; Mader, T.L.; Dunshea, F.R. Adaptation strategies: Ruminants. *Anim. Front.* **2019**, *9*, 47–53. [CrossRef]
113. Ratnakara, P.A.; Sejian, V.; Jose, V.S.; Vaswani, S.; Bagath, M.; Krishnan, G.; Beena, V.; Devi, P.I.; Varma, G.; Bhatta, R. Behavioral Responses to Livestock Adaptation to Heat Stress Challenges. 2017. Available online: http://krishi.icar.gov.in/jspui/handle/123456789/27610 (accessed on 6 September 2021).
114. Chambwera, M.; Heal, G.; Dubeux, C.; Hallegatte, S.; Leclerc, L.; Markandya, A.; McCarl, B.A.; Mechler, R.; Neumann, J.E. Economics of adaptation. In *Climate Change 2014: Impacts, Adaptation, and Vulnerability Part A: Global and Sectoral Aspects Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*; Cambridge University Press: Cambridge, UK, 2014; Chapter 17.
115. Bernabucci, U.; Lacetera, N.; Baumgard, L.H.; Rhoads, R.P.; Ronchi, B.; Nardone, A. Metabolic and hormonal acclimation to heat stress in domesticated ruminants. *Animal* **2010**, *4*, 1167–1183. [CrossRef]
116. Daghir, N.J. (Ed.) *Poultry Production in Hot Climates*, 2nd ed.; CABI: Wallingford, UK, 2008; Available online: http://www.cabi.org/cabebooks/ebook/20083163627 (accessed on 26 October 2020).
117. Zumbach, B.; Misztal, I.; Tsuruta, S.; Sanchez, J.P.; Azain, M.; Herring, W.; Holl, J.; Long, T.; Culbertson, M. Genetic components of heat stress in finishing pigs: Parameter estimation. *J. Anim. Sci.* **2008**, *86*, 2076–2081. [CrossRef] [PubMed]
118. Hoffmann, I. Adaptation to climate change–exploring the potential of locally adapted breeds. *Animal* **2013**, *7*, 346–362. [CrossRef] [PubMed]
119. Hayes, B.J.; Lewin, H.A.; Goddard, M.E. The future of livestock breeding: Genomic selection for efficiency, reduced emissions intensity, and adaptation. *Trends Genet.* **2013**, *29*, 206–214. [CrossRef] [PubMed]
120. Renaudeau, D.; Collin, A.; Yahav, S.; De Basilio, V.; Gourdine, J.L.; Collier, R.J. Adaptation to hot climate and strategies to alleviate heat stress in livestock production. *Animal* **2012**, *6*, 707–728. [CrossRef]
121. Barendse, W. Climate adaptation of tropical cattle. *Annu. Rev. Anim. Biosci.* **2017**, *5*, 133–150. [CrossRef]
122. Zhang, Y.W.; Hagerman, A.D.; McCarl, B.A. Influence of Climate Factors on Spatial Distribution of Texas Cattle Breeds. *Clim. Change* **2013**, *118*, 183–195. [CrossRef]
123. Mitlöhner, F.M.; Morrow, J.L.; Dailey, J.W.; Wilson, S.C.; Galyean, M.L.; Miller, M.F.; McGlone, J.J. Shade and water misting effects on behavior, physiology, performance, and carcass traits of heat-stressed feedlot cattle. *J. Anim. Sci.* **2001**, *79*, 2327–2335. [CrossRef]
124. Morrison, S.R.; Givens, R.L.; Lofgreen, G.P. Sprinkling Cattle for Relief from Heat Stress. *J. Anim. Sci.* **1973**, *36*, 428–431. [CrossRef]

125. Huynh, T.T.T. Heat Stress in Growing Pigs: Wageningen University and Research. 2005. Available online: https://www.proquest.com/docview/2449468017/abstract/BAD39E82C2B7419EPQ/1 (accessed on 2 August 2021).
126. Schauberger, G.; Mikovits, C.; Zollitsch, W.; Hörtenhuber, S.J.; Baumgartner, J.; Niebuhr, K.; Piringer, M.; Knauder, W.; Anders, I.; Andre, K.; et al. Global warming impact on confined livestock in buildings: Efficacy of adaptation measures to reduce heat stress for growing-fattening pigs. *Clim. Change* **2019**, *156*, 567–587. [CrossRef]
127. West, J.W. Effects of heat-stress on production in dairy cattle. *J. Dairy Sci.* **2003**, *86*, 2131–2144. [CrossRef]
128. Mader, T.L.; Davis, M.S. Effect of management strategies on reducing heat stress of feedlot cattle: Feed and water intake1. *J. Anim. Sci.* **2004**, *82*, 3077–3087. [CrossRef]
129. Baumgard, L.; Abuajamieh, M.; Stoakes, S.; Sanz-Fernandez, M.; Johnson, J.; Rhoads, R.; Eastridge, M. Feeding and managing cows to minimize heat stress. In Proceedings of the 23rd Tri-State Dairy Nutrition Conference, Fort Wayne, IN, USA, 22–23 April 2014; pp. 14–16. Available online: http://kimiyaroshd.com/wp-content/uploads/2021/06/Feeding-and-Managing-Cows-to-Minimize-Heat-Stress.pdf (accessed on 10 January 2022).
130. Cottrell, J.J.; Liu, F.; Hung, A.T.; DiGiacomo, K.; Chauhan, S.S.; Leury, B.J.; Furness, J.B.; Celi, P.; Dunshea, F.R. Nutritional strategies to alleviate heat stress in pigs. *Anim. Prod. Sci.* **2015**, *55*, 1391–1402. [CrossRef]
131. Dos Santos, L.S.; Pomar, C.; Campos, P.H.R.F.; da Silva, W.C.; de Gobi, J.P.; Veira, A.M.; Fraga, A.Z.; Hauschild, L. Precision feeding strategy for growing pigs under heat stress conditions1. *J. Anim. Sci.* **2018**, *96*, 4789–4801. [CrossRef]
132. Mayorga, E.J.; Kvidera, S.K.; Seibert, J.T.; Horst, E.A.; Abuajamieh, M.; Al-Qaisi, M.; Lei, S.; Ross, J.W.; Johnson, C.D.; Kremer, B.; et al. Effects of dietary chromium propionate on growth performance, metabolism, and immune biomarkers in heat-stressed finishing pigs1. *J. Anim. Sci.* **2019**, *97*, 1185–1197. [CrossRef]
133. Lin, H.; Jiao, H.C.; Buyse, J.; Decuypere, E. Strategies for preventing heat stress in poultry. *World's Poult. Sci. J.* **2006**, *62*, 71–86. [CrossRef]
134. Wasti, S.; Sah, N.; Mishra, B. Impact of Heat Stress on Poultry Health and Performances, and Potential Mitigation Strategies. *Animals* **2020**, *10*, 1266. [CrossRef]
135. Levchenko, M.; Silivanova, E.; Balabanova, G.; Bikinyaeva, R. Insecticide susceptibility of house flies (*Musca domestica*) from a livestock farm in Tyumen region, Russia. *Bulg. J. Vet. Med.* **2019**, *22*, 213–219. [CrossRef]
136. Axtell, R.; Arends, J. Ecology and management of arthropod pests of poultry. *Annu. Rev. Entomol.* **1990**, *35*, 101–126. [CrossRef]
137. Battu, R.S.; Singh, B.; Kang, B.K. Contamination of liquid milk and butter with pesticide residues in the Ludhiana district of Punjab state, India. *Ecotoxicol. Environ. Saf.* **2004**, *59*, 324–331. [CrossRef]
138. Axtell, R.C. Livestock integrated pest management (IPM): Principles and prospects. *Syst. Approach Anim. Health Prod.* **1981**, 31–40.
139. Megersa, B.; Markemann, A.; Angassa, A.; Ogutu, J.O.; Piepho, H.-P.; Zárate, A.V. Livestock diversification: An adaptive strategy to climate and rangeland ecosystem changes in southern Ethiopia. *Hum. Ecol.* **2014**, *42*, 509–520. [CrossRef]
140. Martin, G.; Barth, K.; Benoit, M.; Brock, C.; Destruel, M.; Dumont, B. Potential of multi-species livestock farming to improve the sustainability of livestock farms: A review. *Agric. Syst.* **2020**, *181*, 102821. [CrossRef]
141. Díaz-Solís, H.; Grant, W.E.; Kothmann, M.M.; Teague, W.R.; Díaz-García, J.A. Adaptive management of stocking rates to reduce effects of drought on cow-calf production systems in semi-arid rangelands. *Agric. Syst.* **2009**, *100*, 43–50. [CrossRef]
142. Mu, J.E.; McCarl, B.A.; Wein, A.M. Adaptation to climate change: Changes in farmland use and stocking rate in the, U.S. *Mitig. Adapt. Strateg. Glob. Chang.* **2013**, *18*, 713–730. [CrossRef]
143. Ryschawy, J.; Choisis, N.; Choisis, J.P.; Joannon, A.; Gibon, A. Mixed crop-livestock systems: An economic and environmental-friendly way of farming? *Animal* **2012**, *6*, 1722–1730. [CrossRef]
144. Alves, B.J.R.; Madari, B.E.; Boddey, R.M. Integrated crop–livestock–forestry systems: Prospects for a sustainable agricultural intensification. *Nutr. Cycl. Agroecosyst.* **2017**, *108*, 1–4. [CrossRef]
145. Thornton, P.K.; Herrero, M. Potential for reduced methane and carbon dioxide emissions from livestock and pasture management in the tropics. *Proc. Natl. Acad. Sci. USA* **2010**, *107*, 19667–19672. [CrossRef]
146. Havlík, P.; Valin, H.J.P.; Herrero, M.; Obersteiner, M.; Schmid, E.; Rufino, M.C.; Mosnier, A.; Thornton, P.K.; Böttcher, H.; Conant, R.T.; et al. Climate change mitigation through livestock system transitions. *Proc. Natl. Acad. Sci. USA* **2014**, *111*, 3709–3714. [CrossRef]
147. Knapp, J.R.; Laur, G.L.; Vadas, P.A.; Weiss, W.P.; Tricarico, J.M. Invited review: Enteric methane in dairy cattle production: Quantifying the opportunities and impact of reducing emissions. *J. Dairy Sci.* **2014**, *97*, 3231–3261. [CrossRef]
148. Caro, D.; Kebreab, E.; Mitloehner, F.M. Mitigation of enteric methane emissions from global livestock systems through nutrition strategies. *Clim. Change* **2016**, *137*, 467–480. [CrossRef]
149. Rebellon, L.F.M. *Waste Management: An Integrated Vision*; BoD—Books on Demand: Norderstedt, Germany, 2012; 363p.
150. Montes, F.; Meinen, R.; Dell, C.; Rotz, A.; Hristov, A.N.; Oh, J.; Waghorn, G.; Gerber, P.J.; Henderson, B.; Makkar, H.P.S.; et al. SPECIAL TOPICS—Mitigation of methane and nitrous oxide emissions from animal operations: II. A review of manure management mitigation options1. *J. Anim. Sci.* **2013**, *91*, 5070–5094. [CrossRef] [PubMed]
151. Kaparaju, P.; Rintala, J. Mitigation of greenhouse gas emissions by adopting anaerobic digestion technology on dairy, sow and pig farms in Finland. *Renew. Energy* **2011**, *36*, 31–41. [CrossRef]
152. Battini, F.; Agostini, A.; Boulamanti, A.K.; Giuntoli, J.; Amaducci, S. Mitigating the environmental impacts of milk production via anaerobic digestion of manure: Case study of a dairy farm in the Po Valley. *Sci. Total Environ.* **2014**, *481*, 196–208. [CrossRef] [PubMed]

153. Stuart, D.; Schewe, R.L.; McDermott, M. Reducing nitrogen fertilizer application as a climate change mitigation strategy: Understanding farmer decision-making and potential barriers to change in the U.S. *Land Use Policy* **2014**, *36*, 210–218. [CrossRef]
154. Balafoutis, A.; Beck, B.; Fountas, S.; Vangeyte, J.; van der Wal, T.; Soto, I.; Gómez-Barbero, M.; Barnes, A.; Eory, V. Precision agriculture technologies positively contributing to GHG emissions mitigation, farm productivity and economics. *Sustainability* **2017**, *9*, 1339. [CrossRef]
155. Pikaar, I.; Matassa, S.; Bodirsky, B.L.; Weindl, I.; Humpenöder, F.; Rabaey, K.; Boon, N.; Bruschi, M.; Yuan, Z.; Van Zanten, H.; et al. Decoupling Livestock from Land Use through Industrial Feed Production Pathways. *Environ. Sci. Technol.* **2018**, *52*, 7351–7359. [CrossRef]
156. Thornton, P.K.; Herrero, M. Adapting to climate change in the mixed crop and livestock farming systems in sub-Saharan Africa. *Nat. Clim. Change* **2015**, *5*, 830–836. [CrossRef]
157. Karimi, V.; Karami, E.; Keshavarz, M. Vulnerability and Adaptation of Livestock Producers to Climate Variability and Change. *Rangel. Ecol. Manag.* **2018**, *71*, 175–184. [CrossRef]

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Abstract

This study evaluates the dynamics of soil organic carbon (SOC) under perennial crops across the globe. It quantifies the effect of change from annual to perennial crops and the subsequent temporal changes in SOC stocks during the perennial crop cycle. It also presents an empirical model to estimate changes in the SOC content under crops as a function of time, land use, and site characteristics. We used a harmonized global dataset containing paired-comparison empirical values of SOC and different types of perennial crops (perennial grasses, palms, and woody plants) with different end uses: bioenergy, food, other bio-products, and short rotation coppice. Salient outcomes include: a 20-year period encompassing a change from annual to perennial crops led to an average 20% increase in SOC at 0–30 cm (6.0 ± 4.6 Mg/ha gain) and a total 10% increase over the 0–100 cm soil profile (5.7 ± 10.9 Mg/ha). A change from natural pasture to perennial crop decreased SOC stocks by 1% over 0–30 cm (−2.5 ± 4.2 Mg/ha) and 10% over 0–100 cm (−13.6 ± 8.9 Mg/ha). The effect of a land use change from

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forest to perennial crops did not show significant impacts, probably due to the limited number of plots; but the data indicated that while a 2% increase in SOC was observed at 0–30 cm (16.81 ± 55.1 Mg/ha), a decrease in 24% was observed at 30–100 cm (−40.1 ± 16.8 Mg/ha). Perennial crops generally accumulate SOC through time, especially woody crops; and temperature was the main driver explaining differences in SOC dynamics, followed by crop age, soil bulk density, clay content, and depth. We present empirical evidence showing that the FAO *perennialization* strategy is reasonable, underscoring the role of perennial crops as a useful component of climate change mitigation strategies.

KEYWORDS

agriculture, arable crops, carbon balance, emission factors, fruit crops, land use change, meta-analysis, woody crops

1 | INTRODUCTION

Soils store approximately 1,550 Gt of organic carbon out of the 2,110 Gt of organic carbon estimated to be present in the biosphere (Lal, 2004). Thus, soil organic carbon (SOC) accounts for about 70% of total terrestrial carbon (C), and represents more than twice the 760 Gt of atmospheric C (IPCC, 2014). The size of the SOC pool means that land use and land use changes (LUCs) that cause soil disturbance can lead to substantial loss of SOC and greenhouse gas (GHG) emissions. Indeed, conversion from natural to agricultural ecosystems causes a major loss of SOC: up to 60% or 75% in temperate and tropical regions, respectively (Lal, 2004), and this C is released to the atmosphere as carbon dioxide, CO_2, a GHG source. Agriculture is practiced on 49% of the global ice-free land surface, 12% as cropland, and 37% as pasture, and is responsible for 12% of the total direct anthropogenic GHG emissions (IPCC, 2019). If, in addition, LUC and degradation are considered, the contribution of agriculture rises to one third of the total anthropogenic emissions (Wollenberg, Tapio-Bistrom, Grieg-Gran, & Nihart, 2011). Furthermore, the reduction in SOC causes soil degradation and hence reduces plant productivity and yield (Lal, 2006). Agriculture, however, is a basic human activity and a necessity, and as such, providing secure food and energy supply for rising global population while minimizing GHG emissions is one of the main challenges of humanity (Smith et al., 2010). The agriculture, land use, and forestry sectors are the only major sectors with the potential not only to reduce emissions but also deliver negative emissions in some cases (Ledo, Heathcote, Hastings, Smith, & Hillier, 2018). This is achieved via C sequestration (Smith, 2004) and/or offsetting through the supply of feedstock for energy production (Robertson et al., 2017).

It is estimated that agricultural lands have the potential to sequester up to a 66% of historical C loss, if managed properly (Lal, 2004). The "4 per mille" initiative (https://www.4p1000.org/), which aims to increase SOC relies mainly on the application of best agricultural practices and the reduction of deforestation. Tree planting is an effective method increasing SOC (Laganiere, Angers, & Pare, 2010). Another method for increasing SOC is the establishment of perennial crops, which may be applied without loss of productive area. This latter option might deliver food, fiber, energy feedstock, or other goods and ecosystem services including increasing SOC, and as such could represent a win–win scenario. In fact, the FAO has suggested "perennialization" of agricultural lands as a strategy to mitigate climate change, and to enhance food security and ecosystem service delivery (Glover, Reganold, et al., 2010). Nonetheless, to date there has been a lack of evidence about the capacity of perennial crops to store SOC (Ledo et al., 2019). Importantly, studies have been carried out in a range of locations, using different experimental designs and analytical methods, and for a wide variety of crops. Therefore, results are not directly comparable and conclusions on the effect of perennial crops on SOC and soil properties cannot easily be derived. This is a significant limitation and knowledge gap considering that, even currently, perennial crops comprise 30% of global croplands (Ledo et al., 2018). There is thus a clear need to collate and carry out standardized analysis and syntheses of results from these disparate studies in order to understand the global impacts of LUCs and conversions under such significant production systems and/or scale; as well as to identify critical information or data gaps.

Perennial crops in this study are defined as crops that are planted, but not replanted and/or fully harvested annually to obtain goods (this definition excludes naturally occurring perennials and grasslands but includes plants for which the above-ground biomass is annually harvested). Perennial crops can be divided in two main groups: woody plants, such as fruits and nut crops (e.g., apple trees, citrus, almond), beverage crops (e.g., coffee, tea, cocoa), oil crops (e.g., palms), or short rotation coppices (e.g., poplar, willow); and perennial grasses such as sugarcane, switchgrass, *Miscanthus*. They also have different end uses, such as food (e.g., fruits), fiber (e.g., cotton), bioenergy (e.g., *Eucalyptus*, *Miscanthus*). In perennial crop cultivation, tillage and soil disturbances are reduced since, by definition, perennial crops stay on the land for more than 1 year. Moreover, perennial crops ensure vegetation cover and thus photosynthesis all year around which increases the biomass that is produced and left on the site to become SOC. Thus, there is greater potential to maintain or sequester SOC relative to annual crops. Along with potential benefits for soils (Cox, Glover, Tassel, Cox, & DeHaan, 2006; Paustian, Six, Elliott, &

Hunt, 2000) and GHG emission reduction, perennial crops store biomass (Ledo et al., 2018) and/or may be used to displace fossil fuels for energy generation (Dondini, Hastings, Saiz, Jones, & Smith, 2009; Robertson et al., 2017).

LUC and competition for land are urgent challenges for humanity (Foley et al., 2005; Smith et al., 2010). Given current rates of global population growth, the ongoing change from natural to cultivated ecosystems is likely to continue in order to feed an increasing population. It has been documented that a change from a natural ecosystem, forest or grassland, to annual cropland will result in SOC loss (Deng, Zhu, Tang, & Shangguan, 2016; Don, Schumacher, & Freibauer, 2011; IPCC, 2014). However, changes from natural ecosystems to perennial crops have been documented only locally and results are not consistent, reporting SOC gain (Post & Kwon, 2000; Robertson et al., 2017), SOC loss (Crowther et al., 2016; Don et al., 2011) or no change (Fialho & Zinn, 2014; Qin, Dunn, Kwon, Mueller, & Wander, 2016). Moreover, little information is available about the effects on SOC following conversion from annual to perennial crops. Furthermore, the SOC stock changes during the subsequent cultivation of perennial crops are poorly quantified. Turnover of soil organic matter is a function of several interacting variables, such as moisture, temperature, clay content, soil porosity, soil cover, and the composition of the soil microbiota (Aguilera, Lassaletta, Gattinger, & Gimeno, 2013; Blagodatsky & Smith, 2011; Deng et al., 2016; Don, Böhme, Dohrmann, Poeplau, & Tebbe, 2017). However, the most important driver for SOC turnover and changes is the C input via root litter and exudates, above-ground litter, and organic amendments (Kutsch, Bahn, & Heinemeyer, 2009; Rasse, Rumpel, & Dignac, 2005). Differences among crops and geographic areas may be largely explained by differences in these variables. Furthermore, an increase in global temperatures may affect SOC dynamics and C input to the soil (Davidson & Janssens, 2006).

In this study, we have used the first global and harmonized dataset of perennial crops on SOC dynamics (Ledo et al., 2019) to explore, at a global level, SOC in perennial crops. We studied different aspects: First, the changes in SOC stocks after a transition to perennials over a 20-year period or more, from different land uses: annual crops, forest (both natural and secondary forest) and natural grasslands. Secondly, we also evaluated changes in SOC stocks during the lifespan of the perennial crops, between 1 and 20 years after transition. Finally, we explored SOC changes in different biogeographical regions and for different perennial crops in order to identify general or distinctive patterns of SOC dynamics. Our final goal was to provide an empirical model to predict changes in SOC as a function of the main drivers of SOC dynamics found in this study: crop, climate, soil properties, and land use.

2 | METHODS

2.1 | Database creation

We used a global dataset of paired observations containing information about changes in SOC under perennial crops (Ledo et al., 2019), freely downloadable from the figshare file, https://doi.org/10.6084/m9.figshare.7637210 (2019). In addition to the original dataset, we calculated extra fields which were required in this study. This updated dataset is reproduced in Table S1. Firstly, for those plots without bulk density (BD) or soil texture (sand, silt, clay) and/or pH values in the original studies, we gap-filled the missing values as described previously (Ledo et al., 2019). Secondly, in order to standardize the units of SOC we transformed all values of SOC given as C density (SOC_{den}; g/kg) to SOC stocks (SOC_{stock}; Mg/ha) as follows:

$$SOC_{stock} = SOC_{den} * BD * depth \quad (1)$$

where BD is the bulk density (g/cm^3) and depth (cm) was the maximum depth at each particular measured plot.

This transformation may introduce errors and/or bias (Poeplau, Vos, & Don, 2017) but was deemed necessary due to lack of equivalence in reporting. Thirdly, for those plots with values of SOC at different depths, we calculated a single, depth-integrated value per sampling point by adding the SOC values of each layer. Consequently, we created a second database containing a single value of SOC stock per measured plot, whereas the original dataset has points with values of SOC at different depths (from 1 to 200 cm). This second dataset is reproduced in Table S2.

Finally, we calculated the relative change in SOC (ΔSOC_{rel}) for each point i between two times, t_0 (first measurement in time) and t_1 (second measurement in time, more recent, of the paired data information) as:

$$\Delta SOC_{rel_i} = \frac{SOC_{i,t_1} - SOC_{i,t_0}}{SOC_{i,t_0}} \quad (2)$$

We used the values of SOC as provided in the original study, either as SOC stocks (Mg/ha) or as SOC density (g/kg), to minimize errors and bias. SOC_{t_1} is the recorded empirical value of SOC after LUC to perennial crop cultivation; and SOC_{t_0} is the SOC value either (a) on previous land use before conversion to a perennial crop for those plots containing paired observations on two land uses, or (b) the earlier of observations at two different time points for those plots containing paired information on temporal changes on SOC during perennial cultivation. Positive values therefore indicate an SOC gain and negative values SOC loss.

We additionally calculated the stock change for every point i between times t_0 and t_1 in Mg/ha as:

$$\Delta SOC_{stock_i} = SOC_{i,t_1} - SOC_{i,t_0} \quad (3)$$

A summary of the SOC stock values recorded in the dataset evaluated in different biogeographical regions and main crop groups can be found in Appendix S1. The biogeographical regions considered were temperate, tropical, and boreal. The crop types were perennial grasses, woody plants, and palms (Ledo et al., 2019).

2.2 | Effect of LUC to a perennial crop on SOC in a 20-year period

We evaluated the change in SOC stock (ΔSOC_{stock}, Equation 3) from forest, grassland, or annual crops to perennial crops, using paired data. To align with the IPCC standards and provide relative stock changes over a 20-year period, we selected and included in our analysis only those studies where conversion to a perennial crop occurred more than 20 years ago (n = 138 plots). For such observations, we calculated the mean and the standard error of the mean (*SEM*) of the SOC values before and after conversion (ΔSOC_{stock}) and the percentage of SOC stock change. Furthermore, to avoid introducing additional errors and/or bias, rather than unifying values of SOC at a particular depth, we selected those plots containing information on SOC at depths (a) 0–30 cm (n = 105) and (b) 0–100 cm (n = 33).

2.3 | Temporal change in SOC under perennial plantations during the first 20 years after conversion

We evaluated changes on SOC stocks (ΔSOC_{stock}, Equation 3) over a 20-year period, from crop age 1 year to crop age 20 years. We selected a 20-year period as in the previous subsection and for the same reasons. We also included in our analysis those plots with SOC measured at 0–30 cm (n = 111) and 0–100 cm (n = 10) aggregated over different perennial crop types. Additionally, we calculated temporal ΔSOC_{stock} for perennial grasses, woody plants, and palms separately.

2.4 | Model to estimate temporal changes in SOC under perennial crops

We fitted a model to explain and predict the changes in SOC stocks and to identify the most significant explanatory variables and rank their importance. The explanatory variables we considered were (a) climatic: mean annual temperature, annual accumulated precipitation, climatic water deficit defined in Chave et al. (2015), and the variables Bio17 (Isotherma), Bio16 (changes in seasonal temperature), and climatic PT10 parameter, Bio12/(Bio 1 + 10), from the WorldClim database; (b) topographic: elevation, slope, aspect, and roughness (concavity or convexity of the terrain); (c) soil parameters: BD, percent clay, percent silt, percent sand, and pH; and (d) plantation parameters: crops age, years since transition to perennials, previous land use (annual crop, fallow, grassland, or natural forest), and current land use (agroforestry, bioenergy grass, or food and bio-products). More details on these variables can be found in Ledo et al. (2019). The response variable of this model was the rate of change in SOC, ΔSOC_{rel}, and we chose to fit a parametric model to make further predictions feasible. Since the variable ΔSOC_{rel} contained both positive and negative values and was highly skewed, we added 2 to all values and log-transformed the resultant data. After this transformation all the values of the response variable were positive, and the distribution was approximately normal. We then modelled the transformed ΔSOC_{rel} with a generalized lineal mixed model (GLMM), with a Gaussian distribution as identity link function.

To this end, we formulated several GLMMs, including systematically different sets of covariates and combinations, using both a Gaussian and Gamma distribution as identity link functions. Continuous explanatory variables were mainly but not exclusively tested and included as fixed effects and categorical variables were tested mainly, but not exclusively, as random effects. We used a Bayesian inference framework, an approach that allowed us to get information of the dispersion of the fitted parameters. We used the INLA (integrated nested Laplace approximation) method (Rue, Martino, & Chopin, 2009). The INLA method is a computationally efficient method for fitting Bayesian models that speeds up parameter estimation substantially in comparison with the typical Markov chain Monte Carlo routine. To identify the best model, we selected the model with lower log-likelihood among those containing all the covariates that were significant and not highly correlated and which residuals diagnose was acceptable. Including different sets of covariates and checking those that were significant was a manual, stepwise process.

Secondly, we calculated the variance in the data, and the variance explained by the model and by each of the explanatory covariates. In this way, we were able to rank the effect of each variable over the others and assess the importance of all of them in explaining and potentially predicting changes in SOC.

The R code used for all the analyses in this study can be found in Data S1 Programming Code 1.

3 | RESULTS

3.1 | Effect of LUC to perennial crop on SOC in a 20-year period

Overall, a change from an annual to a perennial crop led to a 20% (±10) increase in the SOC average stock values over a 20-year period in the top 30 cm and an increase of 11% (±8) over 100 cm (Table 1). In contrast, SOC stocks decreased when changing from grassland to perennial cops. We observed an averaged 0.6% (±5.65, not significant) SOC stock loss when only the first 30 cm were considered and a −9.6% (±6.7) when 100 cm were analyzed (Table 1). While the C loss in the upper layers was not significant, the effect of SOC loss was more obvious when the entire soil profile was considered. For a change from forest to perennial crops, we observed a 2% (±6.9, not significant) increase in SOC stocks in the upper part of the soil, but a 24% (±9.3) decrease when the entire profile was considered (Table 1). However, only seven paired plots contained information on this kind of LUC and natural and secondary forest were merged.

TABLE 1 Mean values of SOC (soil organic carbon) stocks (Mg/ha) and standard error of the mean before and after conversion to perennial with land use change more than 20 years ago. Significant effects are in bold

Previous land use	SOC before conversion (Mg/ha)	SOC after conversion (Mg/ha)	ΔSOC_{stock} (Mg/ha)	Gain/ loss	% change
Depth 0–30 cm					
Annual crop	41.1 (±5.0)	47.1 (±6.3)	6.1 (±4.6)	**Gain**	**20 (±10.0)**
Grassland	58.7 (±7.4)	55.0 (±6.4)	−2.5 (±4.1)	Loss	−0.6 (±5.6)
Forest	84.5 (±40.8)	100.6 (±12.3)	16.8 (±55.1)	Gain	2.0 (±6.9)
Depth 0–100 cm					
Annual crop	139.0 (±44.9)	144.7 (±42.9)	5.7 (±11.0)	**Gain**	**11 (±8.5)**
Grassland	121.9 (±12.5)	108.3 (±11.8)	−13.6 (±8.9)	**Loss**	**−9.6 (±6.7)**
Forest	173.5 (±22.5)	133.4 (±28.2)	−40.1 (±16.8)	**Loss**	**−24 (±9.3)**

3.2 | Temporal change in SOC stocks during perennial plantation

Overall, an increase in SOC stocks over time after conversion to perennial crops in the upper soil layers was observed (Figure 1a), meaning a gain in SOC through the first 20 years after conversion to perennial crops. This trend was consistent for all crop types, although woody plants tended to accumulate progressively more SOC than grasses and palms (Figure 1b). However, the time lags in which the database contains information also differed between crop types, which was a confounding factor. Upon close observation, it was apparent that SOC stock dynamics did not follow a linear trend with time. After an initial SOC gain, a marked SOC loss particularly under perennial grasses could be observed (Figure 1c), followed by an increasing SOC pattern again. This pattern was also repeatedly observed for single sites with multiple observations (chronosequence), thus confirming this general observation. For depths 0–100 cm, a modest SOC gain during the 20-year period was discernible especially under perennial grasses (Figure 1d), although the temporal increment observed in the upper layers was not as clear and the number of studies was very limited (n = 10).

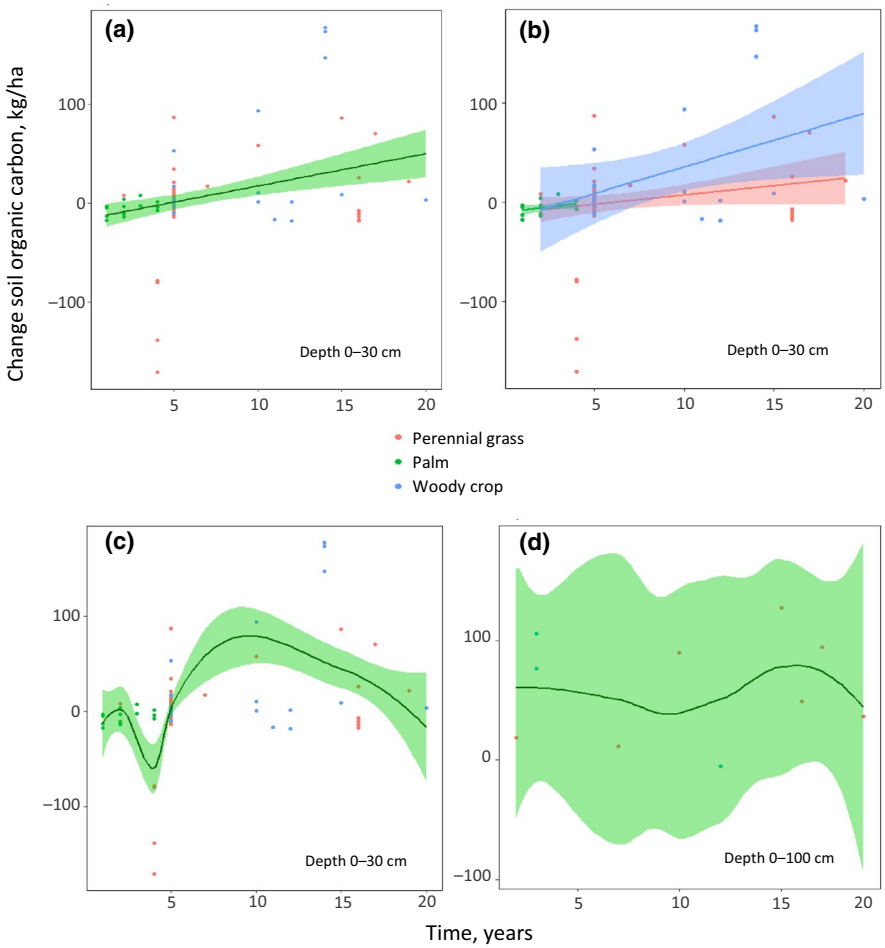


FIGURE 1 Empirical soil organic carbon (SOC) stock change values, in Mg/ha. Red, green, and blue dots are perennial grass, palm, and woody crop, respectively. (a) The green line is the linear trend of the mean value of SOC stock change including all the points (crop types) at depth 0–30 cm together, with the standard deviation in green shaded band. (b) The red, green, and blue lines are fitted linear models for perennial grasses, palms, and woody crop, respectively. (c) Actual empirical trend with the mean of SOC stock change as green line and the standard deviation of the mean in green shaded band, for depths 0–30 cm. (d) Actual empirical trend with the mean of SOC stock change as green line and the standard deviation of the mean in green shaded band, for depths 0–100 cm [Colour figure can be viewed at wileyonlinelibrary.com]

3.3 | Modelling temporal changes in SOC, considering the effect of climate, soil properties, and land use

Temporal changes in SOC were modelled using the GLMM formulations with a Gaussian distribution (a list of all the fitted models can be found in Table S5):

$$\Delta SOC_{rel} = -2 + e^{\zeta} \quad (4)$$

where

$$\zeta = \frac{1}{100}\left(\begin{array}{l} 78.584 - 0.533\,Temp - 0.189\,CropAge - 0.018\,Depth - 0.056 \\ PerClay + 5.352\,BD + |Previous\ land\ use| + |Current\ land\ use| \end{array}\right)$$

are the coefficients of the mean of the posterior fixed effects for: Temp, temperature, in Celsius; CropAge, the crop age (time since the crop was planted) in years; Depth, the profile depth in cm; PerClay, the percentage of clay; and BD, the soil bulk density. The coefficients for the mean posteriors of the random effects are given in Table 2.

The model explained 20% of the dataset variance, regardless of crop type. Although this means that a large proportion of the variance is not explained, this is, nonetheless, not a negligible percentage given the large heterogeneity in the data (including the different experimental methods, geographic regions, crop types, management practices, and ages) and the subsequently elevated Gaussian noise in the model. Of the explained variation, the main driver of the variation in SOC stock changes in perennial crops was temperature (Figure 2), which was negatively correlated with SOC changes. Crop age was second in importance, also negatively correlated with SOC change (Figure 2); changes in SOC were greater at the beginning of the crop establishment. Soil physical properties (BD, clay content) explained SOC changes to a lesser extent, with soils with greater BD and lower clay content showing greater changes in SOC. Depth and previous land use explained a minor proportion of the model variance, but these did improve the model fit (Table S5). Depth at the soil profile was negatively correlated with SOC changes, indicating that greater changes in SOC occurred at upper soil layers (Figure 2).

TABLE 2 Coefficients for the mean posteriors of the random effects of the ΔSOC empirical model

Previous land use			
Annual crop	Fallow	Grassland	Natural Forest
-5.431×10^{-05}	-2.178×10^{-05}	-2.832×10^{-04}	-2.733×10^{-04}
Current land use			
Agroforestry	Bioenergy grass	Food (and bio-products)	
-8.684×10^{-06}	-5.223×10^{-04}	5.647×10^{-04}	

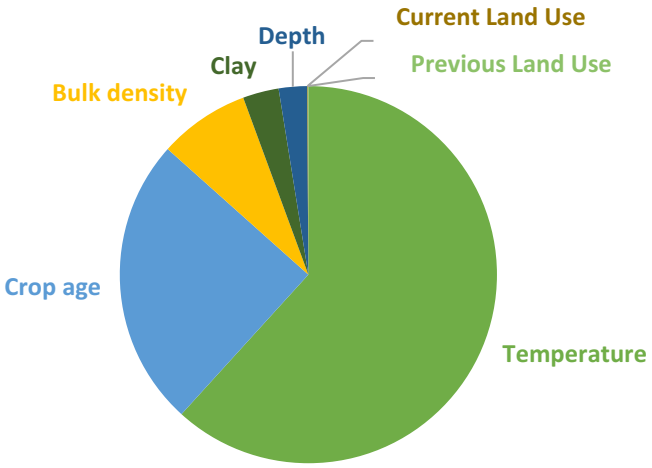


FIGURE 2 Percentage of variance explained by each of the soil organic carbon change model predictors. The previous land use categories are as follows: annual crop, fallow, grassland or natural forest; and the current land use ones: agroforestry, bioenergy grass or food, and bio-products [Colour figure can be viewed at wileyonlinelibrary.com]

4 | DISCUSSION

This study synthesizes the published, yet disparate, data on SOC changes at a global scale and provides for the first-time quantitative evidence about the effect of conversion to perennial crops on SOC relative to alternative land uses or cover types and over time. Specifically, it shows that a change from annual to perennial crops induces a SOC gain (Table 1) which indicates the potential to use perennials to sequester organic C across the cropland sector, especially where doing so has minimal trade-offs between SOC sequestration and food production. Besides, perennials increase the SOC stocks during crop life, at least up to 20 years (Figure 1). Climate, soil characteristics, and previous land use were identified as potential drivers of SOC dynamics in perennial crops at a global scale (Equation 4), with the average annual temperature playing a central role (Figure 2).

4.1 | Land conversion to perennial crops

A transition from an annual to a perennial to crop generally resulted in an average gain of a 20% (±10) in SOC (6.07 Mg/ha) after 20 years or more after conversion in the upper layers. In the 0–100 cm profile, the SOC gain was 11% (±8.5) a total of 5.66 Mg/ha in SOC. These slight differences between the 0–30 cm and 0–100 cm soil profile are partly likely due to the fact that the evaluated plots were different. If so, the information on the 30 upper centimeters is more reliable, since there are more data available (111 plots compared to 33). By contrast, a change from grassland to perennial crops appeared to cause a 1% loss of SOC in the top 30 cm the soil profile (although this is not statistical significant, therefore it should be taken with caution), the loss of SOC over 0–100 cm was more noticeable (−10%) and statistically significant. The effect of LUC from forest to perennials

on SOC varied with the soil depth; where comparisons are restricted to the top 30 cm soil a 2% (16.8 Mg/ha) gain in SOC is observed (the value was not statistically significant, and should be considered only as indicative). But a substantial loss of SOC was observed and was statistically significant (−24% or −40 Mg/ha) when the comparison is extended to the top 100 cm (see also Don et al., 2011). These findings highlight that when evaluating LUC effects on SOC stocks, it is imperative to consider a greater proportion of the soil profile affected by the root system to gain a fuller picture of impacts.

While the finding that a change from any land use to annual crops results in a loss in SOC is consistent among studies (Deng et al., 2016; Don et al., 2011), the effect of a change from a natural ecosystem to a perennial crops plantation is not that clear. Don et al. (2011) found a decrease of 30% in SOC when converting forest to perennials. This finding is not fully consistent with our study, we found a loss of SOC at the top 100 cm (−24%) but no significant effect at the top 30 cm (Table 1).

4.2 | Factors influencing SOC temporal dynamics in perennial crops

The first factor identified to affect SOC changes was crop age, or time after perennial establishment. After the initial LUC disturbance, SOC under perennials increases over 20 years, at an average of 0.05 Mg ha^{-1} $year^{-1}$ (Figure 1a) in the upper layers, 0–30 cm. This result is consistent with the patterns found in their analysis of SOC dynamics in perennial bioenergy crops in the upper soil layers by Ferchaud, Vitte, and Mary (2016). However, Ferchaud et al. (2016) observed a decrease in SOC in deeper horizons, which did not correspond to the findings in our evaluation. We observed that the increase in SOC is especially marked in woody crops where average gains of up to 0.1 Mg/ha (Figure 1b) were seen. However, this observed SOC gain was not constant: SOC increase was larger during the initial years after conversion to perennial crops after which a steady decline in SOC accumulation rate was observed (Figure 2c), consistent with the predictions of the GLMM (Equation 4). This supports the view that changes in SOC are greater at the beginning of the crop establishment and then decline until they reach a steady state (Smith, 2014). This pattern has also been observed in previous studies on SOC on perennial crops (Vicente-Vicente, García-Ruiz, Francaviglia, Aguilera, & Smith, 2016), and also reported for perennial woody crops in tropical savannas: In first cycle Eucalyptus plantations in Brazil, SOC losses after clearing of native vegetation were ascribed to decomposition of antecedent SOC at a faster pace than C was replenished in the young stands, but were reversed after harvest at age 7 years after planting and then by the ensuing coppice growth until age 14 years after planting (Zinn, Lal, & Resck, 2011).

Temperature and precipitation regimes are determining factors for the SOC balance, as they are strongly involved in processes responsible for both SOC inputs (i.e., litterfall production) and outputs (i.e., SOC decomposition, Davidson & Janssens, 2006). Therefore, differences in climate are probably one of the main causes explaining differences in SOC storage patterns among croplands in the world, as has been found for other ecosystems (Carvalhais et al., 2014; Doetterl et al., 2015). This study revealed temperature as one of the main factors affecting SOC changes in perennial crops globally (Figure 2, Equation 4). Temperature was negatively correlated with SOC changes, indicating that in warmer, tropical areas the relative change in SOC is lower than in temperate and boreal areas. We found temperature to be the main predictor of SOC changes over precipitation and over other climate indicators that combine temperature and precipitation together. This suggests that temperature exerts a stronger influence in soil respiratory processes than in plant growth and soil C input processes (which might be co-limited by other factors), thus limiting the potential for a more positive SOC balances in warm regimes. Soil physical properties were also significant in explaining SOC changes in the GLMM model: soils with greater values of BD showed greater changes in SOC, agreeing with the findings in Don et al. (2011), but this merely reflects the large weighting of BD in the calculation of SOC density. Soils with higher BD and lower SOC content are likely to have higher saturation deficit (Six, Conant, Paul, & Paustian, 2002)—the difference between maximum and minimum SOC that could be achieved—and thus may have higher potential to increase the SOC stocks (Vicente-Vicente, Gómez-Muñoz, Hinojosa-Centeno, Smith, & Garcia-Ruiz, 2017). The cultivated crop is a confounding factor in this study, and even with more data this limitation may remain, since some crops have a limited environmental range and are therefore only cultivated in certain climates. Nonetheless, woody crops showed a larger SOC gain on the whole than perennial grasslands (Figure 1).

In addition to the abovementioned factors, there are multiple, possibly interacting factors which affect SOC dynamics beyond the ones analyzed in this study, as indicated by the substantial unexplained variance in our data (Equation 4). Large variability among studies dealing with perennials has also been observed in previous studies (Aguilera et al., 2013; Vicente-Vicente et al., 2016). Some of the potential factors that are also likely to have impact and may improve the predictive capability of the model are management related: fertilizer application (type and rate), plant density, tillage, cover cropping, and other soil disturbances, but these could not be accounted for since there was not sufficient information across the dataset to model their effects. Along these lines, Vicente-Vicente et al. (2016) found that just by allowing the growth of spontaneous plant cover in the inter-row area and applying minimum tillage in Mediterranean orchards, an extra tonne of SOC per hectare and per year could be accumulated. Furthermore, the application of organic fertilizers and shredded pruning debris could increase this value by a factor of 3 to 4. The behavior of the perennial crop type in terms of above-ground biomass input production is also an important factor. Such as in Guava (*Psidium guajava*), leaf fall, bark fall, and also fruit falls in rainy season supply larger C input to soil in addition to the input from roots which helps in accumulation of 133 Mg/ha SOC stock in the top 2-m soil depth in a 31-year-old orchard situated in reclaimed sodic soil of northwest India (Datta, Basak, Chaudhari, & Sharma, 2015).

4.3 | SOC GLMM model caveats

The residuals from the GLMM showed an elevated Gaussian noise, but this was expected due to the large heterogeneity of the data, regarding experimental methods, biogeographic regions, crop types, and age among others. Yet, the predictors explained 20% of the dataset variance, across all crop types, indicating the difficultly associated with predictions of SOC at a global scale based on a purely empirical model with the currently available data. The available data are not only largely heterogeneous; in the light of our results, it becomes clear that more key information such as soil depth and management, which unfortunately are not always reported in studies (Aguilera et al., 2013).

We deliberately chose not to include crop type as a random effect, which indeed accounted for a notable proportion of the variance. There are two main reasons for this consideration; first, the intent was to derive a global/generic model to explain patterns of SOC changes under perennials, and not individual crop types. The dataset contains information on 58 crops at 709 locations (Ledo et al., 2019). Adding a random effect with 58 levels seems unreasonable. Second, and more importantly, many of the crops in the dataset were not duplicated (Ledo et al., 2019; Table S1), specifying crop type as random effect would be an obvious confounding factor.

The large heterogeneity of our dataset and neglecting some potentially important factors has not prevented us from revealing the robust observation that the SOC stocks under perennials are greater than under arable crops. In particular, we were not able to analyze changes in BD after and before perennials since those data were missing from the original dataset (see Ledo et al., 2019 for further details). We thus had to assume a fixed BD, while recommending that future experimental studies record BD before and after transition. Future data and studies might help to refine the estimates and regional distribution as driven by climatic, soil physico-chemical, and management differences across regions and crop types.

4.4 | Potential mechanisms of SOC accumulation in perennial crops

There are two ways of increasing C stock, either via increasing inputs or decreasing outputs. Soils that transition from annual to perennial crops may likely benefit from both: perennials produce more plant residues than annual crops (Ferchaud et al., 2016) and this extra organic matter consequently returns to the soil. Besides, soils under annual crops experience annual tillage or other frequent mechanical disturbances (Powlson et al., 2014), which allows faster decomposition of the SOC in upper layers. Perennials, in contrast, are disturbed usually only at the beginning of the life cycle and not during (Ledo et al., 2018), thus potentially avoiding SOC lost by mechanical soil treatments.

Perennials not only produce more plant residue than annual crops (Ferchaud et al., 2016) but also have the potential additional plant inputs from management interventions such us pruning and on-site retention of litter (Ledo et al., 2018). Rasse et al. (2005) assert that SOC is mainly derived from root C, from root exudates and fine root turnover. The fine root biomass, which typically has a fast turnover, is likely to be soon lost to the atmosphere as CO_2 (Glover, Culman, et al., 2010). However, perennial crops develop larger roots that penetrate and develop fine roots deeper in the soil. Root residues at deeper horizons are less subject to oxidation and thus more likely to remain as SOC in the soil. Additionally, root penetration changes soil texture (Reynolds, Bowman, Drury, Tan, & Lu, 2002) and thus potentially creates a larger and deeper rhizosphere which in turn may increase root exudates and thus soil microbial interactions (Huang et al., 2014), resulting in more C being captured in soil aggregates (Kutsch et al., 2009; Stockmann et al., 2013). In addition, the rhizomes of perennial grasses are known to be important contributors of organic matter and exudates to the soil (Zatta, Clifton-Brown, Robson, Hastings, & Monti, 2014), which would result in an increase in SOC.

The linear trend of SOC stock changes shows an increasing trend (Figure 1a). However, it can be seen that a minor SOC gain is followed by SOC loss for a period of a few years, and only after this does SOC start to consistently accumulate year-on-year (Figure 1c). This observed SOC gain has a subsequent levelling off of SOC accumulation rate and a decline when it stabilizes and reaches a steady state (Figure 1c), which is consistent with the acknowledged patterns of SOC accumulation (Smith, 2014), and also observed in agroforestry systems (Feliciano, Ledo, Hillier, & Nayak, 2018). This might be attributed to the so-called priming effect (Thiessen, Gleixner, Wutzler, & Reichstein, 2013; Wutzler & Reichstein, 2013), or to the disturbance produced when planting perennials (Smith, 2004) or a combination of both, since these are not mutually exclusive.

Another of the conclusions of our study is that the lack of annual soil disturbance contributes to SOC increase. The lack of frequent mechanical interventions may not only reduce SOC losses, but also C inputs to the soil may increase if the herbaceous layer is not removed. However, the soil of some woody cropping systems is kept permanently bare, and if this is the case, it reduces SOC even in no-till treatments (Aguilera et al., 2013). Furthermore, SOC protection mechanisms should also be considered. The physical protection (i.e., organic C within soil microaggregates) isolates the organic C from the activity of the soil microorganisms, preventing its mineralization. SOC physical protection is also affected by tillage (Vicente-Vicente et al., 2017), because of the disruption of the macroaggregates, precursors of soil microaggregates (Six, Bossuyt, Degryze, & Denef, 2004). This may be another mechanism that favors SOC accumulation under perennial crops, due to the lack of mechanical intervention. Another protection mechanism is chemical protection (Six et al., 2002). However, the chemical protection depends mainly on the chemical soil properties (e.g., pH) and, therefore, the management is supposed not to have a large effect on it and may not be a different between annual and perennial crops in this regard.

4.5 | Emission factor of LUC, potential of perennials as climate change mitigation tools, and food security allies

The IPCC (2014) guidelines for preparing GHG emissions inventories provide a default value of 1 as the relative stock change in SOC over a 20-year period in the top 30 cm after conversion from any land use to perennials crops (volume 4, section 5 croplands, tables 5.5 and 5.10), with an uncertainty of 50%. Results from this study suggest that this value can be refined to 1.12, since overall perennial crops accumulate SOC (Figure 1), leaving 50% uncertainty to be conservative. To be more precise, it should be 1.12 for woody plants and 1.06 for perennial grasses (Figure 2; Appendix S1). Furthermore, this study revealed a relative stock change of 1.2 in the case of a change from annual to perennial crop (Table 1). This is not, strictly speaking, a change in land use, since the land use is arable in both cases. However, as the 1.2 value is relevant and important, we suggest that a subcategory may be added and considered in further assessments and recommendations. Similarly, the default value from grasslands and forest would be 1, since we did not find significant differences (Table 1).

A second recommendation for GHG factors and C stock benchmarks is to consider using a soil profile of 0–100 cm depth in future assessments. This study highlights the importance of the SOC stocks stored deeper than 30 cm. This considering only the top 30 cm may favor practices and crops which concentrate SOC in the top 30 cm rather than sequester C across a more relevant profile.

Overall, perennial crops accumulate SOC through time (Figure 1), and a change from annual to perennial crop will lead to a SOC increase during at least 20 years (Table 1). Furthermore, perennial crops have been suggested as a tool to increase food security and ecosystem functioning (Glover, Reganold, et al., 2010). Aside from increasing SOC stocks, perennials could also contribute to reducing soil erosion (Glover, Culman, et al., 2010), and with the potentiality to contribute to food security improvement (Lal, 2004). A significant reduction in soil erosion has been reported when the main crop is accompanied by a cover crop and thus bare soil is avoided (Aguilera et al., 2013; Gómez et al., 2011). A second important climate change mitigation option in perennial crops is adding crop residues back to the ground; perennials produce more plant residues than annual crops (Ferchaud et al., 2016) which inputs extra organic C to the soil. Alongside, bioenergy crops aside from being climate change mitigation tools in the field by increasing SOC (Dondini et al., 2009; Robertson et al., 2017), they usually have an overall GHG reduction benefit favorable when compared with other crops (Whitaker et al., 2018), and also they bring an extra GHG reduction when they are used to replace fossil fuels and may thus contribute to the transition to a low C economy (Qin et al., 2016).

Perennial crops have therefore the potential to be a climate change mitigation, by resulting a negative C balance system or at least storing some C in the ground and thus reducing atmospheric CO_2 concentration. Nonetheless there are some important limitations and the C gain cannot be considered as a universal statement and recipe for C sequestration by itself. Additionally, while some management practices such as reduced- or no-tillage may reduce SOC losses, additional agricultural practices may be required so the full life cycle needs to be considered (Schlesinger & Amundson, 2019). Plant residue management is also important, that is, burning tress at the end of the crop cycle results in net GHG emissions (Ledo et al., 2018). In this case, the C stored in the ground during the perennial plantation may be lower than the C and other GHGs emitted during the combustion, thus resulting in net positive emissions from the plantation. In contrast, using perennials in restoration of degraded agricultural lands, either on their own or in agroforestry combination, can provide additional benefits via coproducts, thus potentially contributing to food security and local economies.

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CONFLICT OF INTEREST

The authors declare no competing interests.

AUTHOR CONTRIBUTION

A.L., J.H., and P.S. initiated and designed the study. A.L. performed the analyses. H.B. participated in the empirical model fitting and diagnosis. E.D.-P. contributed to the further development of the initial study. A.Z. helped writing the first draft. A.L., P.S., A.Z., J.W., J.L.V.-V., Z.Q., N.P.M., Y.L.Z., M.Ll., M.Li., M.K., M.D., A.D., E.D.-P., A.D., H.B., E.A., and J.H. (all the authors) contributed ideas and wrote the manuscript.

DATA AVAILABILITY STATEMENT

The data and programming code used in this study are reproduced in Data S1 of this article. The original database—including details on data gathering and harmonization—is published in Ledo et al. (2019).

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REFERENCES

Aguilera, E., Lassaletta, L., Gattinger, A., & Gimeno, B. S. (2013). Managing soil carbon for climate change mitigation and adaptation in Mediterranean cropping systems: A meta-analysis. *Agriculture, Ecosystems & Environment*, *168*, 25–36. https://doi.org/10.1016/j.agee.2013.02.003

Blagodatsky, S., & Smith, P. (2011). Soil physics meets soil biology: Towards better mechanistic prediction of greenhouse gas emissions from soil. *Soil Biology and Biochemistry*, *47*, 78–92. https://doi.org/10.1016/j.soilbio.2011.12.015

Carvalhais, N., Forkel, M., Khomik, M., Bellarby, J., Jung, M., Migliavacca, M., … Reichstein, M. (2014). Global covariation of carbon turnover times with climate in terrestrial ecosystems. *Nature*, *514*(7521), 213–217. https://doi.org/10.1038/nature13731

Chave, J., Réjou-Méchain, M., Búrquez, A., Chidumayo, E., Colgan, M. S., Delitti, W. B. C., … Vieilledent, G. (2015). Improved allometric models to estimate the aboveground biomass of tropical trees. *Global Change Biology*, *20*(10), 3177–3190. https://doi.org/10.1111/gcb.12629

Cox, T. S., Glover, J. D., Van Tassel, D. L., Cox, C. M., & DeHaan, L. R. (2006). Prospects for developing perennial grain crops. *BioScience*, https://doi.org/10.1641/0006-3568(2006)56[649:PFDPGC]2.0.CO;2

Crowther, T. W., Todd-Brown, K. E. O., Rowe, C. W., Wieder, W. R., Carey, J. C., Machmuller, M. B., … Bradford, M. A. (2016). Quantifying global soil carbon losses in response to warming. *Nature*, *540*(7631), 104–108. https://doi.org/10.1038/nature20150

Datta, A., Basak, N., Chaudhari, S. K., & Sharma, D. K. (2015). Soil properties and organic carbon distribution under different land uses in reclaimed sodic soils of North-West India. *Geoderma Regional*, *4*, 134–146. https://doi.org/10.1016/j.geodrs.2015.01.006

Davidson, E. A., & Janssens, I. A. (2006). Temperature sensitivity of soil carbon decomposition and feedbacks to climate change. *Nature*, *440*(7081), 165–173. https://doi.org/10.1038/nature04514

Deng, L., Zhu, G., Tang, Z., & Shangguan, Z. (2016). Global patterns of the effects of land-use changes on soil carbon stocks. *Global Ecology and Conservation*, *5*, 127–138. https://doi.org/10.1016/j.gecco.2015.12.004

Doetterl, S., Stevens, A., Six, J., Merckx, R., Van Oost, K., Pinto, M. C., … Boeckx, P. (2015). Soil carbon storage controlled by interactions between geochemistry and climate. *Nature Geoscience*, *8*(10), 780–783. https://doi.org/10.1038/ngeo2516

Don, A., Böhme, I. H., Dohrmann, A. B., Poeplau, C., & Tebbe, C. C. (2017). Microbial community composition affects soil organic carbon turnover in mineral soils. *Biology and Fertility of Soils*, *53*(4), 445–456. https://doi.org/10.1007/s00374-017-1198-9

Don, A., Schumacher, J., & Freibauer, A. (2011). Impact of tropical land-use change on soil organic carbon stocks – A meta-analysis. *Global Change Biology*, *17*(4), 1658–1670. https://doi.org/10.1111/j.1365-2486.2010.02336.x

Dondini, M., Hastings, A., Saiz, G., Jones, M. B., & Smith, P. (2009). The potential of *Miscanthus* to sequester carbon in soils: Comparing field measurements in Carlow, Ireland to model predictions. *GCB Bioenergy*, *1*(6), 413–425. https://doi.org/10.1111/j.1757-1707.2010.01033.x

Feliciano, D., Ledo, A., Hillier, J., & Nayak, D. R. (2018). Which agroforestry options give the greatest soil and above ground carbon benefits in different world regions? *Agriculture, Ecosystems & Environment*, *254*, 117–129. https://doi.org/10.1016/j.agee.2017.11.032

Ferchaud, F., Vitte, G., & Mary, B. (2016). Changes in soil carbon stocks under perennial and annual bioenergy crops. *GCB Bioenergy*, *8*(2), 290–306. https://doi.org/10.1111/gcbb.12249

Fialho, R., & Zinn, Y. (2014). Changes in soil organic carbon under eucalyptus plantations in Brazil: A comparative analysis. *Land Degradation & Development*, *25*(5), 428–437. https://doi.org/10.1002/ldr.2158

Foley, J. A., DeFries, R., Asner, G. P., Barford, C., Bonan, G., Carpenter, S. R., … Gibbs, H. K. (2005). Global consequences of land use. *Science*, *309*(5734), 570–574. https://doi.org/10.1126/science.1111772

Glover, J. D., Culman, S. W., DuPont, S. T., Broussard, W., Young, L., Mangan, M. E., … Buckley, D. H. (2010). Harvested perennial grasslands provide ecological benchmarks for agricultural sustainability. *Agriculture, Ecosystems & Environment*, *137*(1-2), 3–12. https://doi.org/10.1016/j.agee.2009.11.001

Glover, J. D., Reganold, J. P., Bell, L. W., Borevitz, J., Brummer, E. C., Buckler, E. S., … Xu, Y. (2010). Increased food and ecosystem security via perennial grains. *Science*, *328*(5986), 1638–1639. https://doi.org/10.1126/science.1188761

Gómez, J. A., Llewellyn, C., Basch, G., Sutton, P. B., Dyson, J. S., & Jones, C. A. (2011). The effects of cover crops and conventional tillage on soil and runoff loss in vineyards and olive groves in several Mediterranean countries. *Soil Use and Management*, *27*(4), 502–514. https://doi.org/10.1111/j.1475-2743.2011.00367.x

Huang, X.-F., Chaparro, J. M., Reardon, K. F., Zhang, R., Shen, Q., & Vivanco, J. M. (2014). Rhizosphere interactions: Root exudates, microbes, and microbial communities. *Botany-Botanique*, *92*(4), 267–275. https://doi.org/10.1139/cjb-2013-0225

IPCC. (2014). *Climate change 2014: Synthesis report. Contribution of working groups I, II and III to the fifth assessment report of the Intergovernmental Panel on Climate Change*. Geneva, Switzerland: Author.

IPCC. (2019). *IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems*. Author. Retrieved from https://www.ipcc.ch/report/SRCCL/

Kutsch, W. L., Bahn, M., & Heinemeyer, A. (2009). *Soil carbon dynamics: An integrated methodology*. Cambridge, UK: Cambridge University Press.

Laganiere, J., Angers, D. A., & Pare, D. (2010). Carbon accumulation in agricultural soils after afforestation: A meta-analysis. *Global Change Biology*, *16*(1), 439–453. https://doi.org/10.1111/j.1365-2486.2009.01930.x

Lal, R. (2004). Soil carbon sequestration impacts on global climate change and food security. *Science*, *304*(5677), 1623–1627. https://doi.org/10.1126/science.1097396

Lal, R. (2006). Enhancing crop yields in the developing countries through restoration of the soil organic carbon pool in agricultural lands. *Land Degradation & Development*, *17*(2), 197–209. https://doi.org/10.1002/ldr.696

Ledo, A., Heathcote, R., Hastings, A., Smith, P., & Hillier, J. (2018). Perennial-GHG: A new generic allometric model to estimate biomass accumulation and greenhouse gas emissions in perennial food and bioenergy crops. *Environmental Modelling and Software*, *102*, 292–305. https://doi.org/10.1016/j.envsoft.2017.12.005

Ledo, A., Hillier, J., Smith, P., Aguilera, E., Blagodatskiy, S., Brearley, F. Q., … Zerihun, A. (2019). A global, empirical, harmonised dataset of soil organic carbon changes under perennial crops. *Scientific Data*, *6*(1). https://doi.org/10.1038/s41597-019-0062-1

Paustian, K., Six, J., Elliott, E. T., & Hunt, H. W. (2000). Management options for reducing CO_2 emissions from agricultural soils. *Biogeochemistry*, *48*, 147–163. https://doi.org/10.1023/A:1006271331703

Poeplau, C., Vos, C., & Don, A. (2017). Soil organic carbon stocks are systematically overestimated by misuse of the parameters bulk density and rock fragment content. *Soil*, *3*(1), 61–66. https://doi.org/10.5194/soil-3-61-2017

Post, W. M., & Kwon, K. C. (2000). Soil carbon sequestration and land-use change: Processes and potential. *Global Change Biology*, *6*(3), 317–327. https://doi.org/10.1046/j.1365-2486.2000.00308.x

Powlson, D. S., Stirling, C. M., Jat, M. L., Gerard, B. G., Palm, C. A., Sanchez, P. A., & Cassman, K. G. (2014). Limited potential of no-till agriculture for climate change mitigation. *Nature Climate Change*, *4*(8), 678–683. https://doi.org/10.1038/nclimate2292

Qin, Z., Dunn, J. B., Kwon, H., Mueller, S., & Wander, M. M. (2016). Soil carbon sequestration and land use change associated with biofuel production: Empirical evidence. *GCB Bioenergy*, *8*(1), 66–80. https://doi.org/10.1111/gcbb.12237

Rasse, D. P., Rumpel, C., & Dignac, M.-F. (2005). Is soil carbon mostly root carbon? Mechanisms for a specific stabilisation. *Plant and Soil*, *269*(1-2), 341–356. https://doi.org/10.1007/s11104-004-0907-y

Reynolds, W. D., Bowman, B. T., Drury, C. F., Tan, C. S., & Lu, X. (2002). Indicators of good soil physical quality: Density and storage parameters. *Geoderma*, *110*(1-2), 131–146. https://doi.org/10.1016/S0016-7061(02)00228-8

Robertson, A. D., Whitaker, J., Morrison, R., Davies, C. A., Smith, P., & Mcnamara, N. P. (2017). A *Miscanthus* plantation can be carbon neutral without increasing soil carbon stocks. *GCB Bioenergy*, *9*(3), 645–661. https://doi.org/10.1111/gcbb.12397

Rue, H., Martino, S., & Chopin, N. (2009). Approximate Bayesian inference for latent Gaussian models by using integrated nested Laplace approximations. *Journal of the Royal Statistical Society: Series B*, *71*(2), 319–392. https://doi.org/10.1111/j.1467-9868.2008.00700.x

Schlesinger, W. H., & Amundson, R. (2019). Managing for soil carbon sequestration: Let's get realistic. *Global Change Biology*, *25*(2), 386–389. https://doi.org/10.1111/gcb.14478

Six, J., Bossuyt, H., Degryze, S., & Denef, K. (2004). A history of research on the link between (micro) aggregates, soil biota, and soil organic matter dynamics. *Soil and Tillage Research*, *79*(1), 7–31. https://doi.org/10.1016/j.still.2004.03.008

Six, J., Conant, R., Paul, E., & Paustian, K. (2002). Stabilization mechanisms of soil organic matter: Implications for C-saturation of soils. *Plant and Soil*, *241*, 155–176. https://doi.org/10.1023/A:1016125726789

Smith, P. (2004). Soils as carbon sinks: The global context. *Soil Use and Management*, *20*(2), 212–218. https://doi.org/10.1111/j.1475-2743.2004.tb00361.x

Smith, P. (2014). Do grasslands act as a perpetual sink for carbon? *Global Change Biology*, *20*(9), 2708–2711. https://doi.org/10.1111/gcb.12561

Smith, P., Gregory, P. J., Van Vuuren, D., Obersteiner, M., Havlík, P., Rounsevell, M., … Bellarby, J. (2010). Competition for land. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *365*(1554), 2941–2957. https://doi.org/10.1098/rstb.2010.0127

Stockmann, U., Adams, M. A., Crawford, J. W., Field, D. J., Henakaarchchi, N., Jenkins, M., … Zimmermann, M. (2013). The knowns, known unknowns and unknowns of sequestration of soil organic carbon. *Agriculture, Ecosystems & Environment*, *164*, 80–99. https://doi.org/10.1016/j.agee.2012.10.001

Thiessen, S., Gleixner, G., Wutzler, T., & Reichstein, M. (2013). Both priming and temperature sensitivity of soil organic matter decomposition depend on microbial biomass – An incubation study. *Soil Biology and Biochemistry*, *57*, 739–748. https://doi.org/10.1016/j.soilbio.2012.10.029

Vicente-Vicente, J. L., García-Ruiz, R., Francaviglia, R., Aguilera, E., & Smith, P. (2016). Soil carbon sequestration rates under Mediterranean woody crops using recommended management practices: A meta-analysis. *Agriculture, Ecosystems & Environment*, *235*, 204–214. https://doi.org/10.1016/j.agee.2016.10.024

Vicente-Vicente, J. L., Gómez-Muñoz, B., Hinojosa-Centeno, M. B., Smith, P., & Garcia-Ruiz, R. (2017). Carbon saturation and assessment of soil organic carbon fractions in Mediterranean rainfed olive orchards under plant cover management. *Agriculture, Ecosystems & Environment*, *245*, 135–146. https://doi.org/10.1016/j.agee.2017.05.020

Whitaker, J., Field, J. L., Bernacchi, C. J., Cerri, C. E. P., Ceulemans, R., Davies, C. A., … McNamara, N. P. (2018). Consensus, uncertainties and challenges for perennial bioenergy crops and land use. *GCB Bioenergy*, *10*(3), 150–164. https://doi.org/10.1111/gcbb.12488

Wollenberg, E., Tapio-Bistrom, M.-L., Grieg-Gran, M., & Nihart, A. (Eds.). (2011). *Climate change mitigation and agriculture*. Oxon: Earthscan. ISBN 9781849713924.

Wutzler, T., & Reichstein, M. (2013). Priming and substrate quality interactions in soil organic matter models. *Biogeosciences*, *10*(3), 2089–2103. https://doi.org/10.5194/bg-10-2089-2013

Zatta, A., Clifton-Brown, J., Robson, P., Hastings, A., & Monti, A. (2014). Land use change from C3 grassland to C4 *Miscanthus*: Effects on soil carbon content and estimated mitigation benefit after six years. *GCB Bioenergy*, *6*(4), 360–370. https://doi.org/10.1111/gcbb.12054

Zinn, Y. L., Lal, R., & Resck, D. V. (2011). Eucalypt plantation effects on organic carbon and aggregation of three different-textured soils in Brazil. *Soil Research*, *49*(7), 614. https://doi.org/10.1071/SR11264

SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section.

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Original research article

Global patterns of the effects of land-use changes on soil carbon stocks

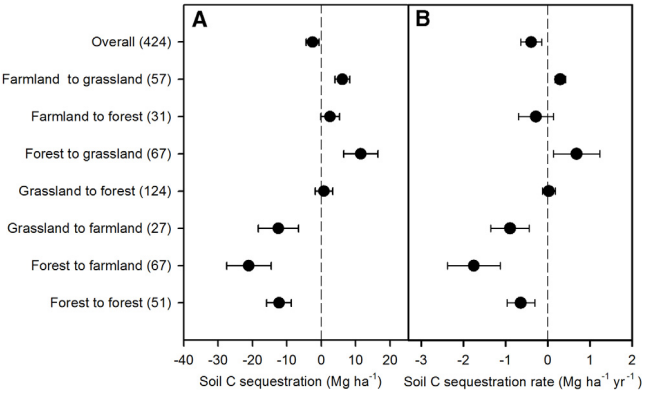
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HIGHLIGHTS

- Soil C sequestrations varied in different land use change types.
- Soil C sequestration dynamics were not determined by age at the global level.
- Globally, land use conversions have significantly reduced soil C stock.

GRAPHICAL ABSTRACT



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ABSTRACT

Despite hundreds of field studies and at least a dozen literature reviews, there is still considerable disagreement about the direction and magnitude of changes in soil C stocks with land use change. This paper reviews the literature on the effects of land use conversions on soil C stocks, based on a synthesis of 103 recent publications, including 160 sites in 29 countries, with the aims of determining the factors responsible for soil C sequestration and quantifying changes in soil C stocks from seven land use conversions. The results show that as an overall average across all land use change examined, land use conversions have significantly reduced soil C stocks (0.39 Mg ha^{-1} yr^{-1}). Soil C stocks significantly increased after conversions from farmland to grassland (0.30 Mg ha^{-1} yr^{-1}) and forest to grassland (0.68 Mg ha^{-1} yr^{-1}), but significantly declined after conversion from grassland to farmland (0.89 Mg ha^{-1} yr^{-1}), forest to farmland (1.74 Mg ha^{-1} yr^{-1}), and forest to forest (0.63 Mg ha^{-1} yr^{-1}). And after conversion from farmland to forest and grassland to forest, soil C stocks did not change significantly. Globally, soil C sequestration showed a significant negative correlation with initial soil C stocks ($P<0.05$), and the

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effects of climatic factors (mean annual temperature and mean annual precipitation) on soil C sequestration varied between the land use conversion types. Also, the relationships between soil C sequestration and age since land use conversion varied in different land use change types. Generally, where the land use changes decreased soil C, the reverse process usually increased soil C stocks and vice versa. Soil C sequestration dynamics were not determined by age since land use conversion at the global level when all land use change types were combined.
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1. Introduction

The terrestrial biosphere can act either as a source or as a sink for atmospheric CO_2, both the vegetation and the soil may play a part in the residual terrestrial uptake (IPCC, 2000; Guo and Gifford, 2002). Organic carbon stored in the world's soils is the largest terrestrial pool of carbon, and is at least three times larger than the pool of atmospheric carbon dioxide (Jobbágy and Jackson, 2000; Amundson, 2001). It has long been recognized that land-cover change and management can alter the amount of organic carbon stored in the soil (Laganière et al., 2010; Deng et al., 2014a), and this in turn affects both soil fertility and atmospheric carbon dioxide (CO_2) concentrations (Powers et al., 2011). Although the contributions of land-cover change to anthropogenic CO_2 atmospheric emissions have recently been revised downward, the estimated current annual contribution of 1.2 Pg, or about 12%–15% of total anthropogenic fluxes, is still significant (Van der Werf et al., 2009). Therefore, a new challenge in the context of climate change mitigation is the management of terrestrial ecosystem to conserve existing carbon stocks and to remove carbon from the atmosphere by adding to stocks.

Land use change can cause a change in land cover and an associated change in carbon stocks (Bolin and Sukumar, 2000; Deng et al., 2014a,b). The change from one ecosystem to another could occur naturally or be the result of human activity. Each soil has a carbon carrying capacity, and an equilibrium carbon content depending on the nature of vegetation, precipitation and temperature (Jobbágy and Jackson, 2000). The equilibrium between carbon inflows and outflows in soil is disturbed by land use change until a new equilibrium is eventually reached in the new ecosystem (Guo and Gifford, 2002). During this process, soil C stocks would have been changed, either as a carbon source or as a carbon sink. Despite hundreds of field studies and dozens of literature reviews, there is still considerable disagreement on the direction and magnitude of changes in soil C stocks with land-use change (Van der Werf et al., 2009). Indeed, the current knowledge remains inconclusive on both the magnitude and direction of C stock changes in mineral soils associated with land use type, management and other disturbances, and cannot support broad generalizations (IPCC, 2006).

Recently, some studies have reviewed the effects of certain land use changes on soil C stocks, for example, Post and Kwon (2000) found an average rate of soil C accumulation after afforestation of former farmlands with the value of 0.338 Mg ha^{-1} yr^{-1} although values vary greatly among studies, however, Vesterdal et al. (2002) observed that afforestation of former farmlands did not lead to increase of SOC in three decades. In addition, for a tropical regions study, the conversion of forests to farmland reduced soil C stocks by an average of 15.4% or 18.5%, respectively. Interestingly, both the conversions of forests to grassland and grassland to secondary forests increased soil C stocks, and the establishment of perennial tree plantations on lands that were previously grazed or cropped increased soil C stocks, but the conversion of unmanaged forests, or grasslands to plantations had no effect (Powers et al., 2011). Globally, although Guo and Gifford (2002) concluded that soil C stocks significantly increased after the conversion from farmland to grassland (19%), tree plantation (18%) and secondary forest (53%), they uses a relative percentage change. In order to understand how C stocks change after land use conversions, the changes need to be recalculated as absolute values to meet the challenge of managing soil C stocks world-wide and to help understand the contribution of carbon emissions due to land use change to the global climate change.

In addition, understanding the factors that govern the size of the current land carbon stock and the balance between plant carbon inputs and soil carbon losses is crucial to predicting the effects of future land use change on the net greenhouse gas balance, and to the development of policy for 'carbon conscious' management of the land surface. Although several authors (Post and Kwon, 2000; Paul et al., 2002; Laganière et al., 2010) have analyzed the factors determining soil C stocks during the establishment of perennial vegetation, a consensus on the relative significance of these factors has yet to be achieved. While Paul et al. (2002) found that climate is one of the most important factors influencing soil C change after cropland conversion, Laganière et al. (2010) concluded that climate had a smaller effect on soil C accumulation during afforestation when compared to previous land use, tree species planted, soil clay content and preplanting disturbance. However, at a global scale, we had difficulties in getting access to many factors that may influence the soil C stock after land use change from the existing field studies, except for climatic factors, so this paper mainly analyzed the effects of mean annual precipitation and temperature on soil C sequestration after land use conversions, as was done by other national or global studies (Guo and Gifford, 2002; Paul et al., 2002; Yang et al., 2011).

The objectives of this study were: (1) explore the effect of various land use changes on soil C sequestration; (2) establish the temporal pattern of soil C sequestration for different land use changes; and (3) study those factors driving the changes in soil C. To achieve these objectives we synthesized the findings of 103 recent publications from the literature in which

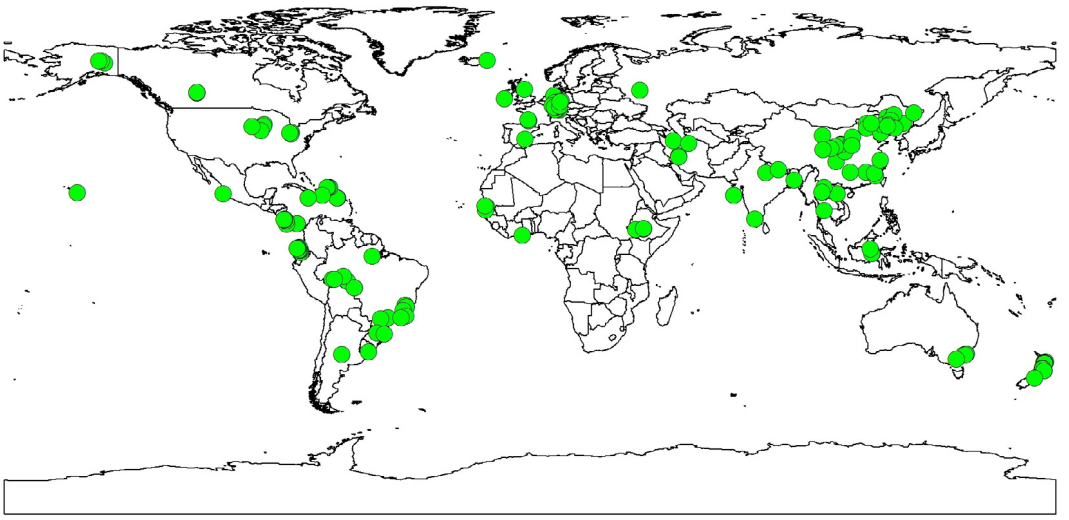


Fig. 1. Global sampling sites distribution of observed soil C change after land use conversions in the collected dataset.

seven land use conversions (from farmland to forest, from forest to farmland, from farmland to grassland, from grassland to farmland, from grassland to forest, from forest to grassland, from forest to forest) were related to changes in soil C values.

2. Materials and methods

2.1. Data preparation

We compiled data from the literature on the influence of land use change on soil C stocks and characterized each study according to the following categories of land use change: from farmland to forest, from forest to farmland, from farmland to grassland, from grassland to farmland, from grassland to forest, from forest to grassland, from forest to forest. The following criteria were used to select papers for synthesis: soil C stocks were provided or could be calculated based on SOC or SOM concentration, bulk density and soil depth; there were data on both the immediate land use (LUn) and the prior land use (LU0); the experiments used paired sites, chronosequences or retrospective designs, had similar soil conditions for both LUn and LU0; the number of years since land use conversion were either clearly given or could be directly derived. In the studies, only the first rotation of land use conversion was considered and data for 0–20 cm soil layers were extracted (Appendix Dataset S1). In addition, studies were excluded if they lacked replications or if the paired sites or sites of chronosequence were confounded by different soil types. In total, the final dataset comprised 103 studies (Appendix Table S1) most of them published between 2000 and 2014, and three studies published in 1994, 1997 and 1999, respectively, including 424 observations at 160 sites in 29 countries (Appendix Table S2) (Fig. 1). In the current study, the definition of forest is native forest before it is cleared for other land use. Pasture is land used for grazing purposes including natural grassland. Farmland includes lands cultivated for food products. The current forest is the plantation forest by human establishment. The ages of land use conversions were divided into four groups, as follows: 0–10, 11–20, 21–30, and >30 yr.

The raw data were either obtained from tables or extracted by digitizing graphs using the GetData Graph Digitizer (version 2.24, Russian Federation). For each paper, the following information was compiled: sources, location (longitude and latitude), climatic data (mean annual temperature and precipitation), land-use conversion types (including both prior and current land use types), age (years since land use conversion), soil depth from soil surface, soil bulk density, and amount of SOC or soil C stocks in each layer of 0–100 cm soil (Appendix Dataset S2).

2.2. Data calculation

If the samples reported only had SOM, their SOC were calculated by the relation between SOM and SOC. The formula for the calculation is as follows (Guo and Gifford, 2002):

$$\mathrm{SOC} = \mathrm{SOM} \times 0.58 \tag{1}$$

where SOC is the soil organic carbon and SOM is the soil organic matter.
The SOC stocks was calculated using the following equation (Guo and Gifford, 2002):

$$C_s = \frac{\mathrm{SOC} \times \mathrm{BD} \times \mathrm{D}}{10} \tag{2}$$

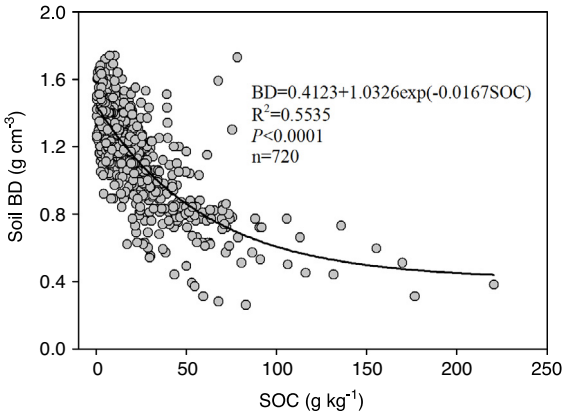


Fig. 2. Empirical functions for estimating the missing soil BD based on data from studies reporting SOC concentration and soil BD.

in which, C_s is soil organic carbon stocks (Mg ha^{-1}); SOC is soil organic carbon concentration (g kg^{-1}); BD is soil bulk density (g cm^{-3}); and D is soil thickness (cm).

Soil BD estimates are critical for calculations of C_s, but many studies did not measure this attribute. We established an empirical relationship between soil BD and SOC concentration with the reported values from the Appendix Dataset S2 (Fig. 2). Then, the missing values of soil BD were interpolated using the predicted values from the empirical functions in Fig. 2. The formula for the calculation is as follows (Eq. (3)):

$$\mathrm{BD} = 0.4123 + 1.0326e^{-0.0413\mathrm{soc}}. \tag{3}$$

Although it is desirable to compare changes in soil C stocks between land uses based on common soil mass rather than on volume because of compaction, it is impossible for us to correct data for all these studies, as not all the studies reported bulk densities, especially bulk densities for different soil depths. Thus, similar to other meta-analysis (Guo and Gifford, 2002; Laganière et al., 2010; Powers et al., 2011), we did not adjust reported data to a common mass, but we used mass-corrected soil C stocks when authors presented them. Not adjusting for an equivalent mass of soil could only result in a slight bias in the estimation of changes in soil C stocks, which is supported by our data and also by other studies (Laganière et al., 2010).

To increase the comparability of data derived from different studies, the methodology adopted by Yang et al. (2011) was used in the present study. The original soil C data were converted to the soil C stocks in the top 20 cm using the depth functions developed by Jobbágy and Jackson (2000) according to the following equations:

$$Y = 1 - \beta^d \tag{4}$$

$$X_{20} = \frac{1-\beta^{20}}{1-\beta^{d0}} \times X_{d0} \tag{5}$$

where Y represents the cumulative proportion of the soil C stocks from the soil surface to depth d (cm); β is the relative rate of decrease in the soil C stocks with soil depth; X_{20} denotes the soil C stocks in the upper 20 cm; $d0$ denotes the original soil depth available in individual studies (cm); and X_{d0} is the original soil C stocks. For soil C, although Jobbágy and Jackson (2000) provided the depth distributions for 11 biome types globally, there was no significant difference ($P > 0.98$), ANOVA LSD test using PASW 18 (SPSS Inc., Chicago, IL, USA) in the depth distribution among biome types or between individual biomes and the global average. Therefore, in this study, the global average depth distributions for C were adopted to calculate the value of β (0.9786) in Equations.

It should be noted that potential uncertainties may be introduced by this dataset standardization, mainly as a result of the difference in C distribution over the soil profile between prior land use types and immediate land use sites, and among different stages of vegetation (forest, shrub and grassland) development. However, as has been stated, there was no significant difference among the 11 biome types included in Jobbágy and Jackson (2000) or between individual biomes and the global average in terms of the soil C distribution with depth. The same method (i.e., converting the original C stocks to the stocks in the top 20 cm using the depth functions in order to increase comparability) was used by Yang et al. (2011) and Li et al. (2012), and it was concluded that depth correction did not alter the overall pattern of soil C stocks dynamics during vegetation development.

C sequestration rate is estimated depending on the changes of soil C stocks in different time sequences of time. The study set the C stocks of prior land use types as the baseline for calculating the rate of C stocks change in the restoration process after land use conversions. We first calculate the carbon sequestration (Mg ha^{-1}) in every site after land use conversion (Eq. (6)),

$$\Delta C_s = C_{LUn} - C_{LU0} \tag{6}$$

in which, C_{LUn} is represent soil carbon stocks at immediate land use sites (Mg ha^{-1}), and C_{LU0} is soil carbon stocks of prior land use types before land use conversion (Mg ha^{-1}).

We used mean annual absolute rate of change in soil C stock to indicate soil C sequestration rate (R_s, Mg ha^{-1} yr^{-1}). The calculated equation is as follows:

$$\text{Soil C sequestration rate (Mg ha}^{-1}\text{ yr}^{-1}) : R_s = \frac{\Delta C_s}{\Delta Age}. \tag{7}$$

In order to reflect the dynamics of soil C stocks, soil C sequestration were summed for each category. In this case, a methodology reported previously (Luo et al., 2006, 2009) was used to calculate 95% CI of means for soil C sequestration, as shown in Eqs. (8) and (9):

$$SE_{total} = \sqrt{\frac{V_S}{N}} \tag{8}$$

$$95\%\ CI = 1.96 \times SE_{total} \tag{9}$$

where SE_{total} denotes the standard error of the relative change in soil C stock. V_S and N are the variance of relative soil C stock change and the number of observations, respectively. In this study, the 95% confidence interval (CI) was calculated for the overall data and for each category. And the observed effect sizes are considered statistically different from zero if the 95% CI does not include zero, and the grouping factors are considered significantly different from each other if their 95% CI does not overlap.

2.3. Data analysis

ANOVA results of the effects of land use conversions, years since land use conversion (Age), and their interactions on soil C sequestration in different land use conversion types with general linear model (GLM) tests. Differences were evaluated at the 0.05 significance level. Stepwise regression analysis was used to analysis the relationship between soil C sequestration (ΔC_s) and mean annual temperature (MAT), mean annual precipitation (MAP), age since land use conversions (Age), and initial soil C stocks (I) in each land use conversion types. Pearson correlation coefficients between soil C sequestration and various other factors (Age, I, MAT, and MAP) were determined following land-use conversions. All statistical analyses were performed using the software program SPSS, ver. 17.0 (SPSS Inc., Chicago, IL, USA).

3. Results

3.1. Global patterns of soil C stock changes due to land use conversions

As an overall average across all land use change examined, land use conversions had significantly reduced soil C stock (−2.52 Mg ha^{-1}, rate = 0.39 Mg ha^{-1} yr^{-1}) (Fig. 3). However, not all land use conversions have reduced soil C stock. Soil C stocks significantly increased after the conversion from farmland to grassland (+6.16 Mg ha^{-1}, rate = 0.30 Mg ha^{-1} yr^{-1}), forest to grassland (+11.53 Mg ha^{-1}, rate = 0.68 Mg ha^{-1} yr^{-1}) (Fig. 3). Soil C stocks had significantly declined after the conversion from grassland to farmland (−12.45 Mg ha^{-1}, rate = 0.89 Mg ha^{-1} yr^{-1}), forest to farmland (−21.05 Mg ha^{-1}, rate = 1.74 Mg ha^{-1} yr^{-1}) and forest to forest (−12.28 Mg ha^{-1}, rate = 0.63 Mg ha^{-1} yr^{-1}) (Fig. 3). The highest soil C stock increases occurred in land-use conversions from forest to grassland, and soil C stocks declined the most after conversion from forest to farmland. After conversions of farmland to forest and grassland to forest, soil C stocks did not change significantly (Fig. 3).

3.2. Temporal patterns of soil C stocks after land use conversions

Overall, after land use conversions, the differences in soil C sequestration were not significant among different age groups ($P > 0.05$) (Table 1), but soil C sequestration changes fluctuated over time (Fig. 4). With the land-use change from farmland to grassland, soil C sequestration change was not significant during 0–10 years, and then it was significantly increased (Fig. 5(A)). Soil C sequestration had significantly difference among different age groups ($P < 0.01$) (Table 1). With the land-use change from grassland to farmland, soil C sequestration had not significantly difference among different age groups ($P > 0.05$) (Table 1). Soil C stocks had been reducing in the first 30 years (0–30 yr), and then soil C stock began to increase (>30 yr) (Fig. 5(B)), however, soil C stock still reduced compared to the initial soil C stock. With the land-use change from farmland to forest, soil C sequestration had significant differences among different age groups ($P < 0.01$) (Table 1). Soil C sequestration was significantly reduced in the first 10 years (0–10 yr), and then it was significantly increased (>10 years) (Fig. 5(C)). With the land-use change from forest to farmland, soil C sequestration had no significant difference among different age groups ($P > 0.05$) (Table 1). Soil C stock was similar to the conversion from grassland to farmland that soil C stocks had been reducing in the first 30 years (0–30 yr), and then soil C stock began to increase (>30 yr) (Fig. 5(D)). With the land-use change from grassland to forest, soil C sequestration had significant differences among different age groups

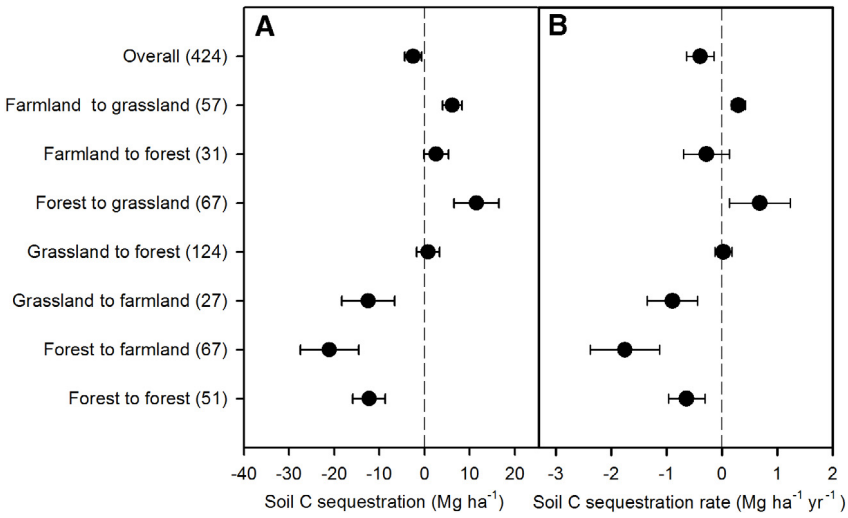


Fig. 3. The effects of the land use changes on soil C sequestration and soil C sequestration rate. Note: dots with error bars denote the overall mean values and the 95% CI, and numbers of observations are in the parenthesis. The dash line indicates $x = 0$.

Table 1
ANOVA results of between-subjects effects of years since land use conversion (Age), and their interactions on soil C sequestration in different land use conversion types (LUE) with general linear model (GLM) tests.

Land use change types	Source	df	F	Sig. (P)
Farmland to grassland	Age	3	11.793	0.000**
Grassland to farmland	Age	3	0.973	0.422
Farmland to forest	Age	3	13.535	0.000**
Forest to farmland	Age	3	1.331	0.272
Grassland to forest	Age	3	4.451	0.005**
Forest to grassland	Age	3	2.883	0.043*
Forest to forest	Age	3	3.953	0.014*
	LUE	6	27.565	0.000**
Overall	Age	3	2.307	0.076
	LUE × Age	18	2.361	0.001**

Note: Age were divided into four groups, as follows: 0–10, 11–20, 21–30, and >30 yr.
* Indicates significant at $P < 0.05$.
** Indicates significant at $P < 0.01$.

($P < 0.01$) (Table 1). Soil C stock was not significantly reduced in the first 10 years, and then it was significant increased (11–20 yr), but it also tended to significantly reduce from 21 to 30 years, and then increase after 30 years (Fig. 5(E)). With the land-use change from forest to grassland, soil C sequestration had significant differences among different age groups ($P < 0.05$) (Table 1). Soil C stock was increased after land use conversion (Fig. 5), especially after conversion for more than 30 years, soil C stock increased 24.40 Mg ha^{-1} compared with the initial soil C stock (Fig. 5(F)). With the land-use change from forest to forest, soil C stock was reduced especially after more than 30 years (−19.45 Mg ha^{-1}) (Fig. 5(G)). And soil C sequestration had significant differences among different age groups ($P < 0.05$) (Table 1).

3.3. Factor effects on soil C stocks

Pearson correlations analysis showed that in different age groups, the factors affecting soil C sequestrations were different (Table 2). However, after land use conversions, soil C sequestration had significant negative correlations with the initial soil C stocks in every land use conversion type ($P < 0.05$) (Table 2). In addition, after the conversion of farmland to grassland and forest, soil C sequestration also had significant positive correlations with the age since land use conversion, but it showed negative correlations after the conversion of forest to forest (Table 2). For the conversion of grassland to forest, soil C sequestration also had significant positive correlations with MAT (Table 2).

Stepwise regression revealed that different land use conversion types had different impact factors (Table 3). The age since land use conversion had significant effects on soil C sequestration after the conversion of farmland to grassland, farmland to forest, and forest to forest (Table 3); the initial soil C stock was the main factor affecting soil C sequestration after the conversion of grassland to farmland, forest to farmland and grassland to forest (Table 3); and climatic factors (MAT and MAP) were the main factors affecting soil C sequestration after the conversion of forest to grassland (Table 3). However, for

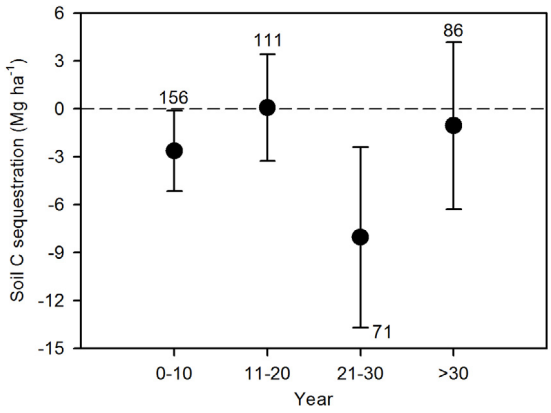


Fig. 4. The effects of the land use changes on soil C sequestration in different age groups. Note: dots with error bars denote the overall mean values and the 95% CI, and numbers of observations above the error bars.

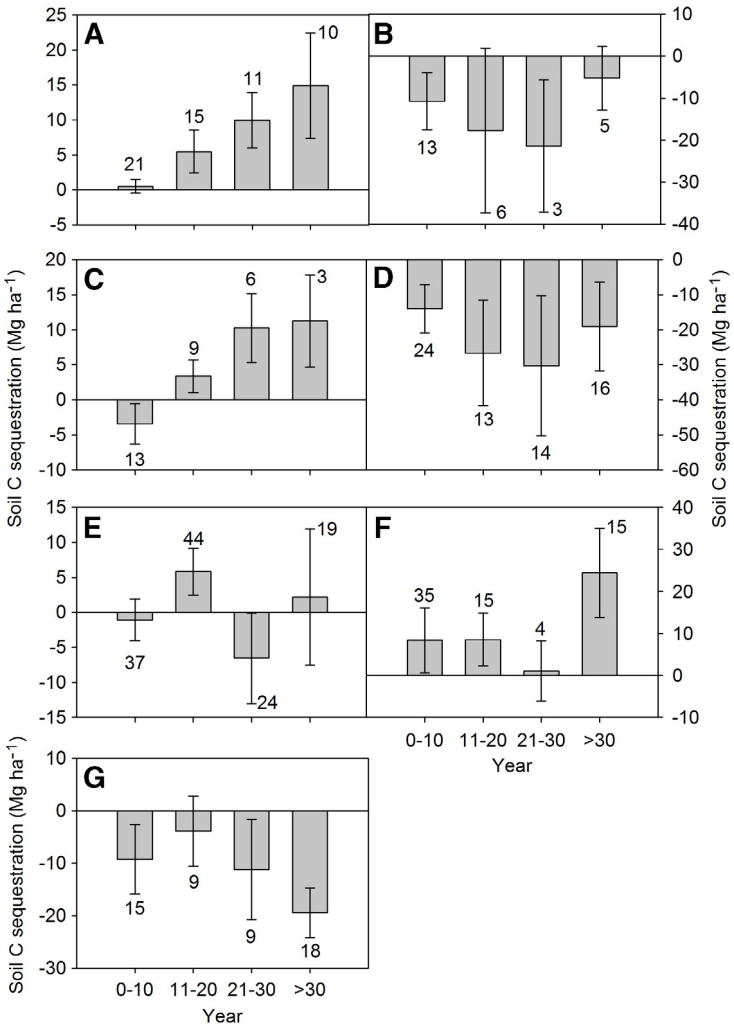


Fig. 5. The effects of the land use changes on soil C stocks in different age groups after the conversion. Note: A, farmland to grassland, B, grassland to farmland, C, farmland to forest, D, forest to farmland, E, grassland to forest, F, forest to grassland, G, forest to forest. Bar charts with error bars denote the overall mean values and the 95% CI, and numbers of observations above the error bars.

all land use conversions, the initial soil C stocks and climatic factors had significant effects on soil C sequestration after land use conversions, particularly the initial soil C stocks (Table 3).

Table 2
Pearson correlation coefficients between soil C sequestration and factors: age after land use conversion (Age), initial soil C stocks (I), mean annual temperature (MAT), mean and annual precipitation (MAP) following land-use conversions.

Land use change types	Age groups	Age (yr)	I (Mg ha^{-1})	MAT (°C)	MAP (mm)
Farmland to grassland	0–10	−0.260 ($n = 21$)	0.252 ($n = 21$)	−0.083 ($n = 21$)	−0.014 ($n = 21$)
	11–20	0.539* ($n = 15$)	0.658** ($n = 15$)	0.167 ($n = 15$)	−0.137 ($n = 15$)
	21–30	0.407 ($n = 11$)	−0.334 ($n = 11$)	−0.7** ($n = 11$)	−0.003 ($n = 11$)
	>30	0.714* ($n = 10$)	0.898** ($n = 10$)	−0.393 ($n = 10$)	0.047 ($n = 10$)
	All	0.739** ($n = 57$)	0.639** ($n = 57$)	−0.061 ($n = 57$)	0.228 ($n = 57$)
Grassland to farmland	0–10	−0.499 ($n = 13$)	−0.601* ($n = 13$)	0.375 ($n = 13$)	0.135 ($n = 13$)
	11–20	−0.504 ($n = 6$)	−0.913* ($n = 6$)	0.469 ($n = 6$)	0.424 ($n = 6$)
	21–30	−0.665 ($n = 3$)	−0.663 ($n = 3$)	0.181 ($n = 3$)	−0.996 ($n = 3$)
	>30	0.630 ($n = 5$)	−0.980** ($n = 5$)	0.481 ($n = 5$)	0.526 ($n = 5$)
	All	0.017 ($n = 27$)	−0.741** ($n = 27$)	0.331 ($n = 27$)	0.147 ($n = 27$)
Farmland to forest	0–10	0.357 ($n = 13$)	−0.165 ($n = 13$)	−0.640* ($n = 13$)	−0.600* ($n = 13$)
	11–20	0.181 ($n = 9$)	0.598 ($n = 9$)	−0.067 ($n = 9$)	0.493 ($n = 9$)
	21–30	−0.253 ($n = 6$)	−0.218 ($n = 6$)	0.432 ($n = 6$)	0.570 ($n = 6$)
	>30	0.844 ($n = 3$)	0.727 ($n = 3$)	−0.727 ($n = 3$)	0.727 ($n = 3$)
	All	0.767** ($n = 31$)	−0.415* ($n = 31$)	−0.01 ($n = 31$)	−0.345 ($n = 31$)
Forest to farmland	0–10	−0.246 ($n = 24$)	−0.637** ($n = 24$)	0.137 ($n = 24$)	0.013 ($n = 24$)
	11–20	0.252 ($n = 13$)	−0.699** ($n = 13$)	0.194 ($n = 13$)	−0.031 ($n = 13$)
	21–30	−0.121 ($n = 14$)	−0.874** ($n = 14$)	−0.326 ($n = 14$)	−0.358 ($n = 14$)
	>30	−0.170 ($n = 16$)	−0.701** ($n = 16$)	−0.333 ($n = 16$)	0.108 ($n = 16$)
	All	−0.096 ($n = 67$)	−0.730** ($n = 67$)	−0.098 ($n = 67$)	−0.079 ($n = 67$)
Grassland to forest	0–10	0.096 ($n = 37$)	−0.465** ($n = 37$)	0.221 ($n = 37$)	0.015 ($n = 37$)
	11–20	0.435** ($n = 44$)	−0.178 ($n = 44$)	0.156 ($n = 44$)	0.093 ($n = 44$)
	21–30	−0.251 ($n = 24$)	−0.609** ($n = 24$)	0.300 ($n = 24$)	0.128 ($n = 24$)
	>30	0.015 ($n = 19$)	−0.723** ($n = 19$)	0.221 ($n = 19$)	0.082 ($n = 19$)
	All	0.01 ($n = 124$)	−0.408** ($n = 124$)	0.241** ($n = 124$)	0.09 ($n = 124$)
Forest to grassland	0–10	−0.212 ($n = 33$)	−0.374* ($n = 33$)	0.201 ($n = 33$)	0.370* ($n = 33$)
	11–20	−0.152 ($n = 15$)	−0.174 ($n = 15$)	−0.551* ($n = 15$)	−0.384 ($n = 15$)
	21–30	−0.938 ($n = 4$)	−0.925 ($n = 4$)	0.461 ($n = 4$)	−0.926 ($n = 4$)
	>30	−0.203 ($n = 15$)	0.075 ($n = 15$)	−0.488 ($n = 15$)	−0.452 ($n = 15$)
	All	0.225 ($n = 67$)	−0.416** ($n = 67$)	−0.107 ($n = 67$)	−0.021 ($n = 67$)
Forest to forest	0–10	−0.029 ($n = 15$)	−0.441 ($n = 15$)	0.328 ($n = 15$)	0.406 ($n = 15$)
	11–20	−0.071 ($n = 9$)	0.599 ($n = 9$)	−0.715* ($n = 9$)	−0.286 ($n = 9$)
	21–30	−0.191 ($n = 9$)	−0.689* ($n = 9$)	−0.316 ($n = 9$)	−0.414 ($n = 9$)
	>30	−0.095 ($n = 18$)	−0.171 ($n = 18$)	−0.153 ($n = 18$)	0.059 ($n = 18$)
	All	−0.356* ($n = 51$)	−0.425** ($n = 51$)	−0.094 ($n = 51$)	−0.026 ($n = 51$)
Overall	0–10	−0.107 ($n = 156$)	−0.410** ($n = 156$)	0.115 ($n = 156$)	0.106 ($n = 156$)
	11–20	0.123 ($n = 111$)	−0.454** ($n = 111$)	0.217* ($n = 111$)	0.172 ($n = 111$)
	21–30	−0.180 ($n = 71$)	−0.753** ($n = 71$)	−0.148 ($n = 71$)	−0.096 ($n = 71$)
	>30	−0.035 ($n = 86$)	−0.468** ($n = 86$)	−0.260* ($n = 86$)	0.036 ($n = 86$)
	All	**−0.010 ($n = 424$)**	**−0.504** ($n = 424$)**	**−0.03 ($n = 424$)**	**0.07 ($n = 424$)**

Note: (value) indicates the number of observations.
* Correlation is significant at the 0.05 level (2-tailed) ($P < 0.05$).
** Correlation is significant at the 0.01 level (2-tailed) ($P < 0.01$).

Table 3
Stepwise regression to detect factors (Age, I, MAT, and MAP) determining soil C sequestration following land-use conversions.

Land use change types	Equations	R^2	Sig. (P)	n
Farmland to grassland	$\Delta C_s = 0.31\text{Age} + 0.20\text{I} - 4.30$	0.630	0.001**	57
Grassland to farmland	$\Delta C_s = -0.48\text{I} + 10.01$	0.537	0.000**	27
Farmland to forest	$\Delta C_s = 0.52\text{Age} - 5.76$	0.589	0.000**	31
Forest to farmland	$\Delta C_s = -0.53\text{I} - 0.25\text{Age} + 19.22$	0.546	0.000**	67
Grassland to forest	$\Delta C_s = -0.35\text{I} + 0.01\text{MAP} + 9.10$	0.402	0.000**	124
Forest to grassland	$\Delta C_s = -1.33\text{MAT} + 0.01\text{MAP} - 0.36\text{I} + 0.17\text{Age} + 38.44$	0.189	0.010**	67
Forest to forest	$\Delta C_s = -0.18\text{Age} - 7.18$	0.127	0.010*	51
Overall	$\Delta C_s = -0.385\text{I} + 0.007\text{MAP} - 0.385\text{MAT} + 11.87$	0.332	0.000**	424

Note: ΔC_s is soil C sequestration following land-use conversions; Age (yr) is the restoration age; I (Mg ha^{-1}) is the initial soil C stocks; MAT (°C) is the average annual temperature; MAP (mm) is the average annual precipitation.
* Indicates significant at $P < 0.05$.
** Indicates significant at $P < 0.01$.

4. Discussion

4.1. Effects of land use changes on soil C stocks

Globally, land-use change can cause a change in soil C stock (Fig. 3). As an overall average across all land use change examined, land use conversions had significantly reduced soil C stock (-2.52 Mg ha^{-1}) (Fig. 3(A)). Similarly, Guo and Gifford (2002) reported land use changes reduced soil C stocks by 9%, but their study only showed the relative percentage change, not the absolute change in soil C sequestration after land use conversions, so our study fills this gap. Guo and Gifford (2002) also reported that soil C stocks decline after land use changes from grassland to plantation (-10%), native forest to plantation (-13%), native forest to farmland (-42%) and grassland to farmland (-59%), and soil C stocks increase after land use changes from native forest to grassland ($+8$%), farmland to grassland ($+19$%), farmland to plantation ($+18$%), and farmland to secondary forest ($+53$%). In our study, soil C stocks significantly increased after the conversion from farmland to grassland ($+6.16$ Mg ha^{-1}) and forest to grassland ($+11.53$ Mg ha^{-1}) (Fig. 3(A)), and soil C stocks significantly declined after the conversion from grassland to farmland (-12.45 Mg ha^{-1}), forest to farmland (-21.05 Mg ha^{-1}) and forest to forest (-12.28 Mg ha^{-1}) (Fig. 3(A)). In addition, after conversion of farmland to forest and grassland to forest, soil C sequestration had no significant change, (Fig. 3(A)), which is similar with the study of Powers et al. (2011), which reported that the conversion of unmanaged forests, grasslands, or savannas to plantations had no effect in the tropical regions. And Powers et al. (2011) also reported that the conversion of forests to shifting cultivation or permanent crops reduced soil C stocks by an average of 15.4% or 18.5%, respectively, and interestingly, both the conversions of forests to pastures and pastures to secondary forests increased soil C stocks, and the establishment of perennial tree plantations on lands that were previously grazed or cropped increased soil C stocks. Generally, where the land use changes decreased soil C, the reverse process usually increased soil C stocks and vice versa.

In addition, despite the considerable soil C sequestration potential that afforestation offers, many studies have reported contradictory findings. Afforestation resulted in either a decrease (Farley et al., 2004) or an increase in soil C stocks (Lemma et al., 2006), or had a negligible effect (Smal and Olszewska, 2008). Also, at the global scale, we found similar patterns (Fig. 3): decline (forest to forest); increase (farmland to forest), and unchanged (grassland to forest). At the national scale, Deng et al. (2014a) calculated the average soil C sequestration rate in the top 20 cm soil to be 0.33 Mg ha^{-1} yr^{-1} following perennial vegetation establishment (mainly forest and shrub) from cropland in China. In addition, the global average soil C sequestration rates following the conversion of cultivated land to forest, shrub and grassland are 0.45, 0.47 and 1.1 Mg ha^{-1} yr^{-1}, respectively (IPCC, 2000; Vleeshouwers and Verhagen, 2002; Shi et al., 2013). In contrast, after the conversion from forest to farmland, a significant decline in soil C stocks was found in many studies (Guo and Gifford, 2002; Murty et al., 2002; Wei et al., 2014). For example, Wei et al. (2014) reported that the largest decrease in soil C stocks was observed in temperate regions (-52%) followed by tropical regions (-41%) and boreal regions (-31%), and for the global scale, soil C stocks declined about 43.1% compared to prior forest land; and the 30% decrease observed by Murty et al. (2002). Also, with the conversion from grassland to farmland, similar pattern was observed, where soil C stocks declined after land use conversion (Fig. 3).

4.2. Temporal changes in soil C stocks after land use conversions

Globally, as an overall average across all land use changes examined, the changes in soil C sequestration with age were not significant ($P > 0.05$). For a specific land use conversion type, in contrast, age since land use conversion can effect soil C sequestration. In our study, soil C sequestration was significant different among different age groups in 5 of 7 land use conversion types (Table 1). Deng et al. (2014a) reported after the conversion from farmland to forest, soil C stocks showed an initial loss in soil during the first few years ($\sim$5 yr), followed by a gradual return of C stocks to levels comparable to those in the control agricultural soil, and then increasing to generate net C gains in some cases; similar temporal patterns of soil C stock changes following farmland conversion have been reported in a number of studies (Turner et al., 2005; Ritter, 2007; Karhu et al., 2011). The duration of the initial decrease in C was reported to last for 3–35 years following agricultural abandonment and there was a significant net accumulation of soil C by 30 years after afforestation (Paul et al., 2002). Nevertheless, Wei et al. (2014) observed that the conversion of forests to agricultural land caused a rapid initial decrease in SOC stocks, followed by a slow decline. In addition, with afforestation on grassland, soil C stocks showed the trend of declined–increased–declined–increased following time (Fig. 5(E)). The possible mechanism was that due to afforestation activity, soils of the previous grassland suffered human disturbance, leading to soil C loss due to strong soil respiration, and following forest development, soil C input into the soils was increased, especially understory vegetation biomass input into the soils, then the forest coverage increased, understory vegetation biomass decreased, so leading to soil C loss again, but then forest litter and dead roots input into the soil were increased, so soil C stocks increased again. In contrast, after the forest was converted to grassland, soil C stocks have been increased on the whole (Fig. 5(F)). However, after afforestation on native forest, soil C stocks were always lower than the values in a comparable natural forest, which agrees with the finding of Smal and Olszewska (2008). For the conversion from farmland to grassland, soil C stocks have been increased after farmland abandonment, which was supported by some studies (Mensah et al., 2003; Nelson et al., 2008; Deng et al., 2013; De Baets et al., 2013; Deng et al., 2014b,c). For example, De Baets et al. (2013) found a logarithmic increase since farmland abandonment. On the contrary, after the conversion from grassland to farmland, soil C stocks had been reducing

in the first 30 years (Fig. 5(B)). The temporal patterns were similar to the conversion from forest to farmland (Fig. 5(D)). Houghton (2003) indicated that clearing forests for new agricultural land caused a release of carbon to the atmosphere. The carbon initially held in trees and other vegetation is released through decomposition of above- and below-ground plant material left in the soil at the time of clearing. Even if the productivity of the new farmland is as high as it was in the forest or grassland, less of the crop production accumulates as litter, most of it is harvested and subsequently consumed or respired. Hence, the process of the conversion from forest or grassland to farmland and management afterward reduces carbon input from litter and enhances the carbon output via breaking the protection of soil organic matter (Guo and Gifford, 2002). For example, Aslam et al. (1999) found that adoption of no-tillage could protect soils from biological degradation and maintain soil quality as compared with plow tillage management after land use change from grassland (pasture) to farmland. However, through long term tillage management, such as increased organic fertilizer input to the topsoil, soil C stock did not always decline. It could reach a new equilibrium point and gradually accumulate at a slower rate (Guo and Gifford, 2002). As in our study, after forest or grassland converted to farmland, soil C stock began to increase after 30 years of cultivation (Fig. 5(B), (D)).

4.3. Factors affecting soil C stocks

Soil C sequestration due to land use change is likely to be affected by multiple factors such as climatic condition, soil texture, site preparation and management, vegetation type, land use history, etc. (Post and Kwon, 2000; Paul et al., 2002; Vesterdal et al., 2002; Guo and Gifford, 2002; Laganière et al., 2010; Li et al., 2012; Shi et al., 2013; Deng et al., 2014). Many studies have reported that age since land use changes plays a consistent and key role in estimated soil C stocks (Guo and Gifford, 2002; Laganière et al., 2010; Li et al., 2012; Shi et al., 2013; Deng et al., 2014). For example, Shi et al. (2013) found that stand age can play an important role in carbon sequestration after afforestation of agricultural sites in the globe. Deng et al. (2014a) have reported that restoration age was the main factor affecting soil C stock change after cropland conversion in China. In our study, our results showed that after the conversion of farmland to grassland and forest, the age since land use conversion also had significant positive correlations with soil C sequestration, but also negative correlations with soil C sequestration after the conversion of forest to forest (Table 2), and for grassland to farmland, forest to farmland, grassland to forest, and forest to grassland, soil C sequestration had no significant correlations with the age since land use conversion (Table 2). Wei et al. (2014) have reported that soil C sequestration has significantly positive correlations with the age. Therefore, these results showed that the relationships between soil C sequestration and age since land use conversion varied between study scales and land use change types.

Climate may affect soil C accumulation through biotic processes associated with the productivity of vegetation and decomposition of organic matter (Li et al., 2012). At the global scale, the restoration of soil C stocks after afforestation was found to vary with climate (Laganière et al., 2010). Post and Kwon (2000) found a tendency for rates of soil C accumulation to increase from temperate regions to subtropical regions, and they inferred that the amounts of organic matter inputs which increased with temperature and moisture were the major factors determining the rate of accumulation. Our results show that soil C sequestration at a global scale had no significant correlation with mean annual temperature and precipitation ($P > 0.05$), but soil C sequestration is positively correlated with MAP, demonstrating that precipitation increases the magnitude of soil C sequestration after land use change, and negatively correlated with MAT, which may be because higher temperature leads to higher losses of soil carbon through decomposition of soil organic matter (Deng et al., 2014b). In addition, our results revealed that the effects of climatic factors (MAT and MAP) on soil C sequestration were closely related to the land use conversion type (Table 3). For example, soil C sequestration had significant positive correlations with MAT for the conversion of grassland to forest (Table 2), and MAT and MAP were the main factors affecting soil C sequestration after the conversion of forest to grassland (Table 3).

Moreover, for all land use conversions in the globe, soil C sequestration showed a significant negative correlation with initial soil C stocks ($P < 0.05$) (Table 2), which was the same with the studies on soil C sequestrations since farmland conversion (Zhang et al., 2010; Deng et al., 2014a). However, in a smaller study scale, i.e. the Loess Plateau, soil C sequestration showed a significant positive correlation with initial soil C stocks ($P < 0.05$) (Deng et al., 2014b). This may be related to the different decomposition rates to be found under the varying nutrient conditions associated with different climate regimes (Zhang et al., 2010; Deng et al., 2014b). The synthesis revealed that initial soil C stocks had strong relations with MAT and MAP (Zhang et al., 2010; Deng et al., 2014b). Also, in our study, we found that the initial soil C stocks and climatic factors (MAT and MAP) had significant effects on soil C sequestration after land use conversions, and were mainly affected by the initial soil C stocks (Table 3), a finding from which Vesterdal et al. (2002) had earlier inferred that slower rates of decomposition might make soil carbon storage increase faster in more nutrient-poor soils following afforestation, and vice versa.

4.4. Uncertainty analysis

This synthesis offers the most accurate estimate on soil carbon sequestration following land use change across the entire global. Strict accuracy is limited due to the uneven distribution of data collected in each category (Age group and land use change types). Additionally, many of the studies have no long term observations and consequently, these measurements may add to the uncertainty. In addition, in our study, we ignored the effect of bulk density substituting Eq. (3) (Fig. 2), i.e.,

the will be equal as long as SOC is the same. In reality, however, bulk density would not only be significantly different among different sites but also experience significant change after land use conversion within a site. Soil types also a limiting factor effecting on the relationship between SOC and soil bulk density. In spite of that, the concern of only the upper soil layer and soil carbon sequestration in the deeper soils also changed due to land use changes, so the problem of the only upper layer consideration have a high influence on the quantity of the result. In future, we should focus on the effects of land use change on deeper soil carbon sequestration to build a functional relationship between topsoil carbon sequestration and deeper soil carbon sequestration.

Conflict of interest

The authors declare they have no actual or potential competing financial interests.

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Appendix A. Supplementary data

Supplementary material related to this article can be found online at http://dx.doi.org/10.1016/j.gecco.2015.12.004.

References

Amundson, R., 2001. The carbon budget of soils. Annu. Rev. Earth Planet Sci. 29, 535–562.
Aslam, T., Choudhary, M.A., Saggar, S., 1999. Tillage impacts on soil microbial biomass C, N, and P, earthworms and agronomy after two years of cropping following permanent pasture in New Zealand. Soil Tillage Res. 51, 103–111.
Bolin, B., Sukumar, R., 2000. Global perspective. In: Watson, R.T., Noble, I.R., Bolin, B., Ravindranath, N.H., Verardo, D.J., Dokken, D.J. (Eds.), Land Use, Land Use Change, and Forestry. Cambridge University Press, Cambridge, UK.
De Baets, S., Meersmans, J., Vanacker, V., Quine, T.A., Van Oost, K., 2013. Spatial variability and change in soil organic carbon stocks in response to recovery following land abandonment and erosion in mountainous drylands. Soil Use Manag. 29, 65–76.
Deng, L., Liu, G.B., Shangguan, Z.P., 2014a. Land use conversion and changing soil carbon stocks in China's 'Grain-for-Green' Program: a synthesis. Global Change Biol. 20, 3544–3556.
Deng, L., Shangguan, Z.P., Sweeney, S., 2013. Changes in soil carbon and nitrogen following land abandonment of farmland on the Loess Plateau, China. PLoS One 8, e71923.
Deng, L., Shangguan, Z.P., Sweeney, S., 2014b. "Grain for Green" driven land use change and carbon sequestration on the Loess Plateau, China. Sci. Rep. 4, 7039.
Deng, L., Sweeney, S., Shangguan, Z.P., 2014c. Long-term effects of natural enclosure: carbon stocks, sequestration rates and potential for grassland ecosystems in the Loess Plateau. Clean Soil Air Water 42, 617–625.
Farley, K.A., Kelly, E.F., Hofstede, R.G.M., 2004. Soil organic carbon and water retention following conversion of grasslands to pine plantations in the Ecuadoran Andes. Ecosystems 7, 729–739.
Guo, L.B., Gifford, R.M., 2002. Soil carbon stocks and land use change: a meta analysis. Global Change Biol. 8, 345–360.
Houghton, R.A., 2003. Revised estimates of the annual net flux of carbon to the atmosphere from changes in land use and land management 1850–2000. Tellus B 55, 378–390.
IPCC, 2000. Land Use, Land-use Change, and Forestry. Cambridge University Press, Cambridge, UK.
IPCC, 2006. In: Eggleston, H.S., Buendia, L., Miwa, K., Ngara, T., Tanabe, K. (Eds.), Forest Land. IPCC Guidelines for National Greenhouse Gas Inventories, Prepared by the National Greenhouse Gas Inventories Programme, Vol. 4. IGES, Hayama, Japan, p. 83. (Chapter 4).
Jobbágy, E.G., Jackson, R.B., 2000. The vertical distribution of soil organic carbon and its relation to climate and vegetation. Ecol. Appl. 10, 423–436.
Karhu, K., Wall, A., Vanhala, P., Liski, J., Esala, M., Regina, K., 2011. Effects of afforestation and deforestation on boreal soil carbon stocks: comparison of measured C stocks with Yasso07 model results. Geoderma 164, 33–45.
Laganière, J., Angers, D.A., Paré, D., 2010. Carbon accumulation in agricultural soils after afforestation: a meta-analysis. Global Change Biol. 16, 439–453.
Lemma, B., Kleja, D.B., Nilsson, I., Olsson, M., 2006. Soil carbon sequestration under different exotic tree species in the southwestern highlands of Ethiopia. Geoderma 136, 886–898.
Li, D.J., Niu, S.L., Luo, Y.Q., 2012. Global patterns of the dynamics of soil carbon and nitrogen stocks following afforestation: a meta analysis. New Phytol. 195, 172–181.
Luo, Y.Q., Hui, D., Zhang, D., 2006. Elevated CO_2 stimulates net accumulations of carbon and nitrogen in land ecosystems: a meta-analysis. Ecology 87, 53–63.
Luo, Y.Q., Sherry, R., Zhou, X., Wan, S.Q., 2009. Terrestrial carbon-cycle feedback to climate warming: experimental evidence on plant regulation and impacts of biofuel feedstock harvest. Global Change Biol.-Bioenergy 1, 62–74.
Mensah, F., Schoenau, J.J., Malhi, S.S., 2003. Soil carbon changes in cultivated and excavated land converted to grasses in east-central Saskatchewan. Biogeochemistry 63, 85–92.
Murty, D., Kirschbaum, M.F., McMurtrie, R.E., McGilvray, H., 2002. Does conversion of forest to agricultural land change soil carbon and nitrogen? A review of the literature. Global Change Biol. 8, 105–123.
Nelson, J.D.J., Schoenau, J.J., Malhi, S.S., 2008. Soil organic carbon changes and distribution in cultivated and restored grassland soils in Saskatchewan. Nutr. Cycl. Agroecosyst. 82, 137–148.
Paul, K.I., Polglase, P.J., Nyakuengama, J.G., Khanna, P.K., 2002. Change in soil carbon following afforestation. For. Ecol. Manag. 168, 241–257.
Post, W.M., Kwon, K.C., 2000. Soil carbon sequestration and land-use change: Processes and potential. Global Change Biol. 6, 317–327.
Powers, J.S., Corre, M.D., Twine, T.E., Veldkamp, E., 2011. Geographic bias of field observations of soil carbon stocks with tropical land-use changes precludes spatial extrapolation. Proc. Natl. Acad. Sci. USA 108, 6318–6322.
Ritter, E., 2007. Carbon, nitrogen and phosphorus in volcanic soils following afforestation with native birch (Betula pubescens) and introduced larch (Larix sibirica) in Iceland. Plant Soil 295, 239–251.
Shi, S.W., Zhang, W., Zhang, P., Yu, Y.Q., Ding, F., 2013. A synthesis of change in deep soil organic carbon stores with afforestation of agricultural soils. Forest Ecol. Manag. 296, 53–63.

Smal, H., Olszewska, M., 2008. The effect of afforestation with Scots pine (Pinus silvestris L.) of sandy post-arable soils on their selected properties. II. Reaction, carbon, nitrogen and phosphorus. Plant Soil 305, 171–187.
Turner, J., Lambert, M.J., Johnson, D.W., 2005. Experience with patterns of change in soil carbon resulting from forest plantation establishment in eastern Australia. Forest Ecol. Manag. 220, 259–269.
Van der Werf, G.R., Morton, D.C., DeFries, R.S., Olivier, J.G., Kasibhatla, P.S., Jackson, R.B., Collatz, G.J., Randerson, J.T., 2009. CO_2 emissions from forest loss. Nature Geosci. 2, 737–738.
Vesterdal, L., Ritter, E., Gundersen, P., 2002. Change in soil organic carbon following afforestation of former arable land. Forest Ecol. Manag. 169, 137–147.
Vleeshouwers, L.M., Verhagen, A., 2002. Carbon emission and sequestration by agricultural land use: a model study for Europe. Globe Change Biol. 8, 519–530.
Wei, X.R., Shao, M.A., Gale, W., Li, L.H., 2014. Global pattern of soil carbon losses due to the conversion of forests to agricultural. Sci. Rep. 4, 1062.
Yang, Y.H., Luo, Y.Q., Finzi, A.C., 2011. Carbon and nitrogen dynamics during forest stand development: a global synthesis. New Phytol. 190, 977–989.
Zhang, K., Dang, H., Tan, S., Cheng, X., Zhang, Q., 2010. Change in soil organic carbon following the 'Grain-for-Green' programme in China. Land Degrad. Dev. 21, 16–28.

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Carbon Storage in Cropland Soils: Insights from Iowa, United States

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Abstract: The restoration of soil organic matter (SOM, as measured by soil organic carbon (SOC)) within the world's agricultural soils is imperative to sustaining crop production and restoring other ecosystem services. We compiled long-term studies on the effect of management practices on SOC from Iowa, USA—an agricultural region with relatively high-quality soil data—to highlight constraints on detecting changes in SOC and inform research needed to improve SOC measurement and management. We found that strip-tillage and no-tillage increased SOC by 0.25–0.43 Mg C ha^{-1} yr^{-1} compared to losses of 0.24 to 0.46 Mg C ha^{-1} yr^{-1} with more intensive tillage methods. The conversion of cropland to perennial grassland increased SOC by 0.21–0.74 Mg C ha^{-1} yr^{-1}. However, diversifying crop rotations with extended rotations, and supplementing synthetic fertilizer with animal manure, had highly variable and inconsistent effects on SOC. The improved prediction of changes in SOC requires: the use of methods that can identify and disentangle multiple sources of variability; looking beyond total SOC and toward systematic collection of data on more responsive and functionally relevant fractions; whole-profile SOC monitoring; monitoring SOC in long-term studies on the effect of multiple conservation practices used in combination; and deeper collaboration between field soil scientists and modelers.

Keywords: soil organic carbon stock; soil management; SOC measurement; SOM; variability; scaling

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1. Introduction

International efforts to limit global warming to 1.5 °C by 2100 are falling short of targets [1], leading to an increasing focus on CO_2 removal to meet climate goals [2,3]. Soil organic carbon (SOC) is an important component of the global carbon (C) balance, and increasing SOC is a form of CO_2 removal, though of limited durability (<100 years) [2]. Some argue that efforts to increase SOC for climate mitigation are misplaced given limitations on measuring and managing this pool [4], but the pace and impacts of anthropogenic climate change requires the consideration of all options. Furthermore, the low capacity and high price of more durable CO_2 removal technologies (e.g., direct air capture and C capture and storage) results in nearly all of the current estimated 2 Gt yr^{-1} of CO_2 removal being due to land management [2].

SOC associated with croplands is highly relevant because of the global extent of agriculture, which covers between 10% and 15% of the total ice-free land area of the Earth, and because these lands are already highly managed. Furthermore, increased SOC can improve the resilience of croplands to extreme weather events associated with anthropogenic climate change [5]. Increasing SOC storage can meet both climate change mitigation and crop production goals, and is aligned with farmers' long-term interests. Yet,

farmers' ability to simultaneously manage for both crop production and SOC storage has largely been undervalued until recently [6]. The importance of measuring, managing, and monetizing SOC is coming into clearer focus with the development of numerous private sector C programs [7–9], corporate net-zero claims requiring documentation of supply chain (i.e., Scope 3) emission reductions [10], USDA initiatives such as the Climate-Smart Commodities Partnership program [11], and provisions of the Inflation Reduction Act [12], such as tax incentives (45Z) for biofuel producers to lower their C intensity, including C impacts of their feedstocks.

SOC is the dominant constituent of soil organic matter (SOM) and C typically accounts for more than half of SOM's dry mass [13]. SOM affects the physical, chemical, and biological properties and functions of soil [14–16]. SOM increases the capacity of soils to store and provide water and nutrients to support plant growth [17]; influences soil structure, soil erosion, water quality, and food security; and decreases the negative impacts of human activities to ecosystems [14]. Paradoxically, some of the key benefits of SOM, such as supplying nitrogen to plants, rely on its continued degradation rather than its accumulation [18–20]. This paradox highlights the ongoing challenge of optimizing soil management with respect to increasing SOM. Developing scientifically sound recommendations for managing these dynamic processes and pools requires long-term experiments and large amounts of high-quality data.

There are numerous challenges and opportunities in achieving, maintaining, and measuring increases in SOC to achieve climate goals and restore soil functions. Our objectives were to consolidate and summarize data from previously published studies on the baseline SOC stocks and the long-term effect of common conservation practices on carbon sequestration as SOC in Iowa, USA, including the ability to detect change and rates of change in SOC, and compare these results to the global literature on SOC response to agricultural management. A further goal was to summarize key issues and associated challenges and opportunities to achieve the reliable, measurable, and sustainable storage of carbon in these soils. Our hope is that knowledge generated from Iowa, a relatively data-rich portion of the world, can facilitate more informed SOC data collection strategies elsewhere.

2. Iowa Soils and Agriculture

The US state of Iowa is widely known for its highly productive, high-organic-matter soils (Table 1, Figure 1). This soil environment has been produced by a nearly ideal intersection of climate, soil parent material, and native vegetation. The state has a humid continental climate with hot summers and cold winters. Mean annual precipitation ranges from 590 to 900 mm, and mean annual temperatures range from 6 °C to 10 °C. Much of the geologic parent material from which the soil was formed has a high silt content (median = 61%; [21]), resulting in soil textures that are silt loam, silty clay loam, or an adjacent texture class. A loamy soil, especially with silt's ideal particle size, provides abundant water-holding capacity at pressure potentials that are readily available for plant uptake. The silty and fine-textured particle size distributions of Iowa soils may also be partly responsible for large SOM stocks, as finer particle sizes promote more persistent SOC [22,23]. Before the 19th century, the native vegetation across much of the state was tallgrass prairie, dominated by diverse and deep-rooted grasses and forbs.

Table 1. Descriptive statistics for silt content (%), soil organic matter (%), and bulk density (g cm^{-3}) in Iowa from 0 to 30 cm as mapped in the USA's Soil Survey [21]. SOC stock was calculated by assuming a 2:1 ratio of SOM and SOC. Although SOC is known to exist below the topsoil (A horizon), this estimation of SOC stock focuses on the thickness of soil with visibly evident organic carbon accumulation as indicated by "mollic" colors.

Measure	Min	Max	Mean	STD	Median	90th Percentile
Silt (%)	1	90	54	15	61	71
Sand (%)	0	96	19	17	9.5	41
Clay (%)	0	60	27	6	28	34
SOM (%)	0	85	4	3	3	6
Bulk Density (g/cm^3)	0.2	1.7	1.3	0.1	1.3	1.5
Mollic Thickness (cm)	0	203	45	36	43	94
SOC Stock (Mg/ha)	0	2309	120	132	95	294

Note: Silt, sand, clay, SOM, and bulk density are based on 0–30 cm data. Mollic thickness and SOC stock are variable, with stock being variable with thickness.

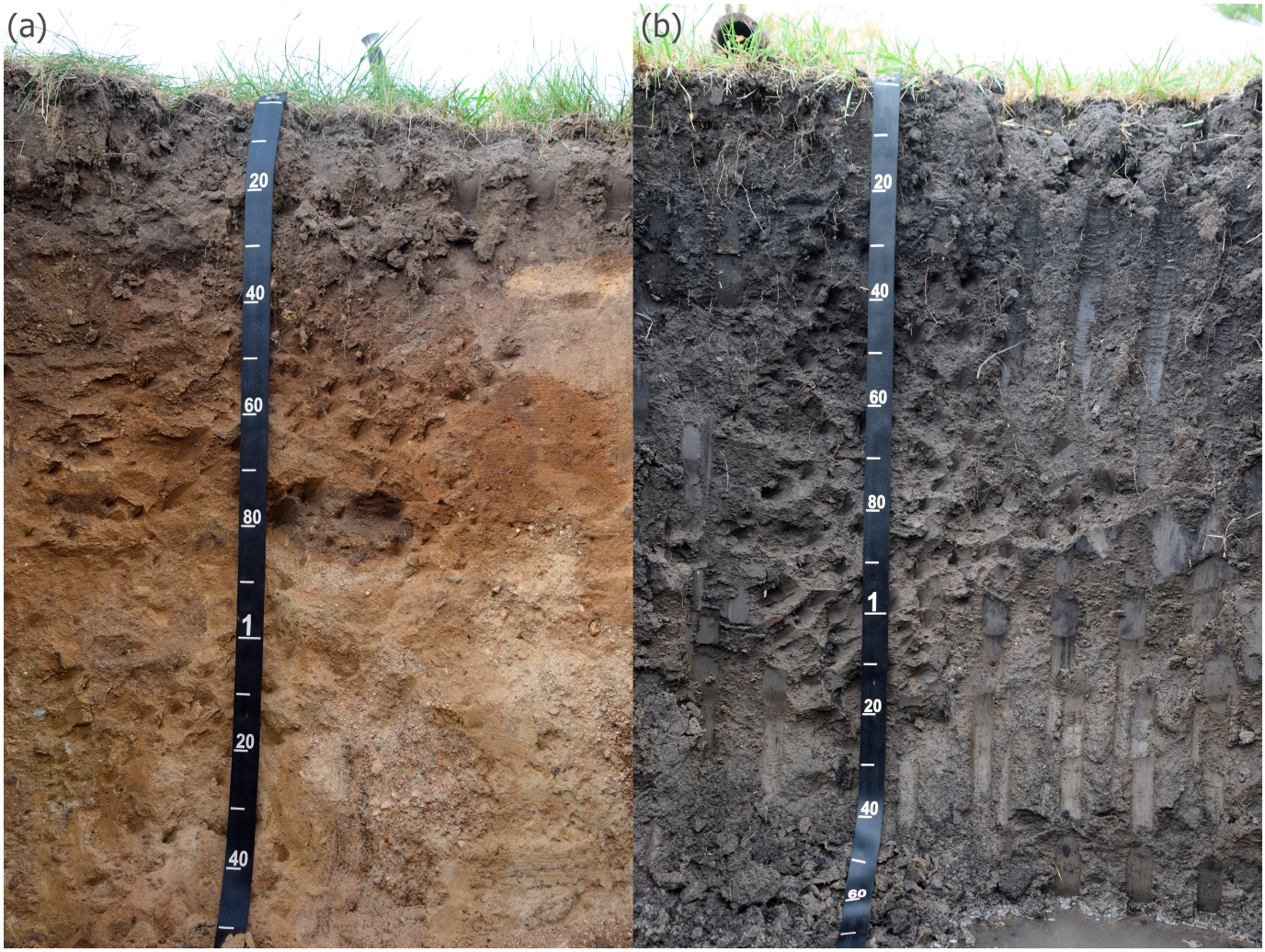


Figure 1. Variable thickness of mollic colors for two common soil series from the intensively drained Des Moines Lobe Landform in north-central Iowa. The (**a**) 30 cm mollic colors profile is a Clarion (fine-loamy, mixed, superactive, mesic Typic Hapludoll), and the (**b**) 60 cm mollic colors profile is a Webster (fine-loamy, mixed, superactive, mesic Typic Endoaquoll). Photos by BA Miller, Iowa State University.

Information about Iowa's soils is a result of over a century of investment from county, state, and federal levels of government. Although many more soil observations were made as part of this cooperative effort, a database of over 8000 deep (>1 m) soil cores documents this work [24]. By combining field experience with aerial photography and then field verification, soil scientists produced soil survey maps at cartographic scales of 1:15,840 and 1:12,000 [25]. These soil maps are among the most detailed in the world, especially for covering such a large extent. The maps were produced county by county (~2330 km^2), with teams of four soil scientists dedicated to surveying each county over a four-year period (Fenton, personal communication).

Iowa's soil and climate conditions are conducive to high yields of summer annual crops. The landscape is dominated by the cultivation of maize and soybeans, used for livestock feeds, vegetable oils, sweeteners, and biofuel feedstock [26,27]. Humans have lived in North America since as early as 5000 BCE, practicing various forms of agriculture [28–30]. Since Euro-American settlement in the 19th century, however, Iowa's topsoil has been drastically altered by the conversion to field crop production. A substantial portion of topsoil has been redistributed by wind, water, and tillage erosion. Even on gently rolling landscapes such as those of north central Iowa, the loss of organic-matter-rich topsoil from some landscape positions is evident [31]. One study based on remotely sensed data has suggested that 37% of Iowa's agricultural fields have no remaining topsoil [32], but this does not account for local sediment movement and deposition. Considering the thickness of topsoil in prairie remnants, spatial modeling suggests that the SOC stock in Iowa soils before Euro-American settlement was about 1.47 billion Mg [9]. A similar analysis calculated from the gSSURGO database [21] suggests the present stock is about 990 million Mg (Figure 2), which indicates a loss of about 32%. Losses and gains are a function of landscape position, with the largest losses measured in the backslope [31]. Preliminary data also suggest a loss of C from upland swales and depressions. Despite slow but continued increases in the adoption of soil conservation practices by farmers [33], the estimated annual statewide average soil loss is 13 Mg ha^{-1} yr^{-1} [34].

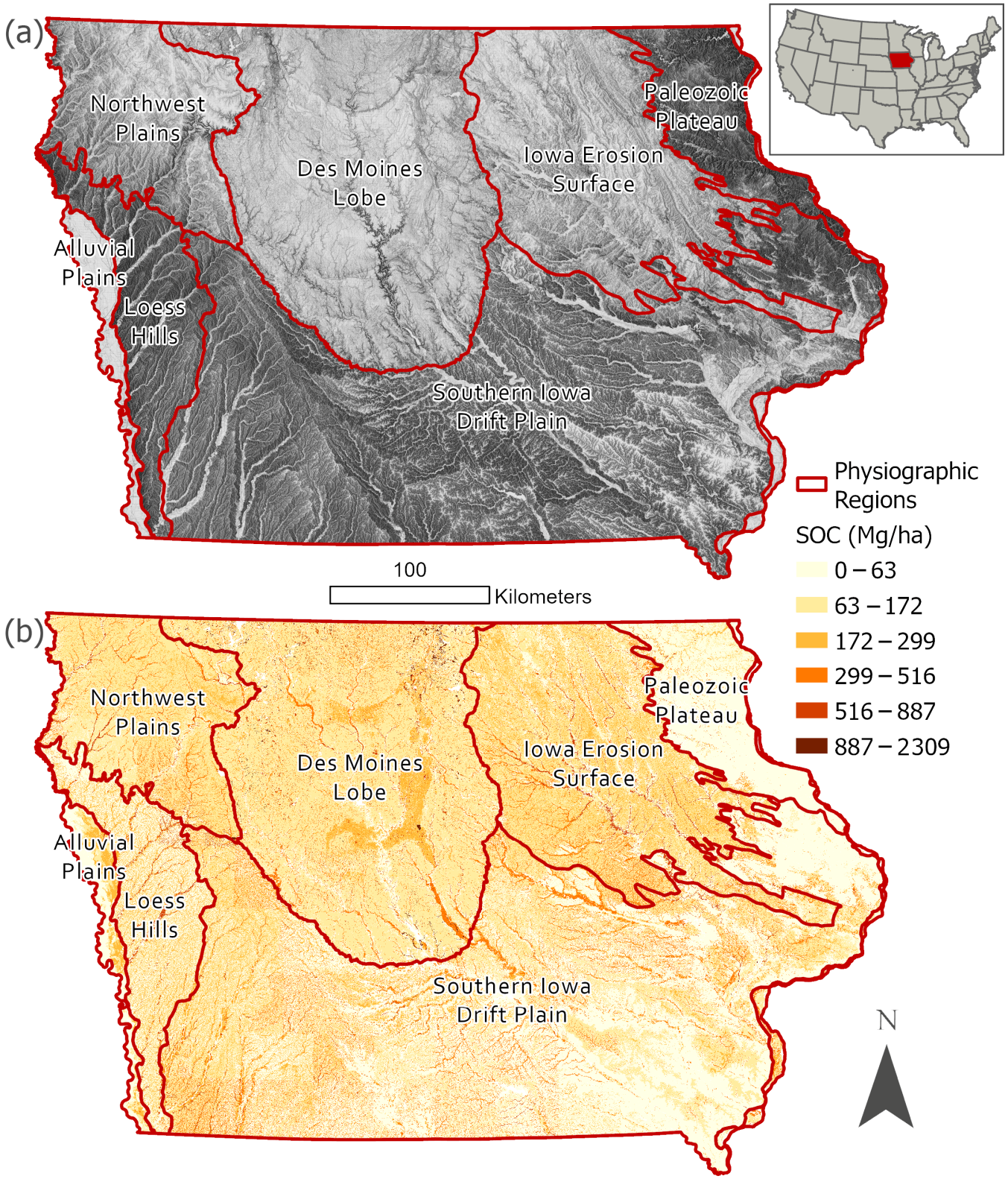


Figure 2. (**a**) The relief of Iowa, USA, displayed by a hillshade model derived from LiDAR elevation data (State of Iowa, 2009), which heavily influences the distribution of (**b**) soil organic carbon (SOC). Estimates of SOC content is based on gSSURGO data [21]. The depth included is variable and is based on the thickness of soil with visible evidence of organic carbon accumulation (i.e., "mollic" colors, a standard for indicating soil most enriched by organic matter). For some soil areas, this thickness may be up to 2 m.

3. Agricultural Management Practices and Soil Organic Carbon: Long-Term Studies in Iowa

On a worldwide basis, SOC stocks have declined by 133 Pg C since the beginnings of cultivation, with the "Corn Belt", of which Iowa is the center, among the areas of greatest loss [35]. While we cannot point to one cause, this SOC loss can be attributed to soil-tillage-induced erosion, extensive tile drainage, improper soil fertility, and increased soil temperatures [36,37]. A long-term study on SOC loss from 23 counties in Iowa reported a net loss of SOC from 0 to 100 cm depth (−10.8%) but gain at 100 to 150 cm (of +1.5%) between the years of 1959 and 2007 [31]. This study represents the status of most Iowa farms regarding SOC, and we do not expect this rate of loss from the upper soil profile to have slowed since the 2007 sampling.

As in other locations around the world, Iowa researchers and farmers have looked toward multiple practices to increase SOC. These include (but are not limited to): reduced tillage [38], residue management [39], diversified crop rotations [40,41], manure or other organic carbon amendments [38,42], using winter cover crops [43], growing perennial crops [44,45], using a living mulch or perennial groundcover [46], and full or partial land conversion to perennial vegetation [47]. These practices reliably reduce soil erosion and improve water quality, but long-term data from these studies suggest that consistent measurement of absolute changes in SOC remains challenging. Here, we summarize patterns in extensive, relatively long-term SOC datasets associated with three practices and collected in Iowa (Table 2).

Table 2. Summary of approaches and methods used in long-term studies of three practices intended to increase soil organic carbon (SOC) in Iowa, USA.

Practice Intended to Increase SOC	Number of Sites/Studies	Length of Studies' SOC Monitoring (years)	Sampling Depth (cm)	Approach	Treatments	References
Reduced Tillage	7	12	0 to 60	Sampled annually, with baseline *	1. Moldboard Plow 2. Chisel Plow 3. Deep Rip 4. Strip Tillage 5. No Tillage	[48]
Diversified Crop Rotations	3	10–12	0 to 30–90	Sporadic sampling, no baseline *	1. Maize-Soybean 2. Maize-(Maize)-Soy-Oat-Alfalfa	[40,41,49–53]
Conversion to Perennial Vegetation	4	7–40	0 to 15–30	Various, chronosequence, most without baseline *	1. Cropland 2. Restored Prairie 3. Native (or Remnant) Prairie	[45,47,54,55]

* Baseline refers to sampling before, or shortly, after practice change. Without baseline sampling, determining net SOC loss/gains is more challenging (see ref. [56]).

3.1. Reduced Tillage

Although the use of no-till in Iowa has increased significantly since the 1980s, full-width tillage is still used on the majority of cropland in Iowa for at least part of the crop rotation [57,58]. Intensive tillage transiently decreases soil bulk density and increases soil aeration, mixes crop residues with mineral soil, and breaks soil aggregates and crop residues into smaller pieces—all of which increase decomposition (and loss of SOC as CO_2). Tillage also dries and warms soils more rapidly in springtime by increasing aeration and decreasing albedo. These soil microclimate benefits and increased decomposition of residues are why many growers in Iowa continue to till—converting to no-tillage has been shown to have a 7.6% maize yield penalty according to a global meta-analysis [59]. However, the SOC benefits to reducing tillage in Iowa are compelling [48] (Figure 3).

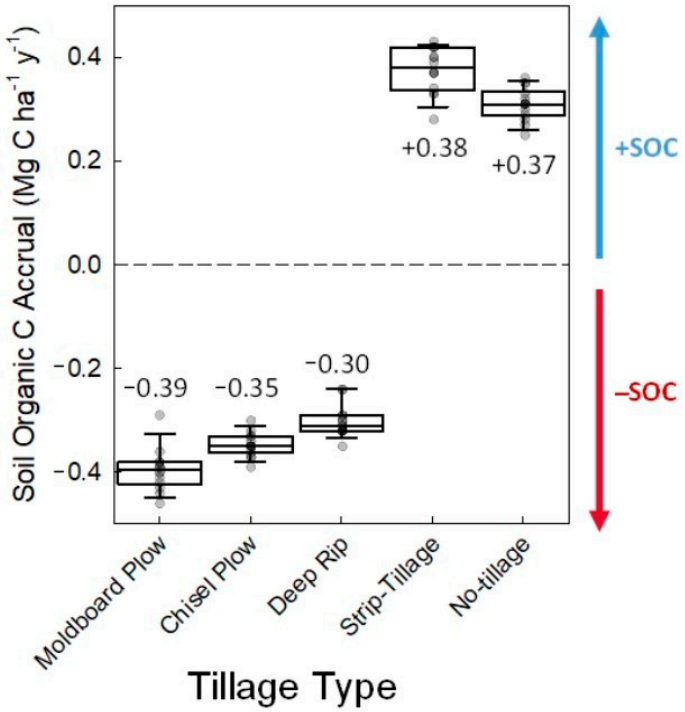


Figure 3. Five tillage types and impact on soil organic carbon (SOC) at 0–60 cm depth from 2002 to 2014. Boxplots include seven sites spread throughout Iowa and two rotations (maize-soybean and maize-maize-soybean) for a total of $n = 14$. Mean state-wide averages are shown with the boxplots. Data from [48].

Al-Kaisi and Kwah-Mensah (2020) [48] compared five tillage methods—moldboard plow, chisel plow, deep rip, strip-tillage, and no-tillage, over a 12-year period across seven locations in Iowa (Figure 3). Soils were sampled and analyzed for SOC in increments to a depth of 60 cm. Prior to the initiation of the study, all sites had been in row crop production using common conservation tillage methods for at least 50 years.

Averaged across seven locations and two rotations, no-tillage and strip-tillage systems added 0.25 to 0.43 Mg SOC ha^{-1} y^{-1} to a depth of 60 cm. Conversely, chisel plow, deep rip, and moldboard plow had losses ranging from −0.24 to −0.46 Mg SOC ha^{-1} y^{-1} over the 12-year study (Figure 3). SOC gains and losses predominantly occurred in the upper 30 cm. Interestingly, there was no tillage interaction with crop rotation or location, despite varying climates and soils [48]. Taken together, this comprehensive Iowa study indicates that reducing tillage improves SOC storage, with a reasonable expectation that, if no-tillage and strip tillage systems replaced more intensive tillage systems across Iowa, SOC stocks in the upper 60 cm of soil could increase at an average net rate of approximately 0.7 Mg SOC ha^{-1} yr^{-1} ([average SOC increase with strip-tillage or no-tillage] + [average avoided SOC loss caused by more intensive tillage systems]).

Globally, the majority of studies have also consistently documented the positive impact of reducing or eliminating tillage on SOC stocks, at least in the upper 30 cm. This is probably best illustrated via meta-analyses, which document a range from <0.1 to 0.57 Mg C ha^{-1} y^{-1} increase in SOC [60–63]. For Iowa climate and soil conditions, Ogle et al. [64] reported a 0.33 Mg C ha^{-1} y^{-1} increase in SOC in the 0–60 cm soil depth following conversion to no-till. While there is some scientific debate, [65–68], most data syntheses point to net SOC accrual (e.g., [63,69,70]). In addition to soil depth, the other many relevant factors affecting SOC response to adopting no-till include climate, soil type, cropping system, and duration [60,61,63,64,69,71]. The potentially nonlinear temporal response of SOC to no-till conversion also poses particular challenges to the accurate measurement and interpretation of results [60].

In addition to increasing SOC, reduced tillage provides multiple environmental co-benefits. Several studies have demonstrated reduced erosion from no-tillage or reduced tillage [72–74]. Soil infiltration [75], structure and porosity [69,76], and microbial biomass and activity [77] also improve. Conversion to no-till also reduced nitrate-nitrogen leaching by 14 ± 10% at a site in northwestern Iowa [78].

3.2. Diversified Rotations

Diverse crop rotations that include small grains and forage crops were widely used across much of Iowa until the 1950s, after which intensive monocultures of continuous maize and maize-soybean became increasingly dominant [79]. A concern with this increased specialization in crop production is the potential negative effects on SOC and other aspects of soil health. Three long-term crop rotation experiments examined the effects (Table 2).

These three experiments compare a conventional maize-soybean rotation with a diversified maize-soybean-oat-alfalfa rotation. The Kanawha experiment was established in 1954 in northern Iowa (42°94′ N, 93°17′ W); the Nashua experiment was established in 1979 in northeast Iowa (42°95′ N, 92°54′ W); and the Marsden experiment was established in 2002 in central Iowa (42°01′ N, 93°47′ W). Detailed information on site history, management, and soil sampling for SOC can be found in several publications [40,41,50,80]. Tillage and fertilization vary somewhat for the three sites, but full-width tillage was used at all sites. Animal manure was incorporated after the alfalfa phase of the rotation at the Marsden site to simulate a diversified, integrated crop-livestock system [80].

Unlike reduced and no-tillage, there are no clear trends in the impacts of crop diversification on multiple soil measures. The coefficients of variation for bulk density, SOC concentration, and SOC stock are high (medians range from 5 to 8%) for both maize-soybean and diversified rotations (Figure 4). Although yield data and allometric equations suggest that below-ground inputs of carbon were 20–35% greater in the diversified rotations compared to the maize-soybean rotation, SOC increases within the total soil profile were minor [41]. Although changes in SOC stock were not consistently observed, changes in certain C fractions were noted. For example, C stored in particulate organic matter (POM), microbial biomass C, and salt-extractable organic carbon were significantly increased with diverse rotations [52,53]. One reason for the lack of a clear trend in SOC may be fertilization: Russell et al. [50] found that nitrogen fertilization tends to negate the effect of increased below-ground inputs of carbon in diverse rotations (SOC increases are maximized at the agronomic optimum nitrogen application rate in Iowa intensive maize and maize-soybean rotations [81]). Furthermore, the formation of mineral-associated organic matter (MAOM) requires substantial amounts of nitrogen, which could pose another limitation for its accumulation [82].

Meta-analyses report SOC increases for both diversified crop rotations [83] and manure inputs [84]. The lack of SOC response to diversified rotations in Iowa is puzzling but similar to recent findings from Wisconsin, a neighboring US state, where the researchers found even 29 years of diversified management was not enough to detect SOC changes between conventional cropping and diversified crop rotation [85]. Climate or soil conditions may make SOC slow to respond to cropping system diversification in this region, if there is a response at all.

Even though changes in SOC stock are difficult to discern, there are a plethora of additional benefits of diversified cropping systems. The four-year diversified rotation in the Marsden experiment dramatically lowered synthetic nitrogen inputs (−86%), herbicide use (−50%), and energy use (−65%); improved many metrics of soil health including reduced soil erosion (−62%); increased crop yields (maize +5%, soybean +20%); and even improved air quality [52,53,86,87].

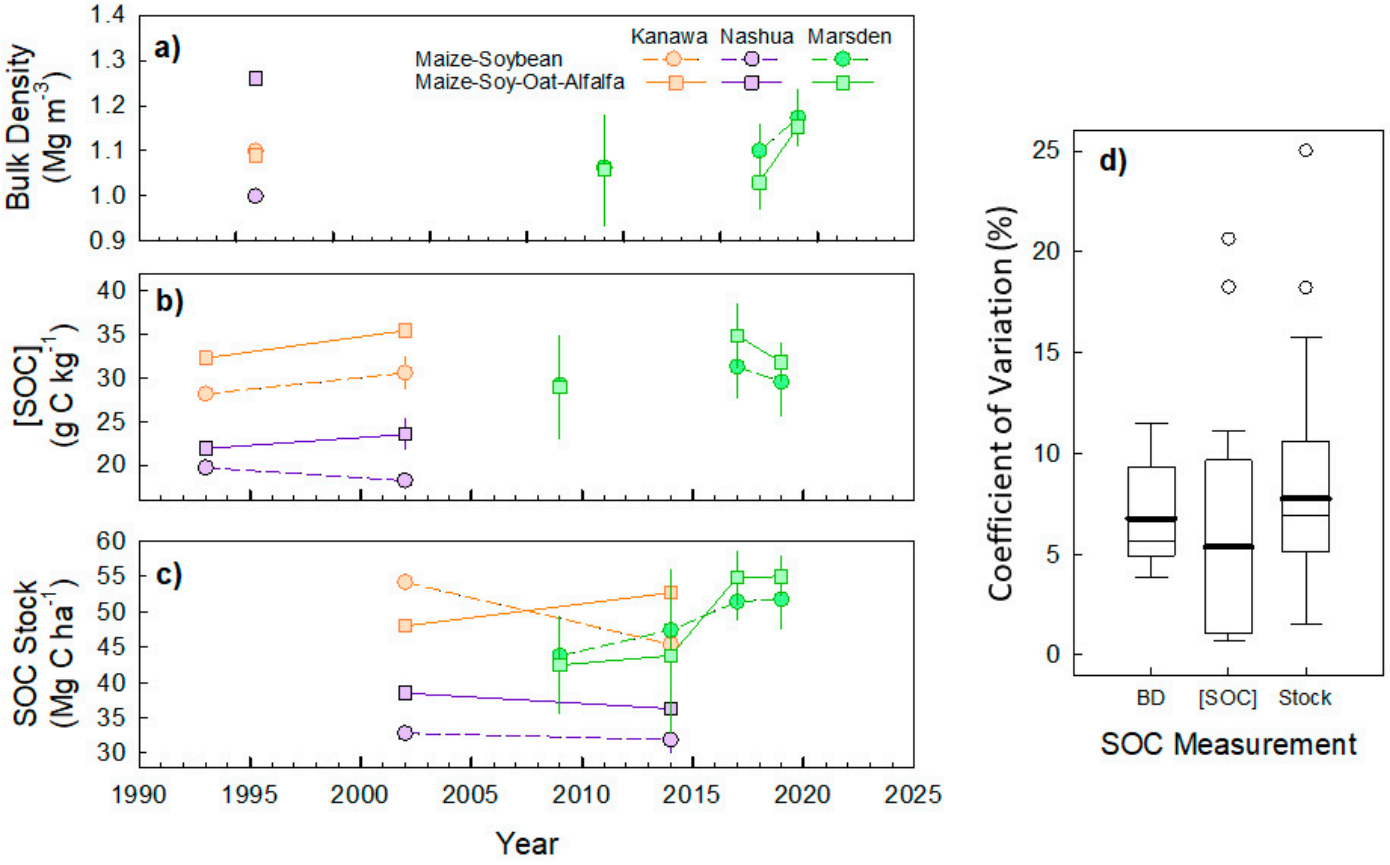


Figure 4. (**a**) soil bulk density, (**b**) soil organic carbon (SOC) concentration, (**c**) calculated SOC stock, and (**d**) the coefficient of variation for all three soil measurements at 0–15 cm depth across time from three long-term crop diversification experiments. Means and standard deviations are compiled from [40,41,49–53], and the coefficient of variation was calculated by treatment and year (n = 6 for BD, n = 10 for [SOC], and n = 12 for SOC stock). The thick dark lines in boxplots are the means.

3.3. Converting Cropland to Perennial Vegetation

Perennial grasslands, called "prairie," once covered 70–80% of Iowa's landscape, but now comprise < 1% [88]. Remnant prairies average 30–60% greater SOC than adjacent cultivated cropland [55,89], suggesting a massive potential sink for SOC with conversion of cropland to native prairie. Numerous environmental benefits have been shown to accrue with the restoration of even modest areas of prairie within Iowa's cropland landscapes, including increased biodiversity, reduced runoff, and increased retention of nitrogen and phosphorus [90]. Converting cropland to perennial grassland vegetation may be particularly beneficial on soils that are marginally productive for annual crops [91], and can be economically feasible if farmers and/or farmland owners receive federal or state cost-share to assist with establishment and management costs, and enroll in a private sector C program [92].

Long-term studies of the effect of conversion of cropland to perennial grassland on SOC in Iowa (Table 3) have included three approaches: (i) a chronosequence approach, sometimes called space-for-time substitution because it involves sampling different fields (ideally under very similar soils and climates) that have been converted to perennial vegetation [47,54,55], (ii) randomized complete block designs that ideally measured SOC at baseline or beginning of the conversion and some years later [45], and (iii) sampling through long time frames (>50 years) and monitoring SOC loss [31].

Table 3. Summary of four studies conducted in Iowa, USA on the effect of cropland conversion to perennial grassland on soil organic carbon stocks and change (at 0–15 cm).

Study Citation	Region in Iowa (Nearest City)	Soil Texture	Classification Based on USDA's Soil Taxonomy	Years since Conversion	Cropland SOC (Mg C ha^{-1})	Restored Perennial Grassland SOC (Mg C ha^{-1})	Native Prairie Remnant SOC (Mg C ha^{-1})	SOC Accrual Rate (Mg C ha^{-1} y^{-1})	Significant Difference between Crop and Restored Grassland
[47]	Central (Prairie City, IA)	Silty clay loam	Aquertic and Typic Argiudolls	14	44	35–39	55	0.74	Variable
[54]	Central (Prairie City, IA)	Silty clay loam	Oxyaquic, Aquertic, and Typic Argiudolls	21	25	40	58	0.59	NA
[45]	Central (Boone, IA)	Clay loam	Typic Endoaquoll, Aquic Hapludoll	7	55	60	NA	0.71 †	No
[55]	North central (Various)	Various	Various	40	49	54	60	0.21	Yes

†: Prairie biomass is harvested. Also had fertilized prairie that increased at 0.29 Mg C ha^{-1} on average (not significantly different at $p < 0.05$). Larger differences between years than between treatments.

The SOC accrual rate in these four long-term studies ranged from 0.21 to 0.74 Mg C ha^{-1} y^{-1}, but SOC in the grasslands was not always significantly greater than in cropland (Table 3). Even after multiple decades (up to 40 years), SOC did not reach levels of nearby undisturbed prairies [47,54,55]. These findings highlight the slow recovery of SOC, and the patience needed to observe "statistically significant" differences between the annual croplands and re-established grasslands. Also, it is important to note that in none of the studies did the perennial grassland reach the SOC stocks measured in the remnant prairie benchmark (Table 3).

The reason for slow and variable recovery of Iowa's SOC from conversion to perennial vegetation, sometimes resembling something like native vegetation, is unclear (Table 3). Variability in soil properties, like clay concentration, limited the ability to detect significant differences in switchgrass plantations compared to other covers [93]. Tile drainage of somewhat poor, and poorly drained sites may promote residue decomposition by aerating the soils for longer periods than under native conditions. Warm-season grass residues may decompose faster than those of cool-season species [92]. Ten-month laboratory incubation studies of central Iowa soils have shown that root residues from unfertilized reconstructed prairie plots dominated by warm-season grasses decomposed rapidly and did not lead to carbon storage in the soil [94]. Reducing soil erosion and increasing the duration of living plant roots and the quantity of other root-derived C inputs are likely the main factors that increase SOC under perennial vegetation [95]. Furthermore, the speed at which the SOC concentrations increases when tilled soils are converted to grassland can be dependent on hillslope position [55]. The more eroded, shoulder-slope positions tended to accrue SOC faster than positions lower down the hillslope [55], perhaps because the change in SOC concentration was easier to discern from the lower background concentration on the eroded sites. Changes in inorganic carbon are often not considered, but impacts can be significant. Conversion from cropland to grassland reduced soil inorganic C by 14.4% [96].

Global meta-analysis has indicated that the conversion of cropland to pasture resulted in increased SOC stocks, especially in the upper soil horizons, but the increases do not reach that of the native conditions on the timescales of most scientific studies [97]. Kristersen et al. [98] note the potential role of incorporating large herbivores in establishing increased and resilient stocks of SOC in grasslands globally. Research interest in understanding potential applications in Iowa is increasing, but data on net GHG impacts and SOC changes in grazed systems in Iowa are scant [9]. Overall, Fargione et al. (2018) [99] estimate modest potential contributions from grassland restoration to climate mitigation as compared to avoided grassland conversion.

4. Implications for Soil Organic Carbon Measurement and Management

The results of these studies suggest that, in Iowa soils, SOC responds slowly to management and has a high variability, such that changes in SOC are difficult to detect with statistical certainty. Here, we discuss the implications of these findings for SOC measurement and management within our broader understanding of soil science literature. We focus on SOC measurement, spatial and temporal variation in SOC, and other considerations.

4.1. What to Measure and Why

Detecting changes in SOC is difficult. Even long-term, well-controlled studies reflect this challenge for some management practices, as we show here for diversified rotations and conversion from cropland to perennial grassland. Several factors influence our ability to detect and interpret SOC changes based on soil management, including the depth measured, bulk density, and the influence of different SOC fractions including highly persistent fractions (naturally occurring or added "biochar").

4.1.1. Soil Depth

The majority of Iowa research studies on the effect of management practices on SOC have focused on the upper 0–15 or 0–30 cm, leaving substantial uncertainty on impacts to deeper layers and changes in whole profile stocks [9]. Of the long-term studies summarized here, only two assessed SOC deeper in the soil profile. Al-Kaisi et al.'s [48] measured to a depth of 60 cm and established a positive influence of no-tillage on SOC across seven study locations. Poffenbarger et al. [41] did not find a consistent effect of cropping system on the vertical distribution of SOC within the soil profiles among three long term trials. More studies including measurements of deeper soil layers may help establish more consistent patterns, especially patterns of SOC that might be stable over long periods of time. Soil carbon sampling protocols and programs are generally focused on SOC changes in the upper 30 cm [8], but we note that subsurface horizons warrant considerable additional investigation because stocks of subsoil C may be substantial in some soils. Those deeper stocks may still be influenced by soil management at the soil surface, and the biochemical and physical processes that stabilize C in subsoils proceed at different rates from those in topsoils [100].

4.1.2. Bulk Density

Bulk density (dry mass per volume) is an essential parameter for the calculation of changes in SOC stocks, but it is difficult and time-consuming to obtain accurate measurements. Uncertainties associated with bulk density measurements are related to both spatial variability and the variety of methods that can be used. These uncertainties can easily exceed those associated with SOC measurement [9]. Automated in-situ tools such as multi-sensing penetrometers that predict bulk density rapidly and to multiple depths have been developed (e.g., [101]), but their use in soils with coarse fragments, gravel, or rocks is uncertain. There has been little testing of these tools in Iowa soils.

4.1.3. SOM Fractions

The components of SOM differ in both chemical and physical characteristics, and their functions and behaviors in soils also differ. Therefore, soil scientists have long investigated ways to chemically, physically, biologically, or through a combination of the three approaches, fractionate total SOM to better understand soil C and explain its behavior. Separating SOM according to its size (and sometimes density) into particulate organic matter C (POM-C) and mineral-associated organic matter C (MAOM-C) has proven useful for this purpose, given that these fractions broadly differ in their persistence, formation pathway, and soil function [102–104]. The POM fraction represents organic particles, usually partially decomposed fragments of plant tissue, that are >50–63 μm in diameter (depending on the specific protocol that is followed). MAOM is empirically defined as organic matter that is finer than 53–63 μm. POM may be located freely between soil

particles or occluded in large aggregates [104]. MAOM comprises organic compounds that may be chemically bound with soil minerals or could be located within micropores or small aggregates (<50–63 μm). The degree of its close physical association with silt and clay particles in an undisturbed soil is likely to be highly variable and dependent on clay type and concentration, pH, metal oxides, and exchangeable cations, as well as faunal activity that intimately mixes organic and inorganic components. In most fractionation schemes, MAOM includes microbial biomass and necromass. Soil organisms—both fauna and microorganisms—that decompose organic residues and environmental conditions regulate the formation and decay of these fractions. Understanding the complex interactions between these SOM pools, the environment, and decomposers is key to choosing the best management strategies to optimize SOM storage [105].

In Iowa croplands, the majority of SOC (>90%) is stored as MAOM-C [41]. Some of the organic matter in this fraction can persist in the soil for long periods (e.g., decades or longer) due to its attachment to or occlusion by minerals, but some MAOM compounds are also readily accessible to microbially derived enzymes and are decomposable. Some soil minerals with a low specific surface area can become saturated with MAOM-C [106–108]. To the extent that MAOM is composed of microbial biomass and necromass, its formation depends on the availability of nitrogen, which could pose another limitation for its accumulation [82]. When the mineral phase of a soil becomes saturated with C-containing compounds, additional C inputs can be stored as POM [107]. Thus, in such situations, it may be recommended to focus on managing POM (e.g., by cultivating crops that add low-quality residues to the soil) [105]. However, determining the C saturation limit for particular soils remains challenging and is subject to ongoing debate [109].

On the other hand, labile fractions like POM have been suggested as useful indicators of soil health compared to total SOM, because they exhibit greater sensitivity to changes in land use and management [110]. Results from a three-year study of different crop systems across a topographic gradient in Iowa indicated that while total SOC stocks remained unchanged, POM-C increased [111]. Additionally, soil aggregation showed a positive correlation with POM stocks, suggesting that improving soil structure enhances the protection of POM against decomposition. Similar findings were obtained when comparing different cropping systems in Iowa: POM-C exhibited changes while total SOC did not [52]. Utilizing data from this study, we also discovered a positive correlation between POM-C concentration and potentially mineralizable nitrogen (Figure 5). These results emphasize the importance of POM in defining soil properties and functions. While MAOM is also significant in certain soil functions, particularly nutrient storage and provision [112], it has received less attention [113].

Some forms of soil organic matter are inherently resistant to decomposition. When plant residues are heated at a high temperature in the absence of oxygen (i.e., pyrolyzed), some of the C present is not combusted but is condensed into chemical structures that resist further decomposition. The solid-phase product of pyrolysis is called char or biochar and can be produced at backyard to industrial scales to create a long-lasting soil carbon amendment [114–116]. In addition to removing C from the atmosphere for decadal to centuries-long periods, biochar soil amendments have been shown to enhance beneficial soil properties like cation and anion exchange capacities and water-holding capacity in soils (e.g., [117–120]).

Some soils already have measurable concentrations of such persistent C. These are hypothesized to be the legacy of naturally occurring fires, of fires created by Indigenous hunters to drive game, of localized and intentional soil amendments by Indigenous farmers before modern agriculture, or of crop residue burning to facilitate the subsequent planting of crops. Studies of Iowa soils have reported that 29–36 percent of the C in surface horizons was composed of such "recalcitrant" forms [121]. This fraction represents SOC that is likely to remain stable in the soil for long periods under many variations of soil management practices—as long as the soil is not eroded. The concentration of such recalcitrant C, which

is not quantitatively known for most soils, also has a significant impact on the uncertainty of predictions of soil C stocks that are made using dynamic models [122].

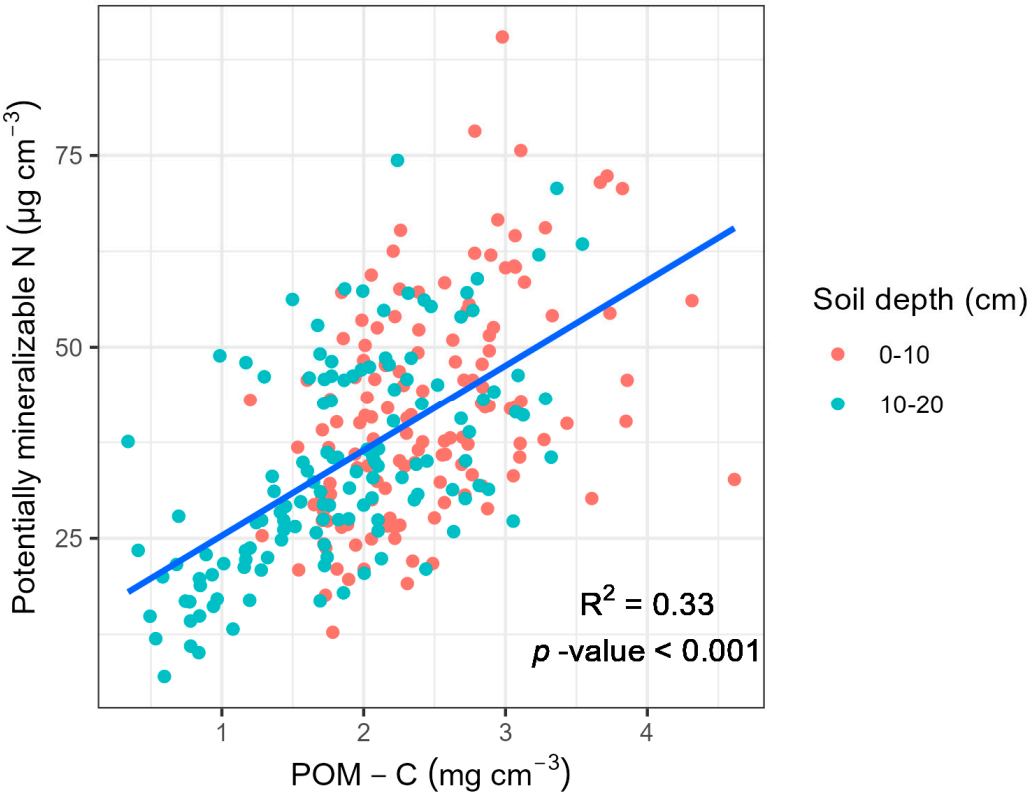


Figure 5. Particulate organic matter carbon (POM-C) relationships with potentially mineralizable nitrogen from Marsden Agricultural Diversification Experiment mentioned in previous section (data from [52]).

There are other soil C pools, usually either measured with an extraction or laboratory incubation, that are implicitly included in MAOM-C. This includes microbial biomass C, or C that is contained in living microorganisms, typically measured using chloroform fumigation-extraction or substrate-induced respiration [123]. Microorganisms in soil constantly reproduce and die at rates that depend on temperature and the availability of water and nutrients. While it is difficult to quantitatively differentiate the carbon associated with living versus dead microorganisms, recent research has estimated that in many cultivated and grassland soils the total necromass can account for as much as 50% of the total organic C in the soil [124,125]. Much bacterial biomass and necromass occurs in the clay size fraction, but fungal biomass also extends to the silt size fraction. Microbial biomass is dominated by the cell walls of the organisms, and those walls are composed of polymers of amino sugars. The breakdown of these polymers provides low-molecular-mass organic compounds that other microorganisms and plants use for energy, respiring the carbon as CO_2. In addition, the N in those polymers serves as an important source of mineralized inorganic N that both plants and soil organisms require. The importance of MAOM components like microbial biomass and necromass in N mineralization has recently been reported [126].

Also, the low-molecular-weight organic C that can be extracted with water (WEOC) has received some recent attention as it is one of three components in the "Haney Test" used in the Midwest US for soil health assessments [127,128]. Yet another way to fractionate SOC is to use soil biota themselves to produce CO_2 in a laboratory incubation—this method of re-wetting dry soils produces a "biologically active" C pool that is typically < 10% of SOC and has been used to predict soil nitrogen supply to crops [129–131]. These methods all

show promise as either proxies for measuring some soil function, like the ability to supply nitrogen, or as indicators of soil health [132,133].

POM has sometimes been treated as a "leading indicator" of long-term changes in organic matter concentrations that result from a change in management practice such as cover crops or reduced tillage. While changes in POM concentrations are more likely to occur over periods of a few years than are changes in total organic matter concentrations, only a minor fraction of POM C will remain unmineralized in most cultivated soils [134]. Thus, predicting the impacts of a management practice on long-term carbon storage by its impact on POM concentrations is problematic. It is also important to note that the most widely used dynamic process models to predict gains or losses of soil organic C are not based directly on POM and MAOM measurements. Models that are based on the CENTURY/DayCent framework (e.g., COMET-Farm, https://comet-farm.com/Home, accessed 17 August 2023) make assumptions about the litter pool (which includes particulates larger than POM), the microbial biomass pool, and the total soil organic matter pool. More recent academic models that include measured POM and MAOM values as input variables have been developed [135–137], but their ability to predict outcomes of soil management practices on soil C has not been tested.

4.2. Spatial and Temporal Variation in SOC

Many factors complicate the accounting of SOC stocks, including spatial and temporal variation. Soil samples are intended to represent a soil landscape, which has spatial connectivity. This condition presents challenges and opportunities. For example, lateral movement challenges assumptions made when comparing repeated location samples. Conversely, the fact that SOC stock is a spatially continuous variable presents opportunities to utilize geographic concepts to reduce uncertainty in SOC estimation for a given area.

The spatial modelling of soil carbon stocks uses auxiliary information such as spatial autocorrelation and remotely sensed covariates to improve the representation of the entity [138,139]. Using this additional information can lessen the uncertainty in assessment of carbon stocks compared to using sampling alone [140]. Similar to the question of how much precision is needed from lab measurements for detecting change, spatial modeling methods also contribute to the uncertainty in calculation of SOC stocks. To illustrate the range of outcomes possible by using different methods to assess the amount of SOC in a field, a variety of spatial modeling approaches were applied to a set of 143 soil samples from a 16-ha field in northern Iowa (Figure 6). Differences among the maps illustrate the potential variability in stock estimation resulting from differences in spatial modeling method and sampling density. The impact of the spatial modeling method is expected to increase for areas with higher variability of SOC stock due to the higher magnitude of spatial differences as the method interacts with the spatial pattern. The combination of field data with remotely sensed data dramatically improves the spatial resolution of prediction. These more highly resolved datasets can inform the precision management of SOC, particularly with regard to the strategic spatial integration of perennial crops or conservation cover [141]. As previously discussed, some portions of a field are likely to have a greater potential to accrue SOC than others.

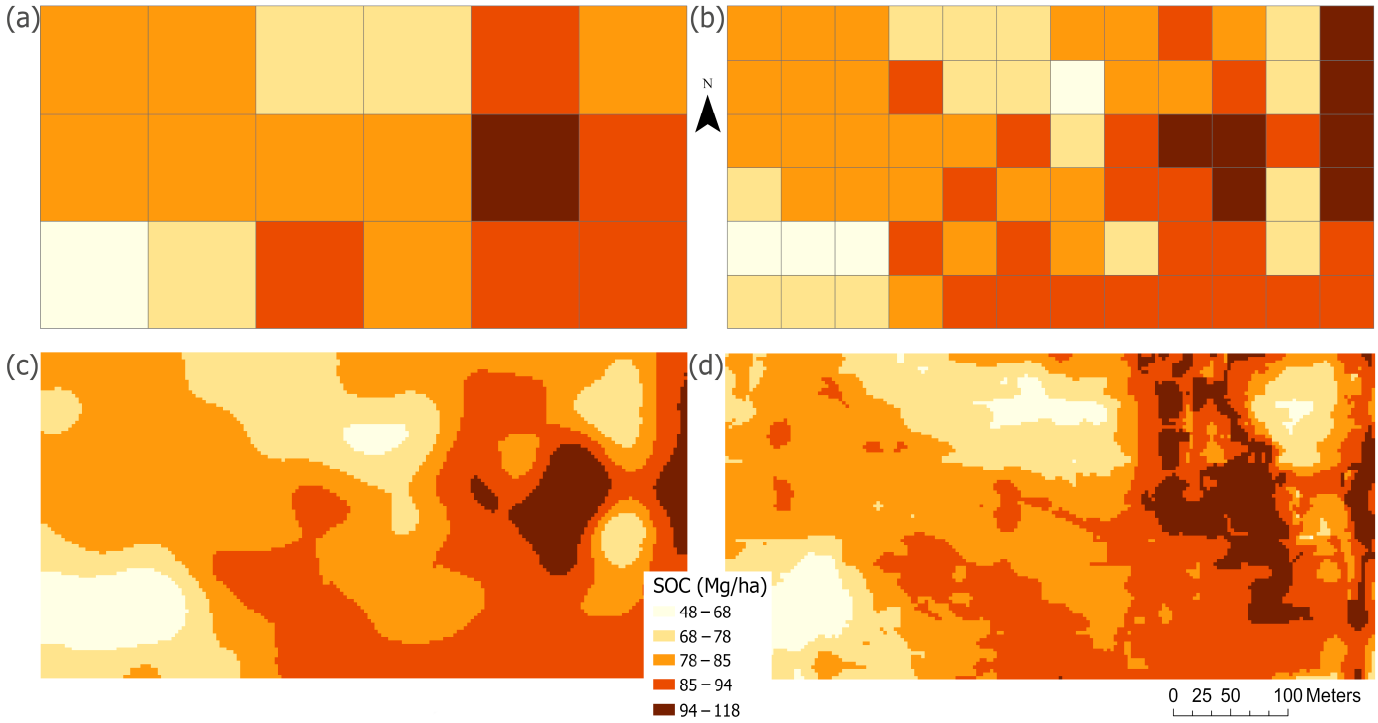


Figure 6. SOC stock maps generated from 143 samples (**a**) "composited" to a 0.4-ha (1-ac), (**b**) "composited" to a 0.1-ha (0.25-ac) grid, (**c**) interpolated using ordinary kriging, and (**d**) used to train a machine learning model with Cubist [142] and remotely sensed covariates.

Appropriate choices for soil sampling design depend on the intended use of that data. If they will be used estimate a field mean, then the goals of representing variability and having enough samples for statistical significance will be the most important. In terms of representing variability, the sampling design should be cognizant of equally representing zones versus the spatial weighting of those zones. A grid sampling design is inherently spatially weighted. If a stratified sampling design is applied, such as landscape position or soil map unit, then a strategy for spatially weighting those stratification zones will be needed for estimating the spatially weighted mean. For example, a field with a skewed distribution of SOM could be represented as a normal distribution with strategic sampling.

The number of samples needed also depends on how that data will be used to represent the field and how much uncertainty is tolerable. When the field is modelled by estimating a mean, field variability will often drive the need for a high number of samples to be able to detect significant change [93,143]. Other approaches to model a field can use geographic principles to spatially predict C stocks in unsampled locations. Spatial interpolation methods (e.g., kriging) rely on spatial autocorrelation to fill in values for the field. Spatial regression methods utilize other, more readily measured variables that tend to covary with the target variable to infer values for the complete field. In theory, the inclusion of additional information should reduce uncertainty in the accounting of soil properties in a field. However, the methods for estimating uncertainty differ among these approaches. More work is needed on comparing these methods and determining which are best suited for monitoring soil carbon stocks.

Temporal variation in SOC accrual rates also complicate accounting. As noted earlier in the context of POM and MAOM fractions, some scientists have hypothesized that soils have an intrinsic, "saturation" limit, that is a steady state status beyond which carbon stocks will not increase; in other words, the rate of carbon addition will be equal to the rate of its loss [105,107,144]. The carbon saturation concept is focused not on how much total carbon can accumulate in a soil, i.e., stored carbon, but on how much might be sequestered or stabilized for long periods, which depends mainly on clay-size minerals—if all other factors

are held constant. Scientists promoting the saturation concept reason that the primary control over the amount of carbon that is stabilized and not subject to loss is the mineral surface area that protects organic matter from being broken down by microbial enzymes. This hypothesis has been used to explain why increasing carbon stocks can be fast in some soils and very slow in others. However, there are some soils in Iowa almost entirely composed of organic matter with little mineral material (Histosols). These soils suggest that, under the right conditions, there is no limit to how much carbon can accumulate in some parts of the landscape.

While the protection of organic matter in association with minerals is one way C can be stabilized, some organic matter associated with clay and silt particles remains susceptible to oxidation. The period required to reach stable carbon stocks will vary not only with the quality and quantity of organic matter inputs but also with soil management practices (e.g., tillage, fertilization), changing climate, and vegetation. Soil amendments of organic matter in forms that are already resistant to decomposition, such as pyrolyzed biochar, will increase SOC in a soil beyond its saturation limits defined by texture. Digestate solids that result from the breakdown of organic matter through anaerobic digestion are also very slow to breakdown after land application and could increase SOC beyond typical saturation limits [145]. These soil management strategies require more research, especially through long-term replicated field trials in which several management factors are investigated in combination.

One concern moving forward is that studies of the past effect of management practices on SOC may not be predictive of future carbon storage given climate change. Climate change has likely contributed to increased maize and soybean yields in Iowa in recent decades due to the timing of humidity, rainfall, and heat [146]. Moreover, Iowa has had the good fortune of not experiencing the same level of warming to date as the global trend (aka, "the warming hole"). This is due in part to a buffering effect on peak summer and early fall temperatures as a result of crop evapotranspiration of spring and early summer rainfall and the high water holding capacity of Iowa's soils [147]. This advantage may be diminishing, as increasing spring rainfall often delays planting and increases soil erosion, and rising humidity increases the growth of molds and fungi [146]. Under a business-as-usual scenario in terms of global emissions, Iowa is likely to experience severe droughts in between high rainfall years from the present to ~2050, and subsequently, high temperatures, heat stress, and reduced growing season rainfall will tend to significantly constrain crop yields [146,148,149]. These changes will likely adversely impact the ability of Iowa soils to sequester carbon. Integration of the DAYCENT model with various Intergovernmental Panel on Climate Change (IPCC) climate models for central Iowa suggests declines in SOC in the latter part of 21st century, largely due to harvest losses, despite increases in net primary productivity [150].

The SOC benefits of converting areas of row crops to perennial grasses are likely to continue, even if slowly. However, profitable uses of perennial grasses are desperately needed to combine this clear SOC benefit with economic viability [151]. There is some nascent research on using perennial grain crops like Kernza® to concomitantly obtain the combined outcomes of grain production and SOC benefits [152,152]. Further research is underway on using perennial, native grasses as plant biomass feedstock for anaerobic digestion [151]. A clear path for recovering SOC, and sustainable agriculture, will likely require cropping systems that maintain continuous living cover, whether through integrating winter crops or through perennial plants: grain crops, forage crops, biomass crops, or restored native grassland species.

4.3. Other Considerations

Another major factor that may affect long-term SOC storage in Iowa soils is artificial drainage. Tile drainage has been used in Iowa since the 19th century to lower water tables and to remove excess soil water to allow earlier planting and to reduce nitrogen loss by denitrification during the growing season. Today, close to 60% of Iowa's cropland

is tiled [58,153,154]. Artificial drainage may also have an impact on the storage of soil carbon because it increases aeration and soil temperatures [155], potentially leading to the increased microbial oxidization of organic carbon [154,156,157].

Cropland soils in low-lying topographic positions tend to have higher soil carbon stocks [158] (e.g., the poorly-drained Webster soils vs. well to moderately well-drained Clarion soils in the same landscape (Figure 1)) because organic-matter-rich eroded sediments accumulated there or because decomposition rates of plant biomass were slow before agricultural exploitation. Subsurface drainage systems can release soil carbon from soils in these positions as CO_2 by lowering the water table, aerating the soil, and promoting decomposition of organic matter. Carbon markets have started to recognize the impacts: adding or improving drainage after the start of a project is not allowed in common soil carbon protocols (e.g., [159]). While subsurface drainage may promote soil carbon loss as CO_2, modeling studies suggest that artificial drainage could, in some years, reduce direct nitrous oxide (N_2O) emissions from maize cropping systems and may thus lead to lower net cumulative GHG emissions [154]. This is important to consider alongside carbon programs because one ton of N_2O traps 265 times more heat in the atmosphere than one ton of CO_2 over a 100-year period [160].

The emission of N_2O is most likely when soils are nearly but not completely saturated with water and the level of oxygen in the soil is low. Long-term measurements from typical maize/soybean rotations on poorly and somewhat poorly drained soils in central Iowa indicate that N_2O emissions from soil can be a significant contribution to atmospheric greenhouse gases [161,162], and they can release more N_2O than well-drained soils in other parts of the Midwest where previous research has been conducted [163]. Water-filled pores in an otherwise unsaturated soil can host microorganisms capable of biochemically reducing oxidized forms of nitrogen, like nitrate, to N_2O gas. Other studies suggest that N_2O emissions associated with practices like no-till, cover crops, and rotations are not likely to offset the lowered warming potential that results by CO_2 removal using those practices (e.g., [164]). More field research is needed to accurately predict N_2O emissions from soils under a greater variety of management regimes. The most important management practices to limit N_2O emissions from Iowa soils are already well known, however, and include (1) timing application of nitrogen fertilizers to crop growth periods when nitrogen is most needed, and (2) effective and timely drainage of somewhat poorly and poorly drained soils during spring snow melt and during the growing season.

Given the cost of data field collection, SOC cannot be sampled and understood at spatial and temporal resolutions sufficient to fully inform each management decision—predictions are necessary. Simulation models play a crucial role by providing a mathematical framework to represent our understanding of SOC dynamics and make predictions under various environmental conditions. Voluntary carbon credit programs rely on such simulation models, and sometimes also on sophisticated statistical analysis, to defensibly align sampling and analysis costs with carbon market values [8,9]. Agroecosystem models now are reasonably adept at prediction of maximum and minimum values from practice changes, but providing predictions of variability at field scale is less robust [9]. While soil measurements from Iowa are more extensive than many regions of the world, data to support model development and use are still limited in several respects. They are limited in both spatial resolution, including depths below 30 cm, and temporal resolution. They are particularly scant regarding the impacts of artificial drainage and newly emerging practices including multispecies cover crops and soil amendment with biochar or digestate [9].

Additional research is needed to improve SOC models. There is further need for models to provide more holistic predictions, integrating other crucial factors, including robust estimates of changes in GHG emissions, crop yield, etc., along with changes in SOC stocks [9]. Collaboration among modelers with researchers who generate empirical data is particularly essential, as the empirical data obtained from experiments is not always the most suitable for these models, and vice versa [165]. For instance, traditional SOM simulation models typically divide SOC into different conceptual pools (usually 3–5 pools,

depending on the model) to represent SOC heterogeneity (e.g., [166,167]); however, most of these pools do not correspond to the readily measurable fractions. This limitation significantly impacts the model's application, calibration, and validation since values for the input variables are assumed from limited and legacy empirical data rather than from contemporary measurements. A new generation of SOC models based on measurable fractions [135–137] and aimed at addressing this issue, represents an example of improved communication between modelers and experimental scientists.

5. Conclusions

There is growing interest in improving the measurement and management of SOC in agroecosystems due to its linkages to soil health and crop productivity, agroecosystem resilience under climate change, developing voluntary C markets, and Scope 3 emissions documentation. In assessing results from long-term studies on the effect of agricultural management on SOC stocks in Iowa—a relatively well studied part of the world—we found increases in SOC of 0.25–0.43 Mg C ha^{-1} yr^{-1} with adoption of strip-tillage and no-tillage compared to losses of 0.24 to 0.46 Mg C ha^{-1} yr^{-1} with more intensive after tillage methods; highly variable and inconsistent effects of diversifying crop rotations with extended rotations on SOC; and increases in SOC of 0.21–0.74 Mg C ha^{-1} yr^{-1} with conversion of cropland to perennial grassland. Results further indicate that SOC is highly variable spatially and responds slowly to management changes, and that changes under some management practices are difficult to detect with statistical certainty. While these general conclusions are not scientifically surprising, they are of increasing importance as society grapples with managing atmospheric CO_2 levels alongside feeding eight billion people and delivering other important ecosystem services. Given this constellation of factors, we suggest improved prediction of changes in SOC requires the development and use of new methods that can identify and disentangle multiple sources of variability; looking beyond total SOC and toward systematic collection of data on more responsive and functionally relevant fractions (including but not limited to POM-C and MAOM-C); monitoring the effects on SOC of multiple conservation practices used in combination in long-term studies; whole-profile SOC monitoring; and deeper collaboration between field soil scientists and modelers, which can help design the long-term studies needed to fill knowledge gaps.

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References

1. IPCC. Summary for Policy Makers. In *Climate Change 2022: Mitigation of Climate Change*; Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change; IPCC: Geneva, Switzerland, 2022.
2. Smith, S.M.; Geden, O.; Nemet, G.; Gidden, M.; Lamb, W.F.; Powis, C.; Bellamy, R.; Callaghan, M.; Cowie, A.; Cox, E.; et al. *The State of Carbon Dioxide Removal*; Smith School of Enterprise and the Environment (SSEE): Oxford, UK, 2023.
3. Robertson, G.P.; Hamilton, S.K.; Paustian, K.; Smith, P. Land-Based Climate Solutions for the United States. *Glob. Chang. Biol.* **2022**, *28*, 4912–4919. [CrossRef]
4. Moinet, G.Y.K.; Hijbeek, R.; van Vuuren, D.P.; Giller, K.E. Carbon for Soils, Not Soils for Carbon. *Glob. Chang. Biol.* **2023**, *29*, 2384–2398. [CrossRef]

5. Bossio, D.A.; Cook-Patton, S.C.; Ellis, P.W.; Fargione, J.; Sanderman, J.; Smith, P.; Wood, S.; Zomer, R.J.; von Unger, M.; Emmer, I.M.; et al. The Role of Soil Carbon in Natural Climate Solutions. *Nat. Sustain.* **2020**, *3*, 391–398. [CrossRef]
6. Vermeulen, S.; Bossio, D.; Lehmann, J.; Luu, P.; Paustian, K.; Webb, C.; Augé, F.; Bacudo, I.; Baedeker, T.; Havemann, T.; et al. A Global Agenda for Collective Action on Soil Carbon. *Nat. Sustain.* **2019**, *2*, 2–4. [CrossRef]
7. Plastina, A. *The U.S. Voluntary Agricultural Carbon Market: Where to From Here?* Farm Foundation: Oak Brook, IL, USA, 2022.
8. Oldfield, E.; Eagle, A.; Rubin, R.; Sanderman, J.; Gordon, D. *Agricultural Soil Carbon Credits: Making Sense of Protocols for Carbon Sequestration and Net Greenhouse Gas Removals*; Environmental Defense Fund: New York, NY, USA, 2021.
9. Schulte, L.A.; Jordahl, J.L. *Carbon Science for Carbon Markets: Emerging Opportunities in Iowa*; Iowa State University Extension and Outreach: Ames, IA, USA, 2022.
10. Erb, T.; Perciasepe, B.; Radulovic, V.; Niland, M. Corporate Climate Commitments: The Trend Towards Net Zero. In *Handbook of Climate Change Mitigation and Adaptation*; Lackner, M., Sajjadi, B., Chen, W.-Y., Eds.; Springer: New York, NY, USA, 2020; pp. 1–34. ISBN 978-1-4614-6431-0.
11. USDA. *Partnerships for Climate-Smart Commodities Project Summaries*; USDA: Washington, DC, USA, 2022.
12. Stokstad, E. New Law's Big Payout for Farming Has Uncertain Climate Payoff. *Science* **2022**, *377*, 800–801. [CrossRef]
13. Pribyl, D.W. A Critical Review of the Conventional SOC to SOM Conversion Factor. *Geoderma* **2010**, *156*, 75–83. [CrossRef]
14. Ontl, T.A.; Schulte, L.A. Soil Carbon Storage. *Nat. Educ. Knowl.* **2012**, *3*, 35.
15. King, A.; Ali, G.; Gillespie, A.; Wagner-Riddle, C. Soil Organic Matter as Catalyst of Crop Resource Capture. *Front. Environ. Sci.* **2020**, *8*, 50. [CrossRef]
16. Cotrufo, M.F.; Lavallee, J.M. Chapter One—Soil Organic Matter Formation, Persistence, and Functioning: A Synthesis of Current Understanding to Inform Its Conservation and Regeneration. In *Advances in Agronomy*; Sparks, D.L., Ed.; Academic Press: Cambridge, MA, USA, 2022; Volume 172, pp. 1–66.
17. Wiesmeier, M.; Urbanski, L.; Hobley, E.; Lang, B.; von Lützow, M.; Marin-Spiotta, E.; van Wesemael, B.; Rabot, E.; Ließ, M.; Garcia-Franco, N.; et al. Soil Organic Carbon Storage as a Key Function of Soils—A Review of Drivers and Indicators at Various Scales. *Geoderma* **2019**, *333*, 149–162. [CrossRef]
18. Ros, G.H.; Temminghoff, E.J.M.; Hoffland, E. Nitrogen Mineralization: A Review and Meta-Analysis of the Predictive Value of Soil Tests. *Eur. J. Soil Sci.* **2011**, *62*, 162–173. [CrossRef]
19. Janzen, H.H. The Soil Carbon Dilemma: Shall We Hoard It or Use It? *Soil Biol. Biochem.* **2006**, *38*, 419–424. [CrossRef]
20. Hopkins, C. Soil Fertility and Permanent Agriculture. *Nature* **1911**, *86*, 272–273. [CrossRef]
21. USDA-NRCS Gridded Soil Survey Geographic (GSSURGO) Database | Natural Resources Conservation Service. Available online: https://www.nrcs.usda.gov/resources/data-and-reports/gridded-soil-survey-geographic-gssurgo-database (accessed on 21 June 2023).
22. Hassink, J. The Capacity of Soils to Preserve Organic C and N by Their Association with Clay and Silt Particles. *Plant Soil* **1997**, *191*, 77–87. [CrossRef]
23. Plante, A.F.; Conant, R.T.; Stewart, C.E.; Paustian, K.; Six, J. Impact of Soil Texture on the Distribution of Soil Organic Matter in Physical and Chemical Fractions. *Soil Sci. Soc. Am. J.* **2006**, *70*, 287–296. [CrossRef]
24. USDA-NRCS National Soil Information System (NASIS) | Natural Resources Conservation Service. Available online: https://www.nrcs.usda.gov/resources/education-and-teaching-materials/national-soil-information-system-nasis (accessed on 29 June 2023).
25. Miller, B.A.; Schaetzl, R.J. The Historical Role of Base Maps in Soil Geography. *Geoderma* **2014**, *230–231*, 329–339. [CrossRef]
26. Most U.S. Fuel Ethanol Production Capacity at the Start of 2022 Was in the Midwest. Available online: https://www.eia.gov/todayinenergy/detail.php?id=53539 (accessed on 27 June 2023).
27. NASS. *Iowa's Rank in United States Agriculture*; United States Department of Agriculture National Agricultural Statistics Service: Washington, DC, USA, 2022.
28. Hurt, R.D. *Indian Agriculture in America: Prehistory to the Present*; University Press of Kansas: Lawrence, KS, USA, 1987; ISBN 978-0-7006-0337-4.
29. Green, W.; Arzigian, C. *Agricultural Origins and Development in the Midcontinent*; The Office of the State Archaeologist: Iowa City, IA, USA, 1994.
30. Landon, A. *The "How" of the Three Sisters: The Origins of Agriculture in Mesoamerica and the Human Niche*; Nebraska Anthropologist; University of Nebraska-Lincoln: Lincoln, NE, USA, 2008.
31. Veenstra, J.J.; Lee Burras, C. Soil Profile Transformation after 50 Years of Agricultural Land Use. *Soil Sci. Soc. Am. J.* **2015**, *79*, 1154–1162. [CrossRef]
32. Thaler, E.A.; Larsen, I.J.; Yu, Q. The Extent of Soil Loss across the US Corn Belt. *Proc. Natl. Acad. Sci. USA* **2021**, *118*, e1922375118. [CrossRef] [PubMed]
33. Sawadgo, W.; Plastina, A. The Invisible Elephant: Disadoption of Conservation Practices in the United States. *Choices* **2022**, *37*, 1–13.
34. USDA. *Summary Report: 2017 National Resources Inventory*; U.S. Department of Agricultuire: Natural Resources Conservation Service: Washington, DC, USA; Center for Survey Statistics and Methodology, Iowa State University: Ames, IA, USA, 2020.
35. Sanderman, J.; Hengl, T.; Fiske, G.J. Soil Carbon Debt of 12,000 Years of Human Land Use. *Proc. Natl. Acad. Sci. USA* **2017**, *114*, 9575–9580. [CrossRef]

36. Aref, S.; Wander, M.M. Long-Term Trends of Corn Yield and Soil Organic Matter in Different Crop Sequences and Soil Fertility Treatments on the Morrow Plots. In *Advances in Agronomy*; Sparks, D.L., Ed.; Academic Press: Cambridge, MA, USA, 1997; Volume 62, pp. 153–197.
37. Nafziger, E.D.; Dunker, R.E. Soil Organic Carbon Trends Over 100 Years in the Morrow Plots. *Agron. J.* **2011**, *103*, 261–267. [CrossRef]
38. Karlen, D.L.; Berry, E.C.; Colvin, T.S.; Kanwar, R.S. Twelve-year Tillage and Crop Rotation Effects on Yields and Soil Chemical Properties in Northeast Iowa. *Commun. Soil Sci. Plant Anal.* **1991**, *22*, 1985–2003. [CrossRef]
39. Barber, S.A. Corn Residue Management and Soil Organic Matter1. *Agron. J.* **1979**, *71*, 625–627. [CrossRef]
40. Robinson, C.A.; Cruse, R.M.; Ghaffarzadeh, M. Cropping System and Nitrogen Effects on Mollisol Organic Carbon. *Soil Sci. Soc. Am. J.* **1996**, *60*, 264–269. [CrossRef]
41. Poffenbarger, H.J.; Olk, D.C.; Cambardella, C.; Kersey, J.; Liebman, M.; Mallarino, A.; Six, J.; Castellano, M.J. Whole-Profile Soil Organic Matter Content, Composition, and Stability under Cropping Systems That Differ in Belowground Inputs. *Agric. Ecosyst. Environ.* **2020**, *291*, 106810. [CrossRef]
42. Hoover, N.L.; Law, J.Y.; Long, L.A.M.; Kanwar, R.S.; Soupir, M.L. Long-Term Impact of Poultry Manure on Crop Yield, Soil and Water Quality, and Crop Revenue. *J. Environ. Manag.* **2019**, *252*, 109582. [CrossRef] [PubMed]
43. Moore, E.B.; Wiedenhoeft, M.H.; Kaspar, T.C.; Cambardella, C.A. Rye Cover Crop Effects on Soil Quality in No-Till Corn Silage–Soybean Cropping Systems. *Soil Sci. Soc. Am. J.* **2014**, *78*, 968–976. [CrossRef]
44. Studt, J.E.; McDaniel, M.D.; Tejera, M.D.; VanLoocke, A.; Howe, A.; Heaton, E.A. Soil Net Nitrogen Mineralization and Leaching under Miscanthus × Giganteus and Zea Mays. *GCB Bioenergy* **2021**, *13*, 1545–1560. [CrossRef]
45. Ibrahim, M.A.; Chua-Ona, T.; Liebman, M.; Thompson, M.L. Soil Organic Carbon Storage under Biofuel Cropping Systems in a Humid, Continental Climate. *Agron. J.* **2018**, *110*, 1748–1753. [CrossRef]
46. Banik, C.; Bartel, C.A.; Laird, D.A.; Moore, K.J.; Lenssen, A.W. Perennial Cover Crop Influences on Soil C and N and Maize Productivity. *Nutr. Cycl. Agroecosyst.* **2020**, *116*, 135–150. [CrossRef]
47. Guzman, J.G.; Al-Kaisi, M.M. Soil Carbon Dynamics and Carbon Budget of Newly Reconstructed Tall-Grass Prairies in South Central Iowa. *J. Environ. Qual.* **2010**, *39*, 136–146. [CrossRef]
48. Al-Kaisi, M.M.; Kwaw-Mensah, D. Quantifying Soil Carbon Change in a Long-term Tillage and Crop Rotation Study across Iowa Landscapes. *Soil Sci. Soc. Am. J.* **2020**, *84*, 182–202. [CrossRef]
49. Robinson, C. Long-Term Cropping System and Nitrogen Management Effects on Soil Properties. Ph.D. Dissertation, Iowa State University, Ames, IA, USA, 1993.
50. Russell, A.E.; Cambardella, C.A.; Laird, D.A.; Jaynes, D.B.; Meek, D.W. Nitrogen Fertilizer Effects on Soil Carbon Balances in Midwestern U.S. Agricultural Systems. *Ecol. Appl.* **2009**, *19*, 1102–1113. [CrossRef]
51. Russell, A.E.; Laird, D.A.; Parkin, T.B.; Mallarino, A.P. Impact of Nitrogen Fertilization and Cropping System on Carbon Sequestration in Midwestern Mollisols. *Soil Sci. Soc. Am. J.* **2005**, *69*, 413–422. [CrossRef]
52. Lazicki, P.A.; Liebman, M.; Wander, M.M. Root Parameters Show How Management Alters Resource Distribution and Soil Quality in Conventional and Low-Input Cropping Systems in Central Iowa. *PLoS ONE* **2016**, *11*, e0164209. [CrossRef] [PubMed]
53. Baldwin-Kordick, R.; De, M.; Lopez, M.D.; Liebman, M.; Lauter, N.; Marino, J.; McDaniel, M.D. Comprehensive Impacts of Diversified Cropping on Soil Health and Sustainability. *Agroecol. Sustain. Food Syst.* **2022**, *46*, 331–363. [CrossRef]
54. Bugeja, S.M.; Castellano, M.J. Physicochemical Organic Matter Stabilization across a Restored Grassland Chronosequence. *Soil Sci. Soc. Am. J.* **2018**, *82*, 1559–1567. [CrossRef]
55. De, M.; Riopel, J.A.; Cihacek, L.J.; Lawrinenko, M.; Baldwin-Kordick, R.; Hall, S.J.; McDaniel, M.D. Soil Health Recovery after Grassland Reestablishment on Cropland: The Effects of Time and Topographic Position. *Soil Sci. Soc. Am. J.* **2020**, *84*, 568–586. [CrossRef]
56. Sanderman, J.; Baldock, J. Accounting for Soil Carbon Sequestration in National Inventories: A Soil Scientist's Perspective. *Environ. Res. Lett.* **2010**, *5*, 034003. [CrossRef]
57. IDALS. *Acessibility Version: Tracking the Iowa Nutrient Reduction Strategy*; Version 1.0; Iowa Department of Agriculture and Land Stewardship, Iowa Department of Natural Resources, Iowa State University: Ames, IA, USA, 2021.
58. 2017 Census by State—Iowa | 2017 Census of Agriculture | USDA/NASS. Available online: https://www.nass.usda.gov/Publications/AgCensus/2017/Full_Report/Census_by_State/Iowa/index.php (accessed on 28 June 2023).
59. Pittelkow, C.M.; Linquist, B.A.; Lundy, M.E.; Liang, X.; van Groenigen, K.J.; Lee, J.; van Gestel, N.; Six, J.; Venterea, R.T.; van Kessel, C. When Does No-till Yield More? A Global Meta-Analysis. *Field Crops Res.* **2015**, *183*, 156–168. [CrossRef]
60. West, T.O.; Post, W.M. Soil Organic Carbon Sequestration Rates by Tillage and Crop Rotation. *Soil Sci. Soc. Am. J.* **2002**, *66*, 1930–1946. [CrossRef]
61. Virto, I.; Barré, P.; Burlot, A.; Chenu, C. Carbon Input Differences as the Main Factor Explaining the Variability in Soil Organic C Storage in No-Tilled Compared to Inversion Tilled Agrosystems. *Biogeochemistry* **2012**, *108*, 17–26. [CrossRef]
62. Meurer, K.H.E.; Haddaway, N.R.; Bolinder, M.A.; Kätterer, T. Tillage Intensity Affects Total SOC Stocks in Boreo-Temperate Regions Only in the Topsoil—A Systematic Review Using an ESM Approach. *Earth-Sci. Rev.* **2018**, *177*, 613–622. [CrossRef]
63. Nicoloso, R.S.; Rice, C.W. Intensification of No-till Agricultural Systems: An Opportunity for Carbon Sequestration. *Soil Sci. Soc. Am. J.* **2021**, *85*, 1395–1409. [CrossRef]

64. Ogle, S.M.; Alsaker, C.; Baldock, J.; Bernoux, M.; Breidt, F.J.; McConkey, B.; Regina, K.; Vazquez-Amabile, G.G. Climate and Soil Characteristics Determine Where No-Till Management Can Store Carbon in Soils and Mitigate Greenhouse Gas Emissions. *Sci. Rep.* **2019**, *9*, 11665. [CrossRef] [PubMed]
65. Baker, J.M.; Ochsner, T.E.; Venterea, R.T.; Griffis, T.J. Tillage and Soil Carbon Sequestration—What Do We Really Know? *Agric. Ecosyst. Environ.* **2007**, *118*, 1–5. [CrossRef]
66. Cai, A.; Han, T.; Ren, T.; Sanderman, J.; Rui, Y.; Wang, B.; Smith, P.; Xu, M.; Li, Y. Declines in Soil Carbon Storage under No Tillage Can Be Alleviated in the Long Run. *Geoderma* **2022**, *425*, 116028. [CrossRef]
67. Powlson, D.S.; Stirling, C.M.; Jat, M.L.; Gerard, B.G.; Palm, C.A.; Sanchez, P.A.; Cassman, K.G. Limited Potential of No-till Agriculture for Climate Change Mitigation. *Nat. Clim. Chang.* **2014**, *4*, 678–683. [CrossRef]
68. Luo, Z.; Wang, E.; Sun, O.J. Can No-Tillage Stimulate Carbon Sequestration in Agricultural Soils? A Meta-Analysis of Paired Experiments. *Agric. Ecosyst. Environ.* **2010**, *139*, 224–231. [CrossRef]
69. Mondal, S.; Chakraborty, D.; Paul, R.K.; Mondal, A.; Ladha, J. No-till Is More of Sustaining the Soil than a Climate Change Mitigation Option. *Agric. Ecosyst. Environ.* **2023**, *352*, 108498. [CrossRef]
70. Simpson, Z.; Jordahl, J.; Simpson, A.; Miguez, F.; Niemi, J.; Schulte, L.; Thompson, M.; Villarino, S.; McDaniel, M. No-Tillage Does Not on Average Reduce Soil Carbon Storage Compared to Conventional Tillage. Comment on "Declines in Soil Carbon Storage under No Tillage Can Be Alleviated in the Long Run" by Cai et al. *Geoderma* **2022**, *430*, 116307. [CrossRef]
71. Alvarez, R. A Review of Nitrogen Fertilizer and Conservation Tillage Effects on Soil Organic Carbon Storage. *Soil Use Manag.* **2005**, *21*, 38–52. [CrossRef]
72. Seitz, S.; Prasuhn, V.; Scholten, T. Controlling Soil Erosion Using No-Till Farming Systems. In *No-Till Farming Systems for Sustainable Agriculture: Challenges and Opportunities*; Dang, Y.P., Dalal, R.C., Menzies, N.W., Eds.; Springer International Publishing: Cham, Switzerland, 2020; pp. 195–211. ISBN 978-3-030-46409-7.
73. Montgomery, D.R. Soil Erosion and Agricultural Sustainability. *Proc. Natl. Acad. Sci. USA* **2007**, *104*, 13268–13272. [CrossRef] [PubMed]
74. Moorman, T.B.; Cambardella, C.A.; James, D.E.; Karlen, D.L.; Kramer, L.A. Quantification of Tillage and Landscape Effects on Soil Carbon in Small Iowa Watersheds. *Soil Tillage Res.* **2004**, *78*, 225–236. [CrossRef]
75. Basche, A.D.; Miguez, F.E.; Kaspar, T.C.; Castellano, M.J. Do Cover Crops Increase or Decrease Nitrous Oxide Emissions? A Meta-Analysis. *J. Soil Water Conserv.* **2014**, *69*, 471–482. [CrossRef]
76. Liu, X.; Wu, X.; Liang, G.; Zheng, F.; Zhang, M.; Li, S. A Global Meta-Analysis of the Impacts of No-Tillage on Soil Aggregation and Aggregate-Associated Organic Carbon. *Land Degrad. Dev.* **2021**, *32*, 5292–5305. [CrossRef]
77. Zuber, S.M.; Villamil, M.B. Meta-Analysis Approach to Assess Effect of Tillage on Microbial Biomass and Enzyme Activities. *Soil Biol. Biochem.* **2016**, *97*, 176–187. [CrossRef]
78. Waring, E.R.; Lagzdins, A.; Pederson, C.; Helmers, M.J. Influence of No-till and a Winter Rye Cover Crop on Nitrate Losses from Tile-Drained Row-Crop Agriculture in Iowa. *J. Environ. Qual.* **2020**, *49*, 292–303. [CrossRef]
79. Brown, P.W.; Schulte, L.A. Agricultural Landscape Change (1937–2002) in Three Townships in Iowa, USA. *Landsc. Urban Plan.* **2011**, *100*, 202–212. [CrossRef]
80. Liebman, M.; Gibson, L.R.; Sundberg, D.N.; Heggenstaller, A.H.; Westerman, P.R.; Chase, C.A.; Hartzler, R.G.; Menalled, F.D.; Davis, A.S.; Dixon, P.M. Agronomic and Economic Performance Characteristics of Conventional and Low-External-Input Cropping Systems in the Central Corn Belt. *Agron. J.* **2008**, *100*, 600–610. [CrossRef]
81. Poffenbarger, H.J.; Barker, D.W.; Helmers, M.J.; Miguez, F.E.; Olk, D.C.; Sawyer, J.E.; Six, J.; Castellano, M.J. Maximum Soil Organic Carbon Storage in Midwest U.S. Cropping Systems When Crops Are Optimally Nitrogen-Fertilized. *PLoS ONE* **2017**, *12*, e0172293. [CrossRef] [PubMed]
82. Cotrufo, M.F.; Ranalli, M.G.; Haddix, M.L.; Six, J.; Lugato, E. Soil Carbon Storage Informed by Particulate and Mineral-Associated Organic Matter. *Nat. Geosci.* **2019**, *12*, 989–994. [CrossRef]
83. McDaniel, M.D.; Tiemann, L.K.; Grandy, A.S. Does Agricultural Crop Diversity Enhance Soil Microbial Biomass and Organic Matter Dynamics? A Meta-Analysis. *Ecol. Appl.* **2014**, *24*, 560–570. [CrossRef] [PubMed]
84. Maillard, É.; Angers, D.A. Animal Manure Application and Soil Organic Carbon Stocks: A Meta-Analysis. *Glob. Chang. Biol.* **2014**, *20*, 666–679. [CrossRef]
85. Rui, Y.; Jackson, R.D.; Cotrufo, M.F.; Sanford, G.R.; Spiesman, B.J.; Deiss, L.; Culman, S.W.; Liang, C.; Ruark, M.D. Persistent Soil Carbon Enhanced in Mollisols by Well-Managed Grasslands but Not Annual Grain or Dairy Forage Cropping Systems. *Proc. Natl. Acad. Sci. USA* **2022**, *119*, e2118931119. [CrossRef]
86. Hunt, N.D.; Liebman, M.; Thakrar, S.K.; Hill, J.D. Fossil Energy Use, Climate Change Impacts, and Air Quality-Related Human Health Damages of Conventional and Diversified Cropping Systems in Iowa, USA. *Environ. Sci. Technol.* **2020**, *54*, 11002–11014. [CrossRef]
87. Hunt, N.D.; Hill, J.D.; Liebman, M. Cropping System Diversity Effects on Nutrient Discharge, Soil Erosion, and Agronomic Performance. *Environ. Sci. Technol.* **2019**, *53*, 1344–1352. [CrossRef]
88. IDNR Prairie Resource Center—Iowa Department of Natural Resources. Available online: https://www.iowadnr.gov/conservation/prairie-resource-center (accessed on 27 June 2023).
89. DeLuca, T.H.; Zabinski, C.A. Prairie Ecosystems and the Carbon Problem. *Front. Ecol. Environ.* **2011**, *9*, 407–413. [CrossRef]

90. Schulte, L.A.; Niemi, J.; Helmers, M.J.; Liebman, M.; Arbuckle, J.G.; James, D.E.; Kolka, R.K.; O'Neal, M.E.; Tomer, M.D.; Tyndall, J.C.; et al. Prairie Strips Improve Biodiversity and the Delivery of Multiple Ecosystem Services from Corn–Soybean Croplands. *Proc. Natl. Acad. Sci. USA* **2017**, *114*, 11247–11252. [CrossRef]
91. Brandes, E.; Mcnunn, G.; Schulte, L.; Bonner, I.; Muth, D.; Babcock, B.; Sharma, B.; Heaton, E. Subfield Profitability Analysis Reveals an Economic Case for Cropland Diversification. *Environ. Res. Lett.* **2016**, *11*, 014009. [CrossRef]
92. Berger, H.; Meyer, C.K.; Mummert, A.; Tirado, L.; Saucedo, L.; Bonello, H.; Van Arsdale, D.; Williams, G. Land Use Dynamics within the Tallgrass Prairie Ecosystem: The Case for the Conservation Reserve Program (CRP). *Theor. Ecol.* **2020**, *13*, 289–300. [CrossRef]
93. Garten, C.T., Jr.; Wullschleger, S.D. Soil Carbon Inventories under a Bioenergy Crop (Switchgrass): Measurement Limitations. *J. Environ. Qual.* **1999**, *28*, 1359–1365. [CrossRef]
94. Ye, C.; Hall, S.J. Mechanisms Underlying Limited Soil Carbon Gains in Perennial and Cover-Cropped Bioenergy Systems Revealed by Stable Isotopes. *GCB Bioenergy* **2020**, *12*, 101–117. [CrossRef]
95. Sokol, N.W.; Bradford, M.A. Microbial Formation of Stable Soil Carbon Is More Efficient from Belowground than Aboveground Input. *Nat. Geosci.* **2019**, *12*, 46–53. [CrossRef]
96. An, H.; Wu, X.; Zhang, Y.; Tang, Z. Effects of Land-Use Change on Soil Inorganic Carbon: A Meta-Analysis. *Geoderma* **2019**, *353*, 273–282. [CrossRef]
97. Guo, L.B.; Gifford, R.M. Soil Carbon Stocks and Land Use Change: A Meta Analysis. *Glob. Chang. Biol.* **2002**, *8*, 345–360. [CrossRef]
98. Kristensen, J.A.; Svenning, J.-C.; Georgiou, K.; Malhi, Y. Can Large Herbivores Enhance Ecosystem Carbon Persistence? *Trends Ecol. Evol.* **2022**, *37*, 117–128. [CrossRef]
99. Fargione, J.E.; Bassett, S.; Boucher, T.; Bridgham, S.D.; Conant, R.T.; Cook-Patton, S.C.; Ellis, P.W.; Falcucci, A.; Fourqurean, J.W.; Gopalakrishna, T.; et al. Natural Climate Solutions for the United States. *Sci. Adv.* **2018**, *4*, eaat1869. [CrossRef]
100. Button, E.S.; Pett-Ridge, J.; Murphy, D.V.; Kuzyakov, Y.; Chadwick, D.R.; Jones, D.L. Deep-C Storage: Biological, Chemical and Physical Strategies to Enhance Carbon Stocks in Agricultural Subsoils. *Soil Biol. Biochem.* **2022**, *170*, 108697. [CrossRef]
101. Wijewardane, N.K.; Hetrick, S.; Ackerson, J.; Morgan, C.L.S.; Ge, Y. VisNIR Integrated Multi-Sensing Penetrometer for in Situ High-Resolution Vertical Soil Sensing. *Soil Tillage Res.* **2020**, *199*, 104604. [CrossRef]
102. von Lützow, M.; Kögel-Knabner, I.; Ludwig, B.; Matzner, E.; Flessa, H.; Ekschmitt, K.; Guggenberger, G.; Marschner, B.; Kalbitz, K. Stabilization Mechanisms of Organic Matter in Four Temperate Soils: Development and Application of a Conceptual Model. *J. Plant Nutr. Soil Sci.* **2008**, *171*, 111–124. [CrossRef]
103. Cotrufo, M.F.; Soong, J.L.; Horton, A.J.; Campbell, E.E.; Haddix, M.L.; Wall, D.H.; Parton, W.J. Formation of Soil Organic Matter via Biochemical and Physical Pathways of Litter Mass Loss. *Nat. Geosci.* **2015**, *8*, 776–779. [CrossRef]
104. Lavallee, J.M.; Soong, J.L.; Cotrufo, M.F. Conceptualizing Soil Organic Matter into Particulate and Mineral-Associated Forms to Address Global Change in the 21st Century. *Glob. Chang. Biol.* **2020**, *26*, 261–273. [CrossRef] [PubMed]
105. Angst, G.; Mueller, K.E.; Castellano, M.J.; Vogel, C.; Wiesmeier, M.; Mueller, C.W. Unlocking Complex Soil Systems as Carbon Sinks: Multi-Pool Management as the Key. *Nat. Commun.* **2023**, *14*, 2967. [CrossRef] [PubMed]
106. Six, J.; Conant, R.T.; Paul, E.A.; Paustian, K. Stabilization Mechanisms of Soil Organic Matter: Implications for C-Saturation of Soils. *Plant Soil* **2002**, *241*, 155–176. [CrossRef]
107. Stewart, C.E.; Paustian, K.; Conant, R.T.; Plante, A.F.; Six, J. Soil Carbon Saturation: Concept, Evidence and Evaluation. *Biogeochemistry* **2007**, *86*, 19–31. [CrossRef]
108. Stewart, C.E.; Plante, A.F.; Paustian, K.; Conant, R.T.; Six, J. Soil Carbon Saturation: Linking Concept and Measurable Carbon Pools. *Soil Sci. Soc. Am. J.* **2008**, *72*, 379–392. [CrossRef]
109. Begill, N.; Don, A.; Poeplau, C. No Detectable Upper Limit of Mineral-Associated Organic Carbon in Temperate Agricultural Soils. *Glob. Chang. Biol.* **2023**, *29*, 4662–4669. [CrossRef]
110. Haynes, R. Labile Organic Matter Fractions as Central Components of the Quality of Agricultural Soils: An Overview. *Adv. Agron.* **2005**, *85*, 221–268. [CrossRef]
111. Ontl, T.A.; Cambardella, C.A.; Schulte, L.A.; Kolka, R.K. Factors Influencing Soil Aggregation and Particulate Organic Matter Responses to Bioenergy Crops across a Topographic Gradient. *Geoderma* **2015**, *255–256*, 1–11. [CrossRef]
112. Daly, A.B.; Jilling, A.; Bowles, T.M.; Buchkowski, R.W.; Frey, S.D.; Kallenbach, C.M.; Keiluweit, M.; Mooshammer, M.; Schimel, J.P.; Grandy, A.S. A Holistic Framework Integrating Plant-Microbe-Mineral Regulation of Soil Bioavailable Nitrogen. *Biogeochemistry* **2021**, *154*, 211–229. [CrossRef] [PubMed]
113. Yu, W.; Huang, W.; Weintraub-Leff, S.R.; Hall, S.J. Where and Why Do Particulate Organic Matter (POM) and Mineral-Associated Organic Matter (MAOM) Differ among Diverse Soils? *Soil Biol. Biochem.* **2022**, *172*, 108756. [CrossRef]
114. Lefebvre, D.; Williams, A.; Meersmans, J.; Kirk, G.J.D.; Sohi, S.; Goglio, P.; Smith, P. Modelling the Potential for Soil Carbon Sequestration Using Biochar from Sugarcane Residues in Brazil. *Sci. Rep.* **2020**, *10*, 19479. [CrossRef] [PubMed]
115. Amonette, J.E.; Blanco-Canqui, H.; Hassebrook, C.; Laird, D.A.; Lal, R.; Lehmann, J.; Page-Dumroese, D. Integrated Biochar Research: A Roadmap. *J. Soil Water Conserv.* **2021**, *76*, 24A–29A. [CrossRef]
116. Lehmann, J.; Cowie, A.; Masiello, C.A.; Kammann, C.; Woolf, D.; Amonette, J.E.; Cayuela, M.L.; Camps-Arbestain, M.; Whitman, T. Biochar in Climate Change Mitigation. *Nat. Geosci.* **2021**, *14*, 883–892. [CrossRef]

117. Mao, J.-D.; Johnson, R.L.; Lehmann, J.; Olk, D.C.; Neves, E.G.; Thompson, M.L.; Schmidt-Rohr, K. Abundant and Stable Char Residues in Soils: Implications for Soil Fertility and Carbon Sequestration. *Environ. Sci. Technol.* **2012**, *46*, 9571–9576. [CrossRef] [PubMed]
118. Basso, A.S.; Miguez, F.E.; Laird, D.A.; Horton, R.; Westgate, M. Assessing Potential of Biochar for Increasing Water-Holding Capacity of Sandy Soils. *GCB Bioenergy* **2013**, *5*, 132–143. [CrossRef]
119. Lawrinenko, M.; Laird, D.A. Anion Exchange Capacity of Biochar. *Green Chem.* **2015**, *17*, 4628–4636. [CrossRef]
120. Fidel, R.B.; Laird, D.A.; Thompson, M.L.; Lawrinenko, M. Characterization and Quantification of Biochar Alkalinity. *Chemosphere* **2017**, *167*, 367–373. [CrossRef] [PubMed]
121. Fang, X.; Chua, T.; Schmidt-Rohr, K.; Thompson, M.L. Quantitative 13C NMR of Whole and Fractionated Iowa Mollisols for Assessment of Organic Matter Composition. *Geochim. Cosmochim. Acta* **2010**, *74*, 584–598. [CrossRef]
122. Smith, P.; Soussana, J.-F.; Angers, D.; Schipper, L.; Chenu, C.; Rasse, D.P.; Batjes, N.H.; van Egmond, F.; McNeill, S.; Kuhnert, M.; et al. How to Measure, Report and Verify Soil Carbon Change to Realize the Potential of Soil Carbon Sequestration for Atmospheric Greenhouse Gas Removal. *Glob. Chang. Biol.* **2020**, *26*, 219–241. [CrossRef]
123. Vance, E.D.; Brookes, P.C.; Jenkinson, D.S. An Extraction Method for Measuring Soil Microbial Biomass C. *Soil Biol. Biochem.* **1987**, *19*, 703–707. [CrossRef]
124. Liang, C.; Amelung, W.; Lehmann, J.; Kästner, M. Quantitative Assessment of Microbial Necromass Contribution to Soil Organic Matter. *Glob. Chang. Biol.* **2019**, *25*, 3578–3590. [CrossRef] [PubMed]
125. Wang, B.; An, S.; Liang, C.; Liu, Y.; Kuzyakov, Y. Microbial Necromass as the Source of Soil Organic Carbon in Global Ecosystems. *Soil Biol. Biochem.* **2021**, *162*, 108422. [CrossRef]
126. Villarino, S.H.; Talab, E.; Contisciani, L.; Videla, C.; Di Geronimo, P.; Mastrángelo, M.E.; Georgiou, K.; Jackson, R.B.; Piñeiro, G. A Large Nitrogen Supply from the Stable Mineral-Associated Soil Organic Matter Fraction. *Biol. Fertil. Soils.* 2023, *in press*. [CrossRef]
127. Haney, R.; Haney, E.; Hossner, L.; Arnold, J. Modifications to the New Soil Extractant H3A-1: A Multinutrient Extractant. *Commun. Soil Sci. Plant Anal.* **2010**, *41*, 1513–1523. [CrossRef]
128. Yost, M.; Veum, K.; Kitchen, N.R.; Sawyer, J.E.; Camberato, J.; Carter, P.R.; Ferguson, R.; Fernández, F.; Franzen, D.; Laboski, C.A.; et al. Evaluation of the Haney Soil Health Tool for Corn Nitrogen Recommendations across Eight Midwest States. *J. Soil Water Conserv.* **2018**, *73*, 587–592. [CrossRef]
129. Franzluebbers, A.J. Soil-Test Biological Activity with the Flush of CO_2: III. Corn Yield Responses to Applied Nitrogen. *Soil Sci. Soc. Am. J.* **2018**, *82*, 708–721. [CrossRef]
130. Franzluebbers, A.J.; Pershing, M.R. Soil-Test Biological Activity with the Flush of CO_2: II. Greenhouse Growth Bioassay from Soils in Corn Production. *Soil Sci. Soc. Am. J.* **2018**, *82*, 696–707. [CrossRef]
131. Franzluebbers, A.J.; Pershing, M.R.; Crozier, C.; Osmond, D.; Schroeder-Moreno, M. Soil-Test Biological Activity with the Flush of CO_2: I. C and N Characteristics of Soils in Corn Production. *Soil Sci. Soc. Am. J.* **2018**, *82*, 685–695. [CrossRef]
132. Leifeld, J.; Kögel-Knabner, I. Soil Organic Matter Fractions as Early Indicators for Carbon Stock Changes under Different Land-Use? *Geoderma* **2005**, *124*, 143–155. [CrossRef]
133. Powlson, D.S.; Prookes, P.C.; Christensen, B.T. Measurement of Soil Microbial Biomass Provides an Early Indication of Changes in Total Soil Organic Matter Due to Straw Incorporation. *Soil Biol. Biochem.* **1987**, *19*, 159–164. [CrossRef]
134. Berthelin, J.; Laba, M.; Lemaire, G.; Powlson, D.; Tessier, D.; Wander, M.; Baveye, P. Soil Carbon Sequestration for Climate Change Mitigation: Mineralization Kinetics of Organic Inputs as an Overlooked Limitation. *Eur. J. Soil Sci.* **2022**, *73*, e13221. [CrossRef]
135. Abramoff, R.; Xu, X.; Hartman, M.; O'Brien, S.; Feng, W.; Davidson, E.; Finzi, A.; Moorhead, D.; Schimel, J.; Torn, M.; et al. The Millennial Model: In Search of Measurable Pools and Transformations for Modeling Soil Carbon in the New Century. *Biogeochemistry* **2018**, *137*, 51–71. [CrossRef]
136. Dwivedi, D.; Tang, J.; Bouskill, N.; Georgiou, K.; Chacon, S.S.; Riley, W.J. Abiotic and Biotic Controls on Soil Organo–Mineral Interactions: Developing Model Structures to Analyze Why Soil Organic Matter Persists. *Rev. Mineral. Geochem.* **2019**, *85*, 329–348. [CrossRef]
137. Zhang, Y.; Lavallee, J.M.; Robertson, A.D.; Even, R.; Ogle, S.M.; Paustian, K.; Cotrufo, M.F. Simulating Measurable Ecosystem Carbon and Nitrogen Dynamics with the Mechanistically Defined MEMS 2.0 Model. *Biogeosciences* **2021**, *18*, 3147–3171. [CrossRef]
138. McBratney, A.B.; Mendonça Santos, M.L.; Minasny, B. On Digital Soil Mapping. *Geoderma* **2003**, *117*, 3–52. [CrossRef]
139. Miller, B.A.; Koszinski, S.; Wehrhan, M.; Sommer, M. Comparison of Spatial Association Approaches for Landscape Mapping of Soil Organic Carbon Stocks. *SOIL* **2015**, *1*, 217–233. [CrossRef]
140. McBratney, A.B.; Webster, R. Optimal Interpolation and Isarithmic Mapping of Soil Properties. *J. Soil Sci.* **1983**, *34*, 137–162. [CrossRef]
141. Asbjornsen, H.; Hernández-Santana, V.; Liebman, M.; Bayala, J.; Chen, J.; Helmers, M.; Ong, C.; Schulte, L.A. Targeting Perennial Vegetation in Agricultural Landscapes for Enhancing Ecosystem Services. *Renew. Agric. Food Syst.* **2013**, *29*, 101–125. [CrossRef]
142. Kuhn, M.; Weston, C.; Coulter, R.; Quinlan, R. Package "Cubist": Rule-and Instance-Based Regression Modeling. Available online: https://cran.r-project.org/web/packages/Cubist/Cubist.pdf (accessed on 15 May 2023).
143. Kravchenko, A.N.; Robertson, G.P. Whole-Profile Soil Carbon Stocks: The Danger of Assuming Too Much from Analyses of Too Little. *Soil Sci. Soc. Am. J.* **2011**, *75*, 235–240. [CrossRef]

144. Castellano, M.J.; Mueller, K.E.; Olk, D.C.; Sawyer, J.E.; Six, J. Integrating Plant Litter Quality, Soil Organic Matter Stabilization, and the Carbon Saturation Concept. *Glob. Chang. Biol.* **2015**, *21*, 3200–3209. [CrossRef]
145. Crolla, A.; Kinsley, C.; Pattey, E. 13—Land Application of Digestate. In *The Biogas Handbook*; Wellinger, A., Murphy, J., Baxter, D., Eds.; Woodhead Publishing Series in Energy; Woodhead Publishing: Sawston, UK, 2013; pp. 302–325. ISBN 978-0-85709-498-8.
146. Takle, E.S.; Gutowski, W.J. Iowa's Agriculture Is Losing Its Goldilocks Climate. *Phys. Today* **2020**, *73*, 26–33. [CrossRef]
147. Pan, Z.; Arritt, R.W.; Takle, E.S.; Gutowski, W.J., Jr.; Anderson, C.J.; Segal, M. Altered Hydrologic Feedback in a Warming Climate Introduces a "Warming Hole". *Geophys. Res. Lett.* **2004**, *31*, L17109. [CrossRef]
148. Hatfield, J.L.; Wright-Morton, L.; Hall, B. Vulnerability of Grain Crops and Croplands in the Midwest to Climatic Variability and Adaptation Strategies. *Clim. Chang.* **2018**, *146*, 263–275. [CrossRef]
149. Jin, Z.; Zhuang, Q.; Wang, J.; Archontoulis, S.V.; Zobel, Z.; Kotamarthi, V.R. The Combined and Separate Impacts of Climate Extremes on the Current and Future US Rainfed Maize and Soybean Production under Elevated CO_2. *Glob. Chang. Biol.* **2017**, *23*, 2687–2704. [CrossRef]
150. Pan, Z.; Andrade, D.; Segal, M.; Wimberley, J.; McKinney, N.; Takle, E. Uncertainty in Future Soil Carbon Trends at a Central U.S. Site under an Ensemble of GCM Scenario Climates. *Ecol. Model.* **2010**, *221*, 876–881. [CrossRef]
151. Schulte, L.A.; Dale, B.E.; Bozzetto, S.; Liebman, M.; Souza, G.M.; Haddad, N.; Richard, T.L.; Basso, B.; Brown, R.C.; Hilbert, J.A.; et al. Meeting Global Challenges with Regenerative Agriculture Producing Food and Energy. *Nat. Sustain.* **2022**, *5*, 384–388. [CrossRef]
152. Culman, S.W.; Snapp, S.S.; Ollenburger, M.; Basso, B.; DeHaan, L.R. Soil and Water Quality Rapidly Responds to the Perennial Grain Kernza Wheatgrass. *Agron. J.* **2013**, *105*, 735–744. [CrossRef]
153. Nakagaki, N.; Wieczorek, M. *Estimates of Subsurface Tile Drainage Extent for 12 Midwest States 2012*; United States Geological Survey: Reston, VA, USA, 2016.
154. Castellano, M.J.; Archontoulis, S.V.; Helmers, M.J.; Poffenbarger, H.J.; Six, J. Sustainable Intensification of Agricultural Drainage. *Nat. Sustain.* **2019**, *2*, 914–921. [CrossRef]
155. Jin, C.; Sands, G.; Kandel, H.; Wiersma, J.; Hansen, B. Influence of Subsurface Drainage on Soil Temperature in a Cold Climate. *J. Irrig. Drain. Eng.* **2008**, *134*, 83–88. [CrossRef]
156. Meersmans, J.; Van Wesemael, B.; De Ridder, F.; Fallas Dotti, M.; De Baets, S.; Van Molle, M. Changes in Organic Carbon Distribution with Depth in Agricultural Soils in Northern Belgium, 1960–2006. *Glob. Chang. Biol.* **2009**, *15*, 2739–2750. [CrossRef]
157. Fernández, F.G.; Fabrizzi, K.P.; Naeve, S.L. Corn and Soybean's Season-Long in-Situ Nitrogen Mineralization in Drained and Undrained Soils. *Nutr. Cycl. Agroecosyst.* **2017**, *107*, 33–47. [CrossRef]
158. James, H.R.; Fenton, T.E. Water Tables in Paired Artificially Drained and Undrained Soil Catenas in Iowa. *Soil Sci. Soc. Am. J.* **1993**, *57*, 774–781. [CrossRef]
159. Climate Action Reserve. *Soil Enrichment Protocol: Reducing Emissions and Enhancing Soil Carbon Sequestration on Agricultural Lands*; Version 1.1; Climate Action Reserve: Los Angeles, CA, USA, 2022.
160. EPA. *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990–2021*; EPA: Washington, DC, USA, 2023.
161. Parkin, T.B.; Kaspar, T.C. Nitrous Oxide Emissions from Corn–Soybean Systems in the Midwest. *J. Environ. Qual.* **2006**, *35*, 1496–1506. [CrossRef]
162. Parkin, T.B.; Kaspar, T.C.; Jaynes, D.B.; Moorman, T.B. Rye Cover Crop Effects on Direct and Indirect Nitrous Oxide Emissions. *Soil Sci. Soc. Am. J.* **2016**, *80*, 1551–1559. [CrossRef]
163. Lawrence, N.C.; Tenesaca, C.G.; VanLoocke, A.; Hall, S.J. Nitrous Oxide Emissions from Agricultural Soils Challenge Climate Sustainability in the US Corn Belt. *Proc. Natl. Acad. Sci. USA* **2021**, *118*, e2112108118. [CrossRef]
164. Guenet, B.; Gabrielle, B.; Chenu, C.; Arrouays, D.; Balesdent, J.; Bernoux, M.; Bruni, E.; Caliman, J.-P.; Cardinael, R.; Chen, S.; et al. Can N2O Emissions Offset the Benefits from Soil Organic Carbon Storage? *Glob. Chang. Biol.* **2021**, *27*, 237–256. [CrossRef]
165. Elliott, E.T.; Paustian, K.; Frey, S.D. Modeling the Measurable or Measuring the Modelable: A Hierarchical Approach to Isolating Meaningful Soil Organic Matter Fractionations. In *Proceedings of the Evaluation of Soil Organic Matter Models*; Powlson, D.S., Smith, P., Smith, J.U., Eds.; Springer: Berlin/Heidelberg, Germany, 1996; pp. 161–179.
166. Coleman, K.; Jenkinson, D.S. RothC-26.3—A Model for the Turnover of Carbon in Soil. In *Proceedings of the Evaluation of Soil Organic Matter Models*; Powlson, D.S., Smith, P., Smith, J.U., Eds.; Springer: Berlin/Heidelberg, Germany, 1996; pp. 237–246.
167. Parton, W.J. The CENTURY Model. In *Proceedings of the Evaluation of Soil Organic Matter Models*; Powlson, D.S., Smith, P., Smith, J.U., Eds.; Springer: Berlin/Heidelberg, Germany, 1996; pp. 283–291.

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Soil carbon maintained by perennial grasslands over 30 years but lost in field crop systems in a temperate Mollisol

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To mitigate climate change, some seek to store carbon from the atmosphere in agricultural soils. However, our understanding about how agriculture affects soil organic carbon is muddied by studies (1) lacking longitudinal data, (2) ignoring bulk density changes, or (3) sampling only surface soils. To better understand soil organic carbon trends, here we measured changes over 30 years in density-corrected, full-soil-depth (90 cm) soil organic carbon stocks under 6 cropping systems and a restored prairie in a Mollisol of southern Wisconsin, USA. Cash-grain systems and alfalfa-based systems lost soil organic carbon. Prairie and rotationally-grazed pasture maintained soil organic carbon. Average soil organic carbon losses for cash-grain and alfalfa-based systems were −0.80 (±0.12) and −0.54 (±0.13) Mg C ha^{-1} yr^{-1}, respectively. Sensitivity analysis showed that incomplete methodologies overestimated soil organic carbon improvements. Our findings using more comprehensive methods demonstrate the inadequacy of row-crop systems and the need for well-managed grasslands to protect soil organic carbon in productive agricultural soils of the Upper Midwest USA.

A politically popular strategy to mitigate agriculture's contributions to climate change is drawing down carbon dioxide (CO_2) from the atmosphere and storing it in agricultural soils via soil organic carbon (SOC) sequestration. SOC sequestration is central to programs such as the "4 per mille Soils for Food Security and Climate" initiative launched at the COP21 and the agricultural aspects of many countries' pledges to the Paris Agreement[1]. Despite its popularity, however, the real potential to sequester substantial SOC through agriculture remains uncertain, in part because of the ubiquitous use of flawed or incomplete methods to measure changes in SOC.

To start, long-term studies are necessary to understand if a practice truly sequesters SOC. Without careful and spatially precise sampling, it can be difficult to delineate short-term SOC changes from natural variation[2]. Further, if SOC gains are temporary, they do not mitigate climate change in the long-term. To truly mitigate climate change, SOC gains must be maintained for decades or more[3]. Among the few long-term studies that track SOC, ubiquitous but incomplete methods have muddied our understanding of the true impact of agricultural management on SOC. Despite decades of research highlighting their flaws, studies still may over- or underestimate SOC change by using common C-accounting methods: (1) comparisons lacking longitudinal baseline data, (2) failing to correct for bulk density (ρ_b) changes, and (3) sampling only surface soils[2,4–6].

Many studies lack longitudinal data and instead compare concurrent SOC stocks, substituting a difference over time with a difference over space ("space-for-time") and assuming implicitly or explicitly that any difference indicates SOC increases in the improved management scenario. However, unless the SOC stocks of the control treatment in such "space-for-time" studies remain constant over time (an unlikely situation in a warming climate[7]), these studies cannot demonstrate C sequestration[8]. Relative differences in SOC stocks can be found in scenarios where the control and improved management treatments are both gaining or both losing SOC, telling us little about the actual rates of SOC accrual in either treatment[6,9].

Further exacerbating these accounting issues, SOC data is often limited to the surface soil (15 or 30 cm deep). Though there are statistical (strongest signal) and logistical (time, equipment) reasons to sample only surface soils, exclusively relying on surface soils may obscure overall SOC effects. For example, if a treatment increases surface SOC while losing more SOC at unsampled depths, it does not actually increase SOC or drawdown atmospheric CO_2[10].

Changes in ρ_b over time also may obscure SOC accrual. Many studies treat depth from the soil surface as a constant through time and between treatments, despite significant soil expansion or compaction as a result of changing management[11,12]. These ρ_b changes can directly affect how much of the soil profile is sampled, making comparisons between treatments difficult[5]. For example, Guillaume et al. (2022) found a 16% underestimation of treatment effect on SOC when changes in ρ_b were ignored[13]. To account for these changes, we must convert depth-based

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measurements to an unchanging reference system, such as equivalent soil mass (ESM). Institutions such as the IPCC and FAO have emphasized the importance of ESM corrections[14,15], but standardization remains lacking in SOC crediting methods[4].

When studies use more comprehensive methodologies (change over time, deep sampling, and ESM corrections) while estimating SOC stock changes, they often demonstrate different magnitudes or even directions of SOC change compared to studies using incomplete methods. One such 8-year study by Liu et al. (2022), investigating the effects of no-till and straw retention on SOC in wheat-maize systems, found that tillage redistributed C through the soil profile but did not lead to significant changes in SOC stocks, while straw retention increased SOC stocks regardless of tillage[16]. These results are inconsistent with those of Al-Kaisi and Kwaw-Mensah (2020) using depth-based methods or Powlson et al. (2014) evaluating only surface soils[17,18]. Both reported potential for SOC gains in no-till systems, a contradiction potentially explained by using incomplete methods.

While we theoretically understand how these methods may affect results, we have a limited understanding of the general effects and relative impact of using them on real data. The few studies that use more comprehensive methods and report the sensitivity of results to incomplete methods tend to address only one cropping system or method, which limits the generalizability of their results. To truly test the impact of incomplete methods on results, we must compare the results of using them versus comprehensive methods on data from multiple cropping systems in an otherwise controlled study.

While accurate accounting of SOC is important for all major soil types, of particular interest are Mollisols, the high-C, fine-textured grassland soils that support much of global intensive agriculture[19]. In the Upper Midwest U.S. and elsewhere, Mollisols are used primarily for the production of commodity cash-grains (maize, soybean, wheat) or forages for livestock (maize for silage, alfalfa, pasture), while a common conservation practice is restoration to grassland. To assess the potential of C sequestration in agricultural Mollisols, we assessed SOC over 30 years at the long-term Wisconsin Integrated Cropping Systems Trial (WICST). Our goals were to (1) explore changes in SOC among three cash-grain systems, three dairy-forage systems, and a restored prairie using comprehensive assessment methods and (2) assess how partial methodologies (using space-for-time methods, omitting ESM corrections, and limiting analysis of SOC stocks to surface soils) affect SOC estimates.

Results

SOC change from baseline in years 20 and 30

A general linear mixed effect model of total 0–90 cm SOC stocks from 1989–2019 (ΔSOC 1989–2019) indicated a significant cropping system effect ($p = 0.03$). For all cropping systems except Management-Intensive Rotation Grazing (MIRG) and Prairie, we estimated a net loss of SOC ($p < 0.05$) (Fig. 1). Of the five cropping systems that lost SOC, the cash-grain rotations, Maize, Maize-Soy (MS), and organic Maize-Soy-Wheat (org. MSW) lost the most SOC (−0.78 Mg ha^{-1} yr^{-1}, −0.70 Mg ha^{-1} yr^{-1}, and −0.93 Mg ha^{-1} yr^{-1}, respectively) (Table 1). We found evidence for SOC loss in all depths in Maize, MS, and MSW ($p < 0.005$). The alfalfa-based dairy-forage systems lost SOC slower than the annual systems with rates of −0.56 Mg ha^{-1} yr^{-1} ($p = 0.0004$) and −0.52 Mg ha^{-1} yr^{-1} ($p = 0.0053$) for Maize-alfalfa-Alfalfa-Alfalfa (MaAA) and organic Maize-oats/alfalfa-Alfalfa (org. Mo/aA), respectively (Table 1). In both, lack of evidence for change in surface 0–15 cm SOC stocks belied the significant ($p < 0.05$) losses in lower depths. In the perennial systems, MIRG and Prairie, there was no evidence for change (+0.11 Mg ha^{-1} yr^{-1}, $p = 0.7$ and +0.24 Mg ha^{-1} yr^{-1}, $p = 0.55$, respectively) in SOC in the 0–90 cm soil profile (Fig. 1). Gains in MIRG's 0–15 cm depth (0.25 Mg ha^{-1} yr^{-1}, $p = 0.0086$) were offset by losses in the 15–30, 30–60, and 60–90 cm depths, despite those losses being nonsignificant ($p > 0.1$) (Table 1). Likewise in Prairie, surface 0–15 cm gains (0.35 Mg ha^{-1} yr^{-1}, $p = 0.024$) were offset by nonsignificant losses in lower depths. We found similar results for

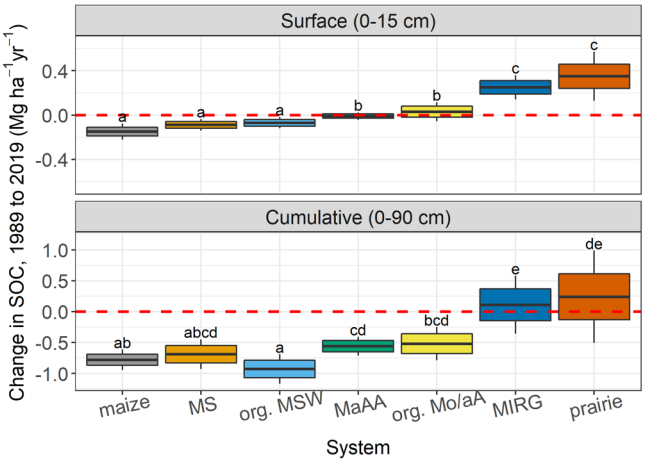


Fig. 1 | ΔSOC in the 0–15 cm and 0–90 cm soil profile from 1989 to 2019. Center bar represents change in soil organic carbon (ΔSOC) between 1989 and 2019 estimated by the linear mixed effects model. Boxes represent +/- the standard error. Whiskers represent upper and lower 90% confidence limits. Letters represent results of pairwise comparisons within each depth at alpha = 0.1. Treatment abbreviations are as follows: *maize*, cropping system of continuous maize; *MS*, minimum tillage cropping rotation of maize to soybean; *org. MSW*, organic cropping rotation of maize to soybean to winter wheat with cover crop; *MaAA*, cropping rotation of maize followed by 3 years of conventional alfalfa; *org. Mo/aA*, organic cropping rotation of maize followed by oats/alfalfa followed by alfalfa; *MIRG*, management intensive rotationally grazed pasture seeded to red clover, timothy grass, smooth bromegrass, and orchardgrass; *prairie*, cool-season grassy waterways established in 1990 planted to soy in 1998 and to warm-season grass mixes in 1999.

$\Delta SOC_{1989\text{-}2009}$ as Sanford et al. in 2012 (Table 1, see Sanford et al.[20] for their 20 year analysis).

SOC change between years 20 and 30

Total 0–90 cm SOC did not significantly change between 2009 and 2019 (Supplementary Information, Table S1) with the exception of org. CSW which experienced continued system wide loss of SOC (−0.71 Mg ha^{-1} yr^{-1}, $p = 0.0389$). Other systems experience changes within depths. In both Maize and MS, losses continued in the 15–30 cm depth (−0.74 Mg ha^{-1} yr^{-1}, $p = 0.0244$, and −0.24 Mg ha^{-1} yr^{-1}, $p = 0.0348$ respectively). Surface gains (0–15 cm) occurred in both the org. Mo/aA and Prairie systems (0.24 Mg ha^{-1} yr^{-1}, $p = 0.044$ and 0.79 Mg ha^{-1} yr^{-1}, $p = 0.0067$ respectively). No horizon-specific significant changes were detected below 30 cm for any of the systems.

Effects of alternative methods

The simulated use of alternative, less comprehensive methods resulted in marked changes to the estimated total $\Delta SOC_{1989\text{-}2019}$ of each system (Fig. 2). These changes were not consistent in magnitude across systems. The space-for-time, shallow sampling, and depth-based methods, compared to the comprehensive results, affected the $\Delta SOC_{1989\text{-}2019}$ by ranges of −0.35–0.62, 0.08–0.58, and −0.10–0.16 Mg ha^{-1} yr^{-1}, respectively.

Incomplete methods altered the trends emerging from the data. Using space-for-time, with 2019 MaAA SOC stocks as the baseline rather than 1989 SOC stocks by location, the losses estimated by the comprehensive assessment in Maize, MaAA, and org. Mo/aA were no longer statistically different from zero (a change of 0.62, 0.58, and 0.33 Mg ha^{-1} yr^{-1}, respectively), and gains in MIRG appeared statistically significant (a change of 0.57 Mg ha^{-1} yr^{-1}) (Supplementary Information. Table S2). Shallow sampling (0–30 cm) rather than sampling to 90 cm had a positive impact on apparent $\Delta SOC_{1989\text{-}2019}$ across systems, with an average increase of 0.33 Mg ha^{-1} yr^{-1}. It also reduced variation in $\Delta SOC_{1989\text{-}2019}$, especially for the perennial systems MIRG and Prairie. The effect of depth-based sampling without ESM corrections was marginal for the cumulative soil

Table 1 | ΔSOC (1989–2009 and 1989–2019) estimated by the linear mixed effects model

Cropping system[a]	Depth	ΔSOC 1989 to 2009 ± SE (Mg ha^{-1} yr^{-1})		Pr > *t*	ΔSOC 1989 to 2019 ± SE (Mg ha^{-1} yr^{-1})		Pr > *t*
maize	0–15	−0.26	±0.14	0.2202	−0.15	±0.04	0.0150
	15–30	−0.63	±0.11	0.0058	−0.14	±0.05	0.0294
	30–60	−0.33	±0.01	0.0190	−0.22	±0.02	0.0427
	60–90	−0.4	±0.19	0.2889	−0.23	±0.04	0.0046
	Cumulative	−1.22	±0.26	0.0249	−0.78	±0.09	0.0228
MS	0–15	−0.21	±0.06	0.0086	−0.09	±0.03	0.0297
	15–30	−0.32	±0.15	0.0599	−0.25	±0.04	0.0003
	30–60	−0.24	±0.02	0.0646	−0.25	±0.06	0.0014
	60–90	−0.33	±0.07	0.0015	−0.18	±0.04	0.0127
	Cumulative	−1.12	±0.24	0.0118	−0.69	±0.14	0.0007
org. MSW	0–15	−0.14	±0.06	0.0330	−0.07	±0.03	0.0287
	15–30	−0.39	±0.12	0.0153	−0.3	±0.06	0.0002
	30–60	−0.27	±0.09	0.1982	−0.33	±0.04	<.0001
	60–90	−0.35	±0.06	0.0019	−0.24	±0.04	0.0040
	Cumulative	−1.09	±0.37	0.0123	−0.93	±0.14	<.0001
MaAA	0–15	−0.02	±0.05	0.6503	−0.01	±0.02	0.8219
	15–30	−0.26	±0.12	0.0619	−0.18	±0.03	0.0005
	30–60	−0.07	±0.13	0.6822	−0.26	±0.03	<.0001
	60–90	−0.23	±0.07	0.0077	−0.18	±0.04	0.0060
	Cumulative	−0.47	±0.32	0.1712	−0.56	±0.09	0.0004
org. Mo/aA	0–15	−0.11	±0.05	0.0632	0.03	±0.05	0.5052
	15–30	−0.26	±0.12	0.0648	−0.21	±0.05	0.0008
	30–60	−0.27	±0.08	0.1862	−0.29	±0.05	<.0001
	60–90	−0.35	±0.07	0.0011	−0.22	±0.05	0.0022
	Cumulative	−0.98	±0.29	0.0122	−0.52	±0.16	0.0053
MIRG	0–15	0.25	±0.1	0.0575	0.25	±0.06	0.0086
	15–30	0.07	±0.22	0.7462	−0.07	±0.07	0.4037
	30–60	−0.13	±0.11	0.4433	−0.08	±0.12	0.5523
	60–90	−0.3	±0.07	0.0080	−0.06	±0.04	0.2194
	Cumulative	0.46	±0.72	0.5573	0.11	±0.26	0.7005
prairie	0–15	0	±0.09	0.9907	0.35	±0.11	0.0240
	15–30	−0.26	±0.13	0.1109	−0.03	±0.11	0.7708
	30–60	−0.51	±0.14	0.1670	−0.15	±0.23	0.5501
	60–90	−0.2	±0.1	0.1028	0.06	±0.16	0.7013
	Cumulative	−1.39	±0.3	0.0155	0.24	±0.37	0.5496

[a]Treatment abbreviations are as follows: *maize* cropping system of continuous maize, *MS* minimum tillage cropping rotation of maize to soybean, *org. MSW* organic cropping rotation of maize to soybean to winter wheat with cover crop, *MaAA* cropping rotation of maize followed by 3 years of conventional alfalfa, *org. Mo/aA* organic cropping rotation of maize followed by oats/alfalfa followed by alfalfa, *MIRG* management intensive rotationally grazed pasture seeded to red clover, timothy grass, smooth bromegrass, and orchardgrass, *prairie* cool-season grassy waterways established in 1990 planted to soy in 1998 and to native warm-season grass mixes in 1999.

profile, but more pronounced in the 0–15 cm depth (Fig. 2), which had experienced greater changes in ρ_b. Within the 0–15 cm depth, losses in Maize, MS, and org. MSW, as well as gains in MIRG were no longer evident in the depth- based scenario (a change of 0.16, 0.08, 0.12, and −0.02 Mg ha^{-1} yr^{-1}, respectively).

Discussion

All cropping systems lost SOC over a 30-year period except MIRG and Prairie. The maintenance of SOC in MIRG and Prairie may stem from high C inputs (above- and below-ground, see Sanford et al.[20]) and absence of tillage, providing an ideal environment for soil aggregation and subsequently SOC protection from loss to the atmosphere[21,22]. Relatedly, Rui et al.[23] reported greater carbon use efficiency (CUE) and lower oxidative enzyme activity in MIRG than the other non-Prairie systems at WICST (Prairie was not included in their analysis), suggesting a greater proportion of the C metabolized by the microbial communities in MIRG was assimilated into microbial biomass rather than respired[23]. Microbial necromass is responsible for much of the C found in mineral-associated organic matter, one of the slowest cycling SOC pools[24]. Rui et al.[23] found that MIRG had more mineral-associated organic carbon than the other non-Prairie systems.

The lack of evidence for SOC change below 15 cm in MIRG and Prairie may reflect limited sample size ($n = 12$ and $n = 6$, respectively), leading to greater uncertainty in our estimates of SOC stocks. The experimental design at WICST results in more plots dedicated to the multiple-phase systems such as MaAA and org. Mo/aA than the single-phase systems such as Maize, MIRG, and Prairie. The low number of

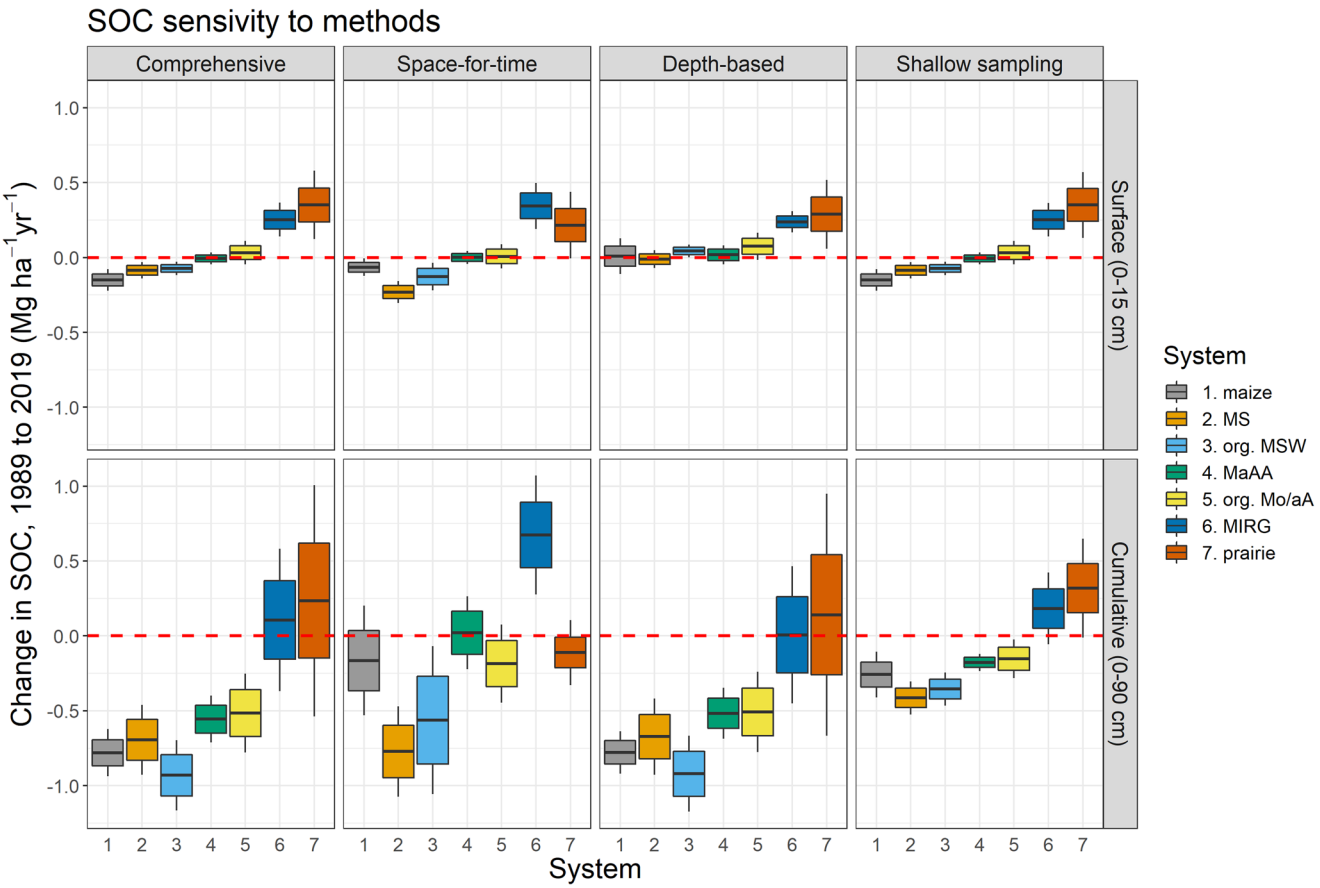


Fig. 2 | ΔSOC in the 0–15 cm and 0–90 cm soil profile from 1989 to 2019 for different data collection and analysis methods. Center bar represents change in soil organic carbon (ΔSOC) between 1989 and 2019 estimated by a linear mixed effects model. Boxes represent +/- the standard error. Whiskers represent upper and lower 90% confidence limits. Treatment abbreviations are as follows: Maize cropping system of continuous Maize, *MS* minimum tillage cropping rotation of Maize to soybean, *org. MSW* organic cropping rotation of Maize to soybean to winter wheat with cover crop, *MaAA* cropping rotation of maize followed by 3 years of conventional alfalfa, *org. Mo/aA* organic cropping rotation of Maize followed by oats/alfalfa followed by alfalfa, *MIRG* management intensive rotationally grazed pasture seeded to red clover, timothy grass smooth bromegrass and orchardgrass, Prairie cool-season grassy waterways established in 1990 planted to soy in 1998 and to native warm-season grass mixes in 1999.

samples taken for Maize ($n = 12$ yr^{-1}), MIRG ($n = 12$ yr^{-1}), and Prairie ($n = 18$ in 1989 and 2009, $n = 6$ in 2019) complicates comparisons with the other systems. That said, the lack of evidence for change in deep SOC in MIRG and Prairie may come from true SOC maintenance, as C inputs may balance outputs in those systems. Deep C inputs may come from exudation and turnover of the deeper, more extensive root systems of perennial grasslands[25,26]. Dissolved organic carbon, thought to be a major precursor of SOC[27], also may be percolating through the soil from the C inputs above, given the improved water infiltration associated with perennial grasslands[28].

In contrast to the perennial grass systems, we found significant losses in all depth increments below 15 cm of all field crop systems (e.g., Maize, MS, org. MSW, MaAA, and org. Mo/aA). Soil warming driven by a changing climate may be responsible for the release of this deeper SOC, as both laboratory and in situ studies have shown that soil warming can induce SOC loss[7,9,29]. Globally, loss of subsoil SOC has been observed in both agricultural and natural systems in the past several decades, suggesting a widespread cause such as warming[6,30,31].

Additionally, our results imply that reduced tillage alone is insufficient to build or maintain SOC stocks in systems with low C inputs. For example, the minimum-tillage cropping system MS lost a significant amount of SOC despite a lack of soil disturbance, likely from the combination of relatively shallow roots and limited biomass returned to the system during the soybean phase. Others have shown that no-till systems require both leguminous cover crops and double cropping to generate C inputs sufficient to offset losses at depth[18,32].

The lack of significant changes between 2009 and 2019 in most systems and depths may have several causes. It is possible that, despite ongoing SOC fluxes, a decade was insufficient to accrue detectable changes on these C-rich Mollisols[33]. Another possibility is that SOC accrual is slowing as these systems approach equilibrium. For MIRG and Prairie, this explanation would align with a meta-analysis of perennial crop age and SOC that found a slowing of SOC gains in perennial systems around 20 years[34]. Using this 20-year benchmark, MIRG should have approached SOC equilibrium around 2009, while the Prairie treatment (established in 1999) should have approached equilibrium around 2019, explaining both the maintenance of SOC in MIRG's upper depths and the ongoing accumulation in Prairie's surface 15 cm.

The use of space-for-time, shallow sampling, or depth-based methods generally resulted in overestimation of ΔSOC. In the case of space-for-time, most systems' ΔSOC were overestimated, although org. MSW and Prairie were underestimated. Space-for-time studies rely on two assumptions. One, that the baseline system (here, MaAA) is at equilibrium, and two, that SOC stocks across systems were reasonably similar at the beginning of the experiment. Our longitudinal data undercuts the first assumption, since MaAA lost SOC at a rate of about −0.56 Mg ha^{-1} yr^{-1} since the start of the experiment. As for the second assumption, despite our randomized complete block design, baseline 1989 SOC stocks for each system were quite

variable (Supplementary Materials, Table S3), which may explain why systems were impacted differently by the switch to the space-for-time method. Using the space-for-time method, one may conclude that MIRG was sequestering SOC, Maize and MaAA were SOC-stable, and only MS, org. MSW, and org. Mo/aA were losing SOC, trends that have been noted in many space-for-time studies[6,35,36]. However, using the comprehensive longitudinal data, we arrived at less sanguine conclusions.

If we had only sampled to 30 cm depth instead of 90 cm, we would have overestimated ΔSOC for all the systems, for an average increase in ΔSOC of −0.258 Mg ha^{-1} yr^{-1}. Under this sampling scheme, estimated losses, especially in Maize, MaAA and org. Mo/aA are reduced, making these annual and semi-perennial systems appear more climate-smart than the comprehensive analysis indicates. Losses of SOC below 30 cm may represent a blind spot in climate models and C market ventures, many of which assume SOC stocks are stable or increasing on agricultural land with improved management (see Mathers et al.[37]), such as minimum-tillage (MS), organic management (org. Mo/aA), and/or cover crops (org. MSW)[38].

If we had neglected to account for changes in bulk density (ρ_b) using ESM conversions, and instead relied on depth-based measurements, the changes in the total 0–90 cm ΔSOC would have been marginal, ranging from −0.10 Mg ha^{-1} yr^{-1} in MIRG to 0.04 Mg ha^{-1} yr^{-1} in MaAA. Within the 0 –15 cm depth, which was most likely to experience change in ρ_b due to management, the use of depth-based measurements had divergent effects on Prairie versus the rest of the systems (Supplementary Materials, Table S2). This divergence likely occurred because Prairie's ρ_b decreased where all other systems' ρ_b increased. Increased ρ_b correlates with increases in ΔSOC when switching to a depth-based method since increased ρ_b leads to more soil (and thus more SOC) sampled[5].

Sensitivity of our comprehensive results to commonly-used incomplete methods, especially space-for-time, demonstrates the importance of long-term, longitudinal, compaction-adjusted studies that measure the entire soil profile. Relying solely on less comprehensive methods, as many studies do, may lead to overestimations of C sequestration. This suggests that C sequestration in agricultural soils may not be as effective in mitigating climate change as previously thought, and other tactics (e.g., reducing combustion of fossil fuels) should be pursued.

The common field crop systems evaluated in this study were sources, not sinks, of atmospheric CO_2. Common SOC accounting methods (space-for-time, depth-based, and shallow sampling) obscured the magnitude of SOC losses in these soils, and in the case of space-for-time, suggested SOC gains in rotationally-grazed pastures where more comprehensive methods showed none. While C sequestration in productive, agricultural soils may not be possible, our work aligns with others suggesting that permanently restored and well-managed perennial grasslands are the best options to mitigate agricultural soils' CO_2 emissions.

Methods

Site description and history

We conducted this work at the University of Wisconsin-Madison's Arlington Agricultural Research Station, in Arlington, WI (43°18'N, 89°20'W) on soils classified as Plano Silt loam (fine-silty, mixed, superactive, Mesic Typic argiudolls). These are relatively deep (about 1 m), well drained soils with little relief that developed under tallgrass prairie vegetation (see Curtis, 1959[39]) in loess deposits over calcareous glacial till. Mean annual temperature and precipitation between 1991 and 2020 were 7.8 °C and 902 mm, respectively[40].

Conversion of tallgrass prairie vegetation to row-crop agriculture (primarily wheat), began in the 1840s with the attempted removal of Indigenous peoples such as the Ho-Chunk by northern Europeans. Between the 1860s and the middle of the 20th Century, after wheat yields crashed due to soil degradation and pest pressure, crops for dairy cattle feed (e.g., alfalfa, clovers, maize, oats) predominated. While agricultural practices shifted substantially following the Green Revolution, dairy forage systems remained dominant at the site, and from the 1960s until the establishment of WICST in 1989, maize (*Zea mays* L.), alfalfa (*Medicago sativa* L.), and soybeans (*Glycine max* (L.) Merr.) were the main crops grown, with dairy manure applied for fertility (see Posner et al., (1995) for additional historical details[41]).

In 1989, maize was planted across the 24-ha site to improve soil uniformity and allow for baseline measurements (crop yield and soil parameters), which were used to determine the boundaries of each block in the core experiment's four-block randomized complete block design[41]. In 1990, six cropping systems were initiated in a staggered start beginning with the legume phase of each rotation (if present). To reduce the potential confounding influence of yearly weather variability, every phase of every cropping rotation is present in one plot per block every year. For example, continuous maize (Maize) has one plot per block, while maize followed by 3 years of alfalfa (MaAA) has four plots per block. These rotations represent three cash-grain and three dairy-forage systems common to the Upper Midwest U.S.

The three cash-grain systems include high-input, or chemically and mechanically intensive, continuous maize (Maize), moderate-input minimum-tillage maize-soybean (MS), and organically managed maize-soybean-winter-wheat with a cover crop (org. MSW) (Table 2). The Maize system represents a conventional, continuous maize rotation, using synthetic fertilizer, tillage and herbicides for weed control, and top-yielding maize hybrids with advanced genetic traits such as herbicide resistance and insecticide (Bt) production. The MS system represents a maize-soybean rotation using minimum tillage, synthetic fertilizers, herbicides for weed control, and top-yielding maize hybrids and soybean varieties with advanced genetic traits. Soybeans are no-till drilled into maize stover, and maize is strip-till planted in soybean stubble. The org. MSW is managed

Table 2 | Wisconsin Integrated Cropping Systems Trial (WICST) experimental cropping system descriptions

Cropping system	System description	Species	Replicate plots
maize	Continuous maize with high inputs of synthetic fertilizers and pesticides.	Maize (*Zea mays* L.)	4
MS	Maize-soybean with minimum tillage and high inputs of synthetic fertilizers and pesticides.	Maize, soybean (*Glycine max* L. Merr.)	8
org. MSW	Organic maize-soybean-winter wheat with clover cover crop	Maize, soybean, winter wheat (Triticum *aestivum* L.), red clover (*Trifolium pratense* L.)	12
MaAA	Maize followed by three years of conventional alfalfa	Maize, alfalfa (*Medicago sativa* L.)	16
org. Mo/aA	Organic maize followed by oats/alfalfa followed by alfalfa	Maize, alfalfa, oats (*Avena sativa* L.)	16
MIRG	Management intensive rotationally grazed pasture seeded to red clover, timothy, smooth bromegrass, and orchardgrass	Timothy (*Phleum pretense* L.), bromegrass (*Bromus inermis* L.), orchardgrass (*Dactlyis glomerata* L.), red clover	4
prairie	Cool-season grassy waterways planted to soy in 1998 and to warm-season grass mixes in 1999. Burned every 2–3 years in spring.	See Liang et al. (2016) for full list of species[46].	6

according to the USDA's National Organic Program Standards. Fertility comes from biologically fixed N, composted poultry manure, and potassium sulfate. Weeds are controlled via tillage and cover crops. High-yielding organically-certified maize hybrids and organically-certified soybean and soft red winter wheat varieties are planted. Following wheat harvest mid-summer, a berseem clover and oats cover crop is planted and grows until terminated the following spring before maize is planted.

The three dairy-forage systems include high-input maize-alfalfa (MaAA), organic maize-oats/alfalfa-alfalfa (org. Mo/aA), and management-intensive rotationally grazed pasture (MIRG) (Table 2). The MaAA system represents a high-input, high-yielding dairy forage rotation, with fertility derived primarily from the application of dairy manure, weed control via herbicides, and top-yielding maize hybrids and alfalfa varieties with advanced genetic traits. Typically, two forage harvests occur during the alfalfa seeding year and between three and four harvests occur during other years of the alfalfa phases of the rotation. The org. Mo/aA system is managed according to the USDA's National Organic Program Standards. Fertility comes from the application of dairy manure, weeds are controlled with tillage, and organically-certified top-yielding maize hybrids and organically-certified leaf hopper resistant alfalfa varieties are planted. Oats are planted with alfalfa to suppress weeds and assist alfalfa establishment in the alfalfa seeding year. Typically, two forage harvests occur during this establishment year; a first harvest of primarily oat biomass with a second harvest of primarily alfalfa biomass later in the growing season. Between three and four alfalfa-only harvests occur during the 2nd year of the alfalfa phase of the rotation. The MIRG system is designed to represent a heifer-raising operation. Heifers rotationally graze the pasture plots from May to October, with a new subsection of the pasture available each day. Fertility comes from biologically fixed N and manure as well as synthetic fertilizer applied according to University-recommended best management practices. Red clover is seeded as necessary to maintain 35% legume levels in the cool season grass pasture.

Plots are relatively large (~0.3 ha, 18 × 156 m) and all fieldwork is carried out with production scale farm equipment, with fertilizer, pesticides, and other inputs applied according to University-recommended best management practices. Additional details on the design of WICST were presented in Posner et al.[41]. In 1990, grassy waterways were established where precipitation preferentially flows in the field. In 1998, these grassy waterways were chisel-plowed, sprayed with glyphosate, and planted to 1 year of soybeans. In 1999, a mix of native prairie legumes, forbs, and C4 grasses were established in a three-block randomized complete block design with two treatments: a high-diversity mix (25 species) and a low-diversity mix (6 species), for a total of six plots of restored prairie (Prairie) (Supplementary Information, Fig. 1)[42].

Soil sampling

In 1989, prior to the establishment of WICST, baseline soil samples were collected across the entire 24-ha field by points on a 27 × 27-m grid. At each sampling point, four cores were taken, divided and homogenized by depth (0–6, 6–12, 12–24, and 24–36 inches, or 0–15, 15–30, 30–60, and 60–90 cm, hereafter in cm). These increments were first chosen to align with standard agronomic soil tests based on surface soil (agronomic fertility, 0–15 cm) and deep soil sampling (soil NO_3–N, 0 to 90 cm). In addition to initial agronomic considerations, the glacial till (found at 80 to 120 cm) precluded consistent deeper sampling across the entire experiment. After initial analysis in 1989, the samples were dried, ground, and archived. In 2009, these dried homogenized samples were cleaned of visible plant material and analyzed for C content, which is expected to be stable in dried archival samples[43]. Full details on soil sampling and processing of the samples from 1989 can be found in Sanford et al.[20].

In June 1989, cores for ρ_b were collected at two sampling depths (0–15 and 15–30 cm) on the same 27 × 27-m grid. Given that detectible change in ρ_b below 30 cm between 1989 and 2009 was unlikely, ρ_b values from 2009 were used for 1989 below 30 cm (see Sanford et al.[20]). Comparison of the 2009 and 2019 ρ_b validated this assumption as no significant differences were found between the two most recent timepoints below 30 cm. Therefore, like Sanford et al.[20], we used ρ_b values from 2009 for the 30–60 and 60–90 cm depths in 1989.

In April through July 2009 and October through November 2019, samples for ρ_b and SOC analysis were collected at the center of each third of each plot (North, Center, South). Full details on soil sampling and processing of the samples from 2009 can be found in Sanford et al.[20]. In 2019, we collected cores for ρ_b in the autumn using a 5.4 cm diameter hydraulic core. Missing or damaged cores for ρ_b (3.5% of total cores) were recollected in October 2020. Cores were divided into 0–15, 15–30, 30–60, and 60–90 cm sections, as in 2009. Prior to weighing, we dried the sections in a 50-°C oven until weights stabilized. After weighing, we sieved the sections to 2 mm to remove rock fragments from glacial till. We subtracted the weight and the estimated volume of these fragments from the total section weight and volume prior to ρ_b calculation, so that ρ_b estimates represent the same soil as the SOC measurements (see von Haden et al.[5]). After this adjustment, we calculated ρ_b by dividing the weight of the dried section by the volume of its section of the soil core.

To align the original 1989 sampling grid with the 2009 and 2019 data, which were collected at locations within plots not yet established in 1989, we georeferenced a map of the original sampling grid and determined the location of the original sampling points relative to plot-level sampling points using ArcGIS. We then used ordinary kriging to spatially interpolate the 1989 data and digitally resample at the plot-level sampling points using R package gstat (v4.3.1). This differs from the approach of Sanford et al. (2012) who used an unweighted average of samplings that occurred within each plot[20].

Organic C determination

Because inorganic C in these soils is negligible (~0.005%)[44] we used total soil C interchangeably with SOC. To confirm this assumption and verify that routine applications of aglime ($CaCO_3$ or $CaMg(CO_3)_2$) had not significantly increased inorganic C in the surface 15 cm, we measured organic C of samples from all recently limed plots using standard methods provided by Thermo Finnignan for use with our Flash EA 1112 CN Automatic Elemental Analyzer[45]. We found no statistical evidence that SOC was different from total soil C, so we continue to assume total soil C is interchangeable with SOC.

Finely powdered subsamples of the dried soils from each depth (0 to 15, 15–30, 30–60, and 60–90 cm) at each point in the 1989 grid or in each location (N, Ct., S) in each plot were weighed into 5 × 9-mm tin capsules. While 8 to 10 mg of soil was used for all depths of the 1989 and 2009 soils (see Sanford et al.)[20], a soil mass of 15, 18, 30, and 50 mg was used for the 0–15, 15–30, 30–60, and 60–90 cm depths, respectively, in 2019 to accommodate declining C content with depth and enhance signal to noise ratio. Total C concentration for each sample was determined by dry combustion using a Flash EA 111d CN Automatic Elemental Analyzer (Thermo Finnigan, Milan, Italy)[45].

Estimating SOC stocks

To determine C stocks, rather than using depth from surface, we used cumulative mineral soil mass from surface as it is a reference system that remains stable over time (i.e., not impacted by changes in ρ_b or changes in organic matter)[5]. The ESM method accounts for compaction, expansion, and addition or loss of organic matter, ensuring the same section of the soil profile is considered each time. For the 20-year analysis, Sanford et al. (2012) used Excel software to convert depth-based measurements to ESM to calculate the SOC stock per unit area[20]. Here, for the 30-year analysis, these calculations were performed using R code provided by von Haden et al.[5].

Analysis of SOC change over time

General linear mixed effects models (PROC GLIMMIX, SAS v 9.4) were used to: (1) estimate change in SOC within each system between 1989, 2009, and 2019 ($\Delta SOC_{1989\text{-}2009}$, $\Delta SOC_{1989\text{-}2019}$, $\Delta SOC_{2009\text{-}2019}$), and (2) compare between systems the estimated change in SOC. The dataset was subset by depth (0–15, 15–30, 30–60, 60–90, and 0–90 cm) and year (2009 and 2019). For each subset, to address the potential influence of outliers, any $\Delta \pm 2$ SD

from the mean for each system were removed. Then, for each subset, a general linear mixed effects model was used to estimate ΔSOC as a function of cropping system. In this analysis, *system* (Maize, MS, org. MSW, MaAA, org. Mo/aA, MIRG, Prairie) was treated as a fixed effect, and *block* (1–4 for the core trial, 5–7 for the prairie) was treated as a random effect. Because of expected spatial and temporal correlations in the data, and to enable variance heterogeneity between cropping systems, we chose a variance-covariance matrix with a first-order heterogeneous autoregressive structure (subject = plot, group = system). Within SAS, LSMEANS was used to determine means, standard errors, and *p*-values for each cropping system. Because of the inherent spatial variability of SOC, we used an alpha level of 0.1 for all statistical comparisons.

Sensitivity analysis of ΔSOC methods

To examine the influence of SOC stock estimation methodology (space-for-time, depth-based, and shallow sampling) used in estimating $\Delta SOC_{1989\text{-}2019}$, we analyzed three datasets, each produced with each method. These were then compared to a dataset generated using a *comprehensive* SOC stock estimation method based on: longitudinal measurements, ESM correction, and the full 90-cm soil profile (Supplementary Information, Table S4). In the simulated space-for-time dataset, only data from 2019 were used. MaAA was chosen as the baseline scenario for calculating ESM conversions and change-from-baseline since it is most like the crop rotation present at the site prior to the establishment of WICST and would thus be assumed at SOC equilibrium in a traditional space-for-time analysis. Equivalent soil mass and change since 1989 were determined using an average of MaAA plots in each block in 2019 as the baseline. For the shallow-sampling dataset, data were converted to ESM to account for ρ_b changes, then SOC data below 30 cm were removed, simulating a scenario where we did not measure below 30 cm. For the depth-based dataset, the full 90-cm SOC stock was included, but not translated to ESM coordinates. Each simulated dataset was then analyzed for change over time using the same linear mixed effects model as the comprehensive dataset to determine estimates of $\Delta SOC_{1989\text{-}2019}$. To quantify the impact on SOC stock estimates of less comprehensive methods, $\Delta SOC_{1989\text{-}2019}$ obtained via each alternative method (space-for-time, depth-based, shallow sampling) was subtracted from $\Delta SOC_{1989\text{-}2019}$ obtained via the comprehensive method to calculate $\Delta(\Delta SOC_{1989\text{-}2019})$.

Reporting summary

Further information on research design is available in the Nature Portfolio Reporting Summary linked to this article.

Data availability

The soil data analyzed in this manuscript are available through Dryad https://doi.org/10.5061/dryad.b8gtht7mv.

Code availability

The SAS code used to generate the linear mixed effects model is available in the Supplementary Information (Supplementary Information, Supplementary Notes 1).

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References

1. Wiese, L. et al. Countries' commitments to soil organic carbon in nationally determined contributions. *Clim. Policy* **21**, 1005–1019 (2021).
2. VandenBygaart, A. J. & Angers, D. A. Towards accurate measurements of soil organic carbon stock change in agroecosystems. *Can. J. Soil Sci.* **86**, 465–471 (2006).
3. Smith, P. An overview of the permanence of soil organic carbon stocks: influence of direct human-induced, indirect and natural effects. *Eur. J. Soil Sci.* **56**, 673–680 (2005).
4. Oldfield, B. E. E., Eagle, A. J., Rubin, R. L., Rudek, J. & Gordon, D. R. Crediting agricultural soil carbon sequestration; regional consistency is necessary for carbon credit integrity. *Science* **375**, 1222–1225 (2022).
5. von Haden, A. C., Yang, W. H. & DeLucia, E. H. Soils' dirty little secret: depth-based comparisons can be inadequate for quantifying changes in soil organic carbon and other mineral soil properties. *Glob. Chang. Biol.* **26**, 3759–3770 (2020).
6. Sanderman, J. & Baldock, J. A. Accounting for soil carbon sequestration in national inventories: a soil scientist's perspective. *Environ. Res. Lett.* **5**, 034003 (2010).
7. Soong, J. L. et al. Five years of whole-soil warming led to loss of subsoil carbon stocks and increased CO2 efflux. *Sci. Adv.* **7**, 1–9 (2021).
8. Don, A. et al. Carbon sequestration in soils and climate change mitigation—definitions and pitfalls (Opinion paper)). *Glob. Chang. Biol.* **00**, e16983 (2023).
9. Rocci, K. S., Lavallee, J. M., Stewart, C. E. & Cotrufo, M. F. Soil organic carbon response to global environmental change depends on its distribution between mineral-associated and particulate organic matter: a meta-analysis. *Sci. Total Environ.* **793**, 148569 (2021).
10. Olson, K. R. & Al-Kaisi, M. M. The importance of soil sampling depth for accurate account of soil organic carbon sequestration, storage, retention and loss. *Catena* **125**, 33–37 (2015).
11. da Silva, A. P., Kay, B. D. & Perfect, E. Management versus inherent soil properties effects on bulk density and relative compaction. *Soil Tillage Res* **44**, 81–93 (1997).
12. Lampurlanés, J. & Cantero-Martínez, C. Soil bulk density and penetration resistance under different tillage and crop management systems and their relationship with barley root growth. *Agron. J.* **95**, 526–536 (2003).
13. Guillaume, T. et al. Carbon storage in agricultural topsoils and subsoils is promoted by including temporary grasslands into the crop rotation. *Geoderma* **422**, 115937 (2022).
14. Intergovernmental Panel on Climate Change (IPCC). *Generic Methodologies Applicable To Multiple Land-Use Categories*. https://www.ipcc-nggip.iges.or.jp/public/2019rf/pdf/4_Volume4/19R_V4_Ch02_Generic%20Methods.pdf 2.40 (2019).
15. Food and Agriculture Organization of the United Nations (FAO). *Measuring and modelling soil carbon stocks and stock changes in livestock production systems: Guidelines for assessment (Version 1)*. Livestock Environmental Assessment and Performance (LEAP) Partnership. 46–48 (Rome, FAO, 2019).
16. Liu, W. S. et al. Effects of tillage and straw management on grain yield and SOC storage in a wheat-maize cropping system. *Eur. J. Agron.* **137**, 126530 (2022).
17. Al-Kaisi, M. M. & Kwaw-Mensah, D. Quantifying soil carbon change in a long-term tillage and crop rotation study across Iowa landscapes. *Soil Sci. Soc. Am. J.* **84**, 182–202 (2020).
18. Powlson, D. S. et al. Limited potential of no-till agriculture for climate change mitigation. *Nat. Clim. Chang.* **4**, 678–683 (2014).
19. Liu, X. et al. Overview of Mollisols in the world: distribution, land use and management. *Can. J. Soil Sci.* **92**, 383–402 (2012).
20. Sanford, G. R. et al. Soil carbon lost from mollisols of the north central U.S.A. with 20 years of agricultural best management practices. *Agric. Ecosyst. Environ.* **162**, 68–76 (2012).
21. Helfrich, M., Ludwig, B. & Potthoff, M. Effect of litter quality and soil fungi on macroaggregate dynamics and associated partitioning of litter carbon and nitrogen. *Soil Biol. Biochem.* **40**, 1823–1835 (2008).
22. Wilson, G. W. T., Rice, C. W., Rillig, M. C., Springer, A. & Hartnett, D. C. Soil aggregation and carbon sequestration are tightly correlated with the abundance of arbuscular mycorrhizal fungi: results from long-term field experiments. *Ecol. Lett.* **12**, 452–461 (2009).
23. Rui, Y. et al. Persistent soil carbon enhanced in mollisols by well-managed grasslands but not annual grain or dairy forage cropping systems. *Proc. Natl. Acad. Sci. USA.* **119**, 1–6 (2022).

24. Kallenbach, C. M., Frey, S. D. & Grandy, A. S. Direct evidence for microbial-derived soil organic matter formation and its ecophysiological controls. *Nat. Commun.* **7**, 13630 (2016).
25. Mosier, S., Córdova, S. C. & Robertson, G. P. Restoring soil fertility on degraded lands to meet food, fuel, and climate security needs via perennialization. *Front. Sustain. Food Syst.* **5**, 1–18 (2021).
26. DuPont, S. T. et al. Root traits and soil properties in harvested perennial grassland, annual wheat, and never-tilled annual wheat. *Plant Soil* **381**, 405–420 (2014).
27. Cotrufo, M. F. & Lavallee, J. M. Soil organic matter formation, persistence, and functioning: a synthesis of current understanding to inform its conservation and regeneration. *Adv. Agron.* **172**, 1–66 (2022).
28. Grunwald, D., Panten, K., Schwarz, A., Bischoff, W. A. & Schittenhelm, S. Comparison of maize, permanent cup plant and a perennial grass mixture with regard to soil and water protection. *GCB Bioenergy* **12**, 694–705 (2020).
29. Zosso, C. U., Ofiti, N. O. E., Torn, M. S., Wiesenberg, G. L. B. & Schmidt, M. W. I. Rapid loss of complex polymers and pyrogenic carbon in subsoils under whole-soil warming. *Nat. Geosci.* **16**, 344–348 (2023).
30. Knotters, M., Teuling, K., Reijneveld, A., Lesschen, J. P. & Kuikman, P. Changes in organic matter contents and carbon stocks in dutch soils, 1998–2018. *Geoderma* **414**, 115751 (2022).
31. Keel, S. G. et al. Loss of soil organic carbon in Swiss long-term agricultural experiments over a wide range of management practices. *Agric. Ecosyst. Environ.* **286**, 106654 (2019).
32. Nicoloso, R. S. & Rice, C. W. Intensification of no-till agricultural systems: an opportunity for carbon sequestration. *Soil Sci. Soc. Am. J.* **85**, 1395–1409 (2021).
33. Necpálová, M. et al. What does it take to detect a change in soil carbon stock? a regional comparison of minimum detectable difference and experiment duration in the north central united states. *J. Soil Water Conserv.* **69**, 517–531 (2014).
34. Siddique, I. A., Grados, D., Chen, J., Lærke, P. E. & Jørgensen, U. Soil organic carbon stock change following perennialization: a meta-analysis. *Agron. Sustain. Dev*. **43**, 58 (2023).
35. Stanley, P. L., Rowntree, J. E., Beede, D. K., DeLonge, M. S. & Hamm, M. W. Impacts of soil carbon sequestration on life cycle greenhouse gas emissions in midwestern USA beef finishing systems. *Agric. Syst.* **162**, 249–258 (2018).
36. Becker, A. E., Horowitz, L. S., Ruark, M. D. & Jackson, R. D. Surface-soil carbon stocks greater under well-managed grazed pasture than row crops. *Soil Sci. Soc. Am. J.* **86**, 1–11 (2022).
37. Mathers, C. et al. Validating DayCent-CR for cropland soil carbon offset reporting at a national scale. *Geoderma* **438**, 116647 (2023).
38. Tautges, N. E. et al. Deep soil inventories reveal that impacts of cover crops and compost on soil carbon sequestration differ in surface and subsurface soils. *Glob. Chang. Biol.* **25**, 3753–3766 (2019).
39. Curtis, J. T. *The Vegetation Of Wisconsin, An Ordination of Plant Communities* 1st edn, Vol. 704, 261–307 (University of Wisconsin Press, 1959).
40. NCEI. National Centers for Environmental Information. U.S. *Climate Normals Quick Access.* https://www.ncei.noaa.gov/access/us-climate-normals/ (2023).
41. Posner, J. L., Casler, M. D. & Baldock, J. O. The Wisconsin integrated cropping systems trial: combining agroecology with production agronomy. *Am. J. Altern. Agric.* **10**, 98–107 (1995).
42. Hedtcke, J. & Posner, J. *Wisconsin Integrated Cropping Systems Trial Ninth Technical Report (2001 and 2002)*. https://wicst.wisc.edu/publications/technical-reports/#9th-wicst-report-20012002 136–144 (2003).
43. Blake, L., Goulding, K. W. T., Mott, C. J. B. & Poulton, P. R. Temporal changes in chemical properties of air-dried stored soils and their interpretation for long-term experiments. *Eur. J. Soil Sci.* **51**, 345–353 (2000).
44. Paul, E. A., Collins, H. P. & Leavitt, S. W. Dynamics of resistant soil carbon of midwestern agricultural soils measured by naturally occurring 14C abundance. *Geoderma* **104**, 239–256 (2001).
45. OEA Team. *AN 703 2009 Total Organic Carbon (Toc) Determination* (OEA Team, 2009).
46. Liang, C. et al. Microorganisms and their residues under restored perennial grassland communities of varying diversity. *Soil Biol. Biochem.* **103**, 192–200 (2016).

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Author contributions

G.R.S. and R.D.J. jointly conceived of the study and general analytical approach. G.R.S. supervised operation of the experiment and sample collection. C.L.D. performed the lab work, processed and analyzed the data, and wrote the manuscript. C.L.D. revised the manuscript with revisions suggested by R.D.J., G.R.S., and M.D.R.

Competing interests

The authors declare no competing interests.

Additional information

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Alfalfa Stand Length and Subsequent Crop Patterns in the Upper Midwestern United States

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ABSTRACT

Alfalfa (*Medicago sativa* L.) can provide many economic and environmental benefits to crop rotations. Our objectives were to quantify alfalfa stand lengths, identify the two crops following alfalfa, and determine the soil and temporal factors affecting them. The USDA-National Agricultural Statistics Service (NASS) Cropland Data Layers (CDLs) for 2006 to 2012 and USDA-NRCS soil survey layers for North Dakota, South Dakota, Nebraska, Minnesota, Iowa, and Wisconsin were combined and used to meet these objectives. Location and soil textural class generally determined stand length, with alfalfa being kept in production longer outside the major Corn Belt area of this region. Soil textural class effects on stand length varied by state. Corn (*Zea mays* L.) was the most common crop planted during the first- and second-year following alfalfa (79 and 61%, respectively), except in North Dakota (35% both years). Soybean [*Glycine max* (L.) Merr.] was grown in 11 and 28% of cases, respectively. Small grains were planted as the first-year crop in 29% of cases in the Dakotas and 6% of cases in the other four states. As a second-year crop, small grains occurred in 26% of cases in North Dakota and 5% of cases in the other five states. Stand length, soil textural class, state, and year significantly influenced grower choice of both following crops. These geographic assessments will guide research and extension education designed to increase use of perennials for economic and environmental benefits. Similar methods can be applied to other crop rotations or U.S. regions.

Alfalfa is the fourth most widely grown and valuable crop in the United States (USDA-NASS, 2013a) after corn, soybean, and wheat (*Triticum aestivum* L.). For 2010 to 2012, USDA-NASS estimated that 7.6 million ha of alfalfa was grown annually in the United States and that this crop had a value of U.S. $7.5 billion. In addition to the economic benefits, alfalfa provides many environmental benefits to cropping systems (Olmstead and Brummer, 2008). Growing alfalfa often improves soil physical properties because tillage does not occur after the crop is established (Raimbault and Vyn, 1991; Russell et al., 2006; Coulter et al., 2013). Other soil quality benefits of alfalfa include: (i) reduced soil NO_3–N losses compared to corn and soybean (Randall et al., 1997; Huggins et al., 2001; Kanwar et al., 2005) primarily because alfalfa provides continuous soil cover, requires no fertilizer N, and can extract soil NO_3–N to depths of at least 2.7 m (Kelner et al., 1997; Entz et al., 2001); and (ii) reduced weed seedbanks and herbicide requirements (Cosgrove and Barrett, 1987).

Alfalfa also provides many benefits to subsequent crops. It often can reduce weed (Ominski et al., 1999; Porter et al., 2003), insect, and disease pressure (Bullock, 1992; Pikul et al., 2005) leading to increased yield for subsequent annual crops. For example, grain yield for first- and second-year corn following alfalfa often is at least 10% higher than adequately fertilized continuous corn (Crookston et al., 1991; Mallarino and Ortiz-Torres, 2006; Stanger and Lauer, 2008). Another well documented benefit of alfalfa is provision of organic or "free" N to subsequent crops. A summary of 471 site-years concluded that the fertilizer N requirement of first-year corn following alfalfa frequently was eliminated or reduced (Yost et al., 2014c). Another 67 site-year summary for second-year corn following alfalfa indicated that fertilizer N was required in only 55% of the cases (Yost et al., 2014b). Alfalfa-supplied N also can benefit the following crop of wheat, but wheat often responds to fertilizer N (Westermann and Crothers, 1993; Malhi et al., 2010) even though its total N requirements are lower than corn. Wheat following alfalfa also can be sensitive to excessive N, which can increase lodging and reduce harvestable grain yield (Kelling et al., 2002). Due to lower water requirements, wheat or other small grains following alfalfa may be preferable to corn for water-stressed environments (Pikul et al., 2005). Finally, the N benefits to subsequent crops may be severely underutilized if N-fixing crops such as soybean or dry bean (*Phaseolus vulgaris* L.) are grown following alfalfa (Robbins and Carter, 1980; Meek et al., 1994).

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Abbreviations: CDL, cropland data layer; NASS, National Agricultural Statistics Service.

Crop rotation benefits of alfalfa depend on the length of time the crop is grown. For example, the frequency and level of fertilizer N response for first-year corn were greater following short (≤2 yr) alfalfa phases than longer (3–7 yr) phases (Yost et al., 2014c). Alfalfa stand length also affects net returns, with optimal phase lengths varying by region. In Wisconsin and western Canada, 2- to 3-yr-long stands (including the establishment year) maximized average annual net return during alfalfa production (Zentner et al., 1986; Barnett, 2006; Undersander and Barnett, 2008), whereas 4- to 5-yr-long stands were optimal in Manitoba (Jeffrey et al., 1993). Despite the stand age importance to alfalfa N contributions for succeeding crops and overall profitability, no geographic and only limited survey data exist quantifying alfalfa stand or phase lengths in the Upper Midwest (i.e., North Dakota, South Dakota, Nebraska, Minnesota, Iowa, and Wisconsin), where about one-third of the nation's alfalfa is produced (USDA-NASS, 2013a). Furthermore, no geographic data are available that describe crop rotation patterns following alfalfa termination. Several factors, including geographic location, soil texture, year, market prices, and weather, are hypothesized to be influencing the perceived role that alfalfa has in this region.

The USDA-NASS provides the most comprehensive estimates of crop area in the United States, with agricultural census data collected every 5 yr plus annual grower surveys. It also provides annual geographic estimates of crop area in CDLs by classifying satellite imagery into raster datasets with 30- or 56-m spatial resolution. With several years of CDLs now available for many states, crop rotation patterns can be examined. Cropland Data Layers have been used to evaluate potato (*Solanum tuberosum* L.) production systems in Maine during 2008 to 2010 (DeFauw et al., 2012), to monitor shifts from corn–soybean rotations towards increased monoculture cropping (four continuous years of either crop) in the central United States during 2003 to 2010 (Plourde et al., 2013), and to determine how increased corn price and production area have changed corn–soybean rotation patterns in Iowa during 2001 to 2010 (Stern et al., 2012). However, to our knowledge, CDLs have not been used to examine rotation patterns of perennial and annual crops.

The objectives of this research were to: (i) describe geographic trends in alfalfa phase length in the Upper Midwest; (ii) determine whether alfalfa phase length is related to soil textural class; and (iii) determine whether alfalfa phase length, soil textural class, or year are related to the two crops grown following alfalfa termination.

MATERIALS AND METHODS

Seven CDLs for North Dakota, South Dakota, Nebraska, Minnesota, Iowa, and Wisconsin (USDA-NASS CDL, 2006–2012) were combined. The CDLs were re-classified into five major crop categories for this region based on area (alfalfa, corn, soybean, small grains, and minor crops) and three other categories (noncropland, water, and a combination of perennial forages called "grass") using Spatial Analyst of ArcGIS (ArcGIS 10.1, ESRI, Redlands, CA). Within the re-classified CDLs, all types of corn were placed in a "corn" category, all major and minor small grains [i.e., wheat, barley (*Hordeum vulgare* L.), oat (*Avena sativa* L.), millet [primarily *Panicum miliaceum* L., *Pennisetum glaucum* (L.) R. Br., and *Setaria italica* (L.) P. Beauv.], rye (*Secale cereale* L.), triticale (× *Triticosecale* Wittm.), spelt (*Triticum spelta* L.), and "other small grains" were placed in a "small grains" category, and all other field, fruit, and vegetable crops were placed in a "minor crops" category. Categories with two crops in a year (i.e., double cropping) were re-classified as the first of the two crops. All subsequent raster and vector data processing, smoothing, merging, selecting attributes, and mapping were conducted using ArcGIS 10.1.

To combine the 7 yr of crop data, CDLs with spatial resolution of 56 m (i.e., 2006–2009) were split into 28-m resolution subsets and resampled at 30-m resolution with the nearest neighbor technique. The conversion from 56- to 30-m resolution, instead of the reverse, was chosen to better utilize the higher resolution data. All CDLs were generalized with two passes of an eight nearest-neighbor majority filter to remove single or small clusters of pixels inside broader agricultural fields or other large areas. After generalization, all seven CDLs within a state were combined into a single raster with the Raster Calculator tool using the equation: 2012 CDL + (2011 CDL × 10) + (2010 CDL × 100) + (2009 CDL × 1000) + (2008 CDL × 10,000) + (2007 CDL × 100,000) + (2006 CDL × 1,000,000). The combined 7-yr raster data were converted to vector data (polygons) for each state. Polygons with ≥1 yr of alfalfa and ≥0.5 ha were selected for further analyses of alfalfa phase length and following crop selection.

The area in hectares for each polygon was calculated by state using the North American (1983) (High Accuracy Reference Network–Transverse Mercator) projected coordinate system for Wisconsin and the World Geodetic System (1984) (Universal Transverse Mercator Zones 14–15 North) projected coordinate system for the other five states. After calculating the areas, the projected coordinate system of each state was converted to the North America Lambert Conformal Conic using the "North American Datum_1983 to High Accuracy Reference Network_Wisconsin" transformation for Wisconsin and "North American Datum_1983_to_World Geodetic System_84_1" transformation for the other five states. This manipulation enabled the data for all six states to be merged into one shapefile.

Soil textural class attributes from the USDA-NRCS soil survey geographic database (Soil Survey Staff, 2011) vector data layer were categorized into three classes and spatially joined to the CDL vectors. The coarse-textured category included sand and loamy sand soils. The fine-textured category included clay, clay loam, and silty clay loam soils. The medium-textured category included loam, silt loam, sandy loam, fine sandy loam, and sandy clay loam soils. Complex soils with multiple series were classified using the dominant series within the complex.

Selection Methods

Two selection methods were used to determine alfalfa phase length and crops grown during the 2 yr following alfalfa termination. The first method was to select all polygons with ≥2 consecutive years of alfalfa that began with and were followed by another crop category for any set of years between 2006 and 2012. The ≥6 and ≥7 yr alfalfa phase lengths ended with alfalfa in 2012 and the ≥7 yr phase length began with alfalfa in 2006. This method is hereafter referred to as the "generalized vectors."

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The second method, referred to as the "adjusted vectors," included all selections from the generalized vectors and followed the same set of rules for selecting an alfalfa phase length, except that the "grass" category was converted to "alfalfa" when the probability of alfalfa being misclassified as grass was 10% higher than the reverse. The comparisons of alfalfa and grass probabilities were based on user's accuracy and commission error rates from USDA-NASS analyses with ground reference data by state (USDA-NASS, 2013b). For example, the user's accuracy of alfalfa in 2009 in North Dakota was 74% and the corresponding commission rate to grass was 19%. The probability of alfalfa being misclassified as grass for this example was calculated as 19/(19 + 74) = 0.20. The product of probabilities for both types of misclassification was calculated for all combinations of two, three, or four consecutive years (2009–2012) with both alfalfa and grass. Probabilities could not be calculated for the 2006 and 2007 CDLs because full error matrices were not available from the USDA-NASS. The full error matrix was available for the 2008 CDLs, but probabilities were not used for this year because the USDA-NASS changed the definition of the "alfalfa" category beginning in 2009 to include two additional types of alfalfa from the USDA-Farm Service Agency reports (i.e., alfalfa–grass mixtures and alfalfa interseeded with small grains). Therefore, for the 2006 to 2008 CDLs, a single or double year of grass was converted to alfalfa when the majority of years for given alfalfa phase lengths were classified as alfalfa in generalized CDLs. For example, "grass" in the code "corn–grass–grass–alfalfa–alfalfa–alfalfa–corn–corn" for the 2006 to 2012 CDLs, respectively, was converted to "alfalfa".

The two crops following alfalfa also were selected using both the generalized and adjusted vectors. First-year crops following ≥2 yr of alfalfa were selected for 2008 to 2012, and the same criterion was used for second-year crops in 2009 to 2012. To test the effect of alfalfa stand length on the type of following crop, data were restricted to first-year crop in 2011 and second-year crop in 2012. Thus, crops following only 2- to ≥5-yr-old alfalfa could be determined for this analysis.

Statistical Analysis

Interactions between categorical variables were analyzed with chi-square statistics at $P \leq 0.05$ by state with $s \times r$ contingency tables (Stokes et al., 2012) using the FREQ procedure of SAS (SAS Institute, 2006). Data were analyzed with alfalfa phase length and year as ordinal variables, and with selection method, soil textural class, and following crop as nominal variables. Spatial clustering in alfalfa phase length across the six states was evaluated with the Getis–Ord Gi* statistic at $P \leq 0.05$ using hot spot analysis in ArcGIS 10.1. The hot spot analysis was conducted with Euclidean distance as the distance method and fixed distance band as the conceptualization of spatial relationships; the default neighborhood threshold was 34.3 km.

RESULTS AND DISCUSSION

Method Assessment

Alfalfa area in the original raster CDLs was severely underrepresented in most years and states, compared to the USDA-NASS census and survey data (Supplemental Table S1). Across the six states, only 38% of the alfalfa area in the census and survey was represented during 2006 to 2010. In 2011 to 2012, alfalfa area estimates increased and 65% of the crop in the census and survey data was accounted for. In contrast, 95 and 97% of corn and soybean area, respectively, was represented across years and states.

The user's accuracy was consistently high (91–99%) across years and states for corn and soybean, but was generally lower and more inconsistent (30–95%) for alfalfa (Supplemental Fig. S1). Nebraska and Wisconsin had the highest user's accuracy (82–95%) for alfalfa across years. Nebraska's accuracy was high likely because nearly one-third of alfalfa was irrigated compared to <4% in the other five states (USDA-NASS, 2013a), making it easier to distinguish spectrally from other crops or noncropland. The high accuracy for Wisconsin may have been due to improved ground reference data, because a higher percentage of total cropland (34%) was planted to alfalfa than in the other states (4–14%; USDA-NASS, 2013a). For the remaining states, the lower accuracy for alfalfa classification relative to annual crops is a concern, especially since alfalfa is the fourth most widely grown crop in both this region and the nation. Overall, the lower alfalfa accuracy is likely related to: (i) difficulty in distinguishing it from other hay types, grassland, and pastures using remote sensing; (ii) inadequate standards for determining how much alfalfa is necessary for a field to be classified as alfalfa vs. another hay type or grassland; and (iii) inadequate and inconsistent ground reference data from the USDA-NASS and the USDA-Farm Service Agency for alfalfa.

To remedy the low alfalfa classification accuracy, we generalized and converted the original raster files to vectors and removed all polygons <0.5 ha. On average, the generalized vector CDL had two-thirds of the original raster CDL area of alfalfa across years in Nebraska and North Dakota and had one-half the area in the remaining states (Supplemental Table S1). This decline likely occurred because: (i) some alfalfa fields in original raster CDLs had more grass pixels than alfalfa, so the alfalfa field was generalized to grass; and (ii) several alfalfa pixels in original raster CDLs were single or small clusters of pixels. Although generalized vector CDLs reduced alfalfa area, the estimates were highly correlated to original raster CDLs across years and states (generalized = 18.0 + 0.458 × original, $r^2 = 0.92$, $P < 0.001$, $n = 42$).

To further account for the original low classification accuracy for alfalfa, we adjusted generalized vector CDLs by converting some grass to alfalfa using classification error rates. This increased alfalfa area by 3 to 11% across years and states relative to generalized vector CDLs (Supplemental Table S1). Adjusted CDL alfalfa area also was highly correlated with the original raster CDLs across years and states (adjusted = 25.8 + 0.451 × original, $r^2 = 0.92$, $P < 0.001$, $n = 42$). For most cases, original raster, generalized vector, and adjusted vector CDLs were poorly correlated to the official census and survey area for alfalfa. We suggest this occurred because classifications of alfalfa during the establishment year and alfalfa–grass mixtures were inconsistent among years, states, and sources.

Selection method (generalized or adjusted vectors) significantly affected alfalfa phase length in all states, but it significantly affected first-year crop type only in Minnesota and Iowa and second-year crop type only in South Dakota (Supplemental Fig. S2). The added alfalfa area and subsequent changes in phase lengths from adjusted vectors differed by state because

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adjustments were dependent on state and year classification error rates (Supplemental Fig. S1). All phase lengths were increased in states with lower alfalfa classification accuracy (North Dakota, South Dakota, Minnesota, and Iowa), whereas only longer phases were affected in states with higher accuracy (e.g., 4 to ≥7 yr phases in Nebraska; ≥6 yr phases in Wisconsin). In general, the proportion of longer alfalfa phases increased in most production areas of this region with adjusted vectors (Supplemental Fig. S3). Both selection methods resulted in significant ($P < 0.001$) interactions for alfalfa phase length × soil textural class, alfalfa phase length × following crop, year × following crop, and soil textural class × following crop. Only the adjusted vector results are presented because of the consistency between methods and ability of adjusted vectors to partially remedy the relatively lower alfalfa classification accuracy in the original raster CDLs.

Alfalfa Phase Length

Geographic Location. Alfalfa stands were maintained for ≤4 yr in a higher proportion of polygons in the eastern states of Iowa (82%), Wisconsin (67%), and Minnesota (62%), than in the drier western states of Nebraska (45%), South Dakota (38%), and North Dakota (12%) (Supplemental Fig. S2), but phase length distributions differed within states (Fig. 1). Areas with spatial clustering of shorter alfalfa phases had 72% of phases ≤4-yr-long, whereas areas with longer phases had 76% of phases ≥5-yr-long; areas with no clustering had an equal number of both phase categories. Shorter phases were typical in Iowa (except for the southern part of the state), the southeastern part of South Dakota, the eastern quarter of Nebraska, and nearly everywhere south of U.S. Interstate 94 in Minnesota. Longer alfalfa phases were typical across the Dakotas (except near the Red River Valley in North Dakota and the southeast area of South Dakota), in western areas of Nebraska, and northern areas of Minnesota. Wisconsin had the greatest spatial complexity in alfalfa phase length, with three to four clusters of both shorter and longer phases.

A survey of 253 growers in Manitoba and Saskatchewan (Entz et al., 1995) found that forage (including alfalfa) phase length was dependent on annual precipitation; phases ranged from 3 to 5 yr in wetter areas and from 6 to 9 yr in the driest areas. Their survey results also revealed that most growers did not rotate according to planned schedules but rather terminated forage when yield declined. Another survey of 528 growers in Minnesota confirmed these results; 98% rotated alfalfa for reasons other than a planned schedule (Yost et al., 2014a). Therefore, the patterns we identified in alfalfa phase length likely were related to climatic zones, which affect alfalfa's productivity and over-wintering ability. Growers in the drier areas of this region (i.e., most areas north, west, and northwest of the major Corn Belt) may be able to maintain alfalfa stands longer because the likelihood of soil compaction and alfalfa disease pressure can be lower than in wetter areas. In contrast, low water availability in drier climates can reduce alfalfa yield and feed quality (Vough and Marten, 1971). Another possible reason for shorter alfalfa stands inside the major Corn Belt area of this region is the higher presence of dairy cattle and alfalfa end-use. Much of the Dairy Belt lies within the Corn Belt area and alfalfa feed quality is typically of higher importance for lactating dairy cow than other cattle rations. Therefore, growers in the Corn Belt may harvest and rotate alfalfa more frequently to maintain high feed quality and to avoid thin

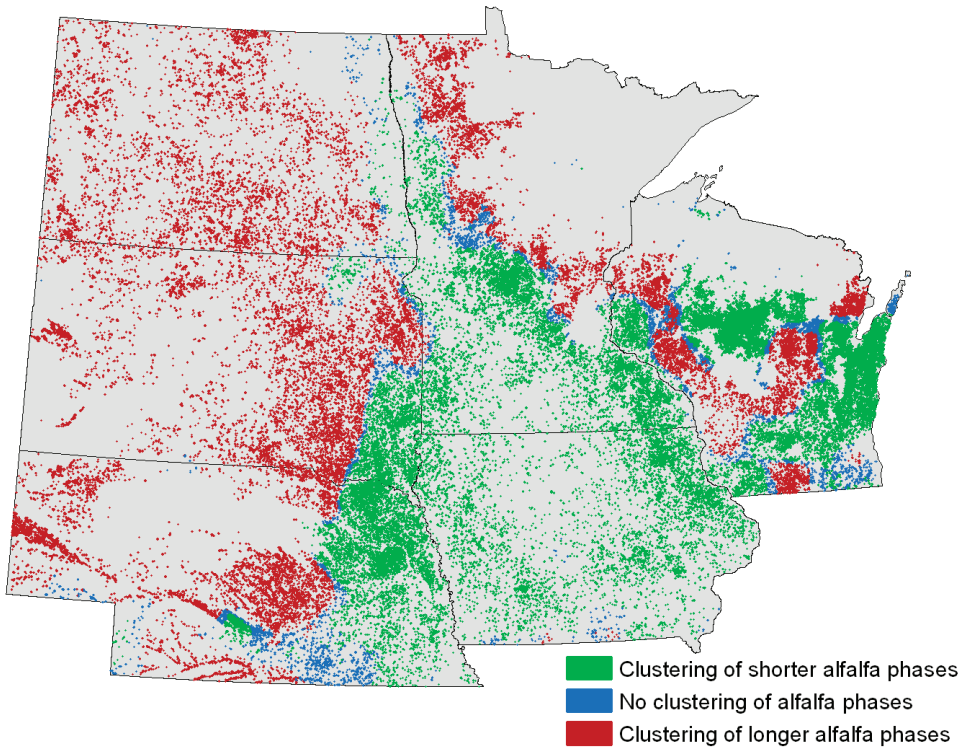


Fig. 1. Spatial clustering patterns of alfalfa phase length (2 to ≥7 yr) in the upper midwestern United States from the adjusted vector USDA-National Agricultural Statistics Service Cropland Data Layers (2006–2012) according to Getis-Ord Gi* statistic at $P \leq 0.05$. Areas with shorter phase clustering had 72% of phases ≤4-yr long, whereas areas with longer phase clustering had 76% of phases ≥5-yr long; areas with no clustering had an equal number of both phases. Polygon borders are enlarged to enhance visibility.

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or weedy stands. Such generalizations do not account for the complex weather variations within and among states that affect alfalfa phase length. Further analyses should determine these effects; dynamic empirical crop rotation models (MacEwan, 2012) may prove useful in that research.

Soil Textural Class. Alfalfa is grown on all three soil textural classes in this six state region. Medium-textured soils had the greatest area and spatial distribution, while coarse-textured soils had the least (Fig. 2; Supplemental Fig. S4). Soil texture affects aeration, water holding capacity, organic matter retention, and other factors that influence crop production. Alfalfa phase lengths in the Dakotas and Iowa were relatively consistent for coarse- and medium-textured soils, but fine-textured soils had a higher frequency of shorter phases (Fig. 3). A similar trend occurred in Nebraska, Minnesota, and Wisconsin, with the exception that phase length generally declined as soil textural class changed from coarse to fine. The trend for longer phases in some of the central sand plains of Wisconsin may be related partially to the lower risk for soil compaction and disease caused by excess water and poor drainage on these soils than on medium- and fine-textured soils. Shorter phases on fine-textured soils across these states, coupled with survey results indicating that most forage growers do not follow planned crop rotations (Entz et al., 1995; Yost et al., 2014a), suggests that fine-textured soils may not support alfalfa stands as long as soils with less clay. Machinery traffic required for multiple alfalfa harvests per year, together with the pressure for timely harvest on soils with greater water holding capacity (fine-textured soils; Hamza and Anderson, 2005) increases the likelihood for soil compaction, which often leads to decreased herbage yield and greater winter damage (Bélanger et al., 2006). Future research and education should focus on whether and how alfalfa management should differ by soil textural class.

Several other management factors including: (i) cultivar characteristics (winter-hardiness, disease resistance, yield potential); (ii) disease, nutrient, pest, and weed management; (iii) harvest timing and frequency; (iv) end-use (feed for on-farm use or hay sold as a cash crop); (v) market prices of alfalfa and other commodity crops; and (vi) sociological conditions (e.g., off-farm employment, dependence on custom harvesting, etc.) also affect how frequently growers terminate alfalfa in this region (Undersander et al., 2011). However, we do not have sufficient data to analyze how these complex factors interact with each other and with climate and/or soil conditions. Future research should seek to identify additional factors beyond geographic location and soil textural class that regulate trends in alfalfa–annual crop rotation patterns.

First-Year Crops following Alfalfa

Many of the complex interacting factors affecting alfalfa phase length also can affect a grower's selection of subsequent crops. We defer speculation regarding which of these factors influenced first- and second-year crop selection following alfalfa, but show geographic distributions of each and present statewide trends to examine generalized grower behavior. Our goal is to help guide future research that may be able to identify specific reasons for these behaviors and how they vary within and among states.

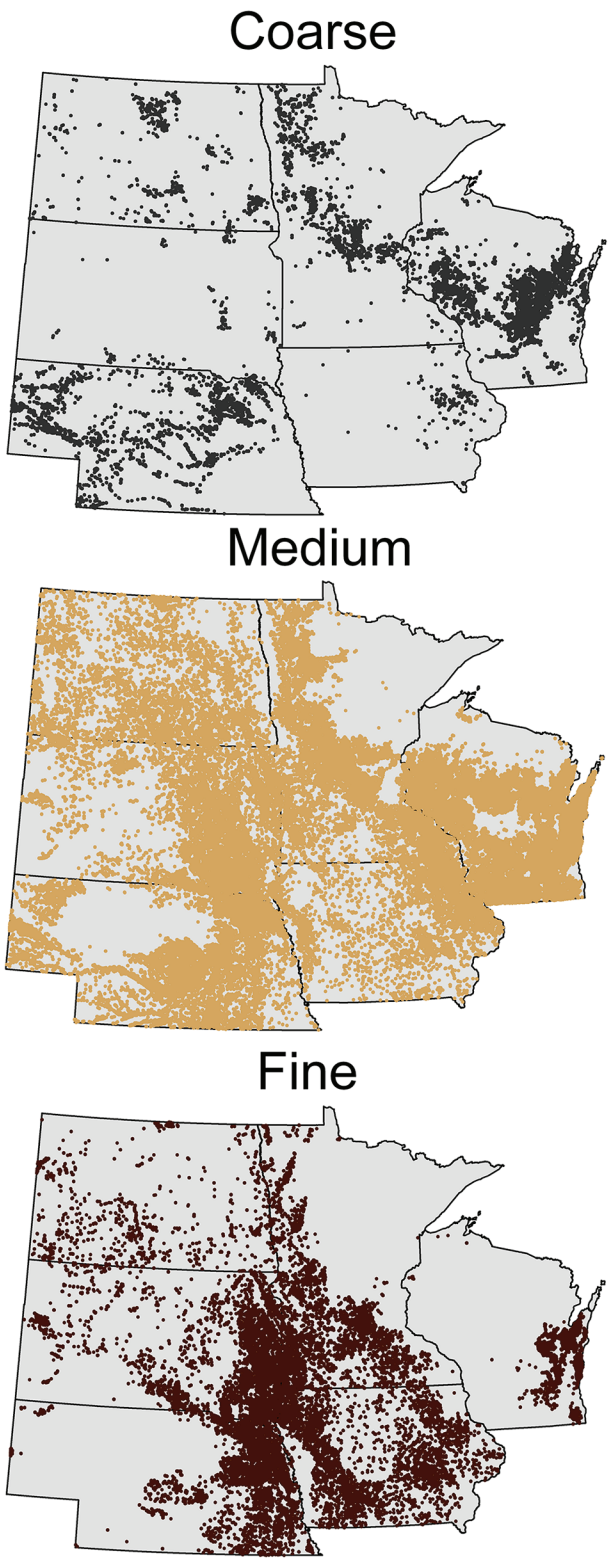


Fig. 2. Soil textural class (coarse, medium, or fine) for polygons where alfalfa phase length or following crops could be determined from the adjusted vector (described in text) USDA-National Agricultural Statistics Service Cropland Data Layers (2006–2012). Polygon borders are enlarged to enhance visibility.

Spatial distributions for corn and soybean as first-year crops were generally similar in all states except Nebraska, where only corn was produced in the western part of the state (Fig. 4; Supplemental Fig. S5). Corn was the most frequent first-year

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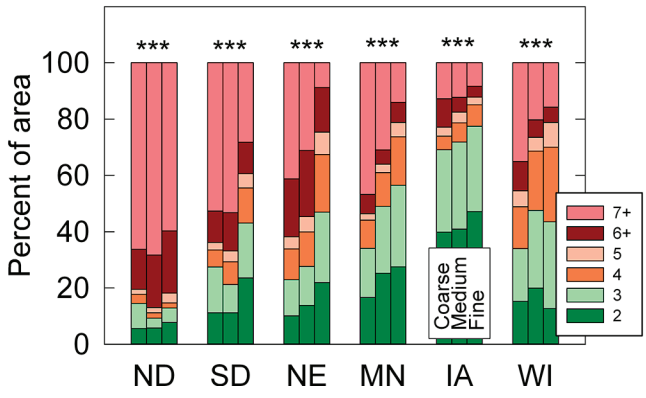


Fig. 3. The percent of total area where the phase length of alfalfa (shading represents years) could be determined from the adjusted vector (described in text) USDA-National Agricultural Statistics Service Cropland Data Layers (2006–2012) by state and soil textural class (coarse, medium, and fine). Differences in alfalfa phase length categorization among soil textural class within states according to chi-squared tests were denoted with *** for $P \leq 0.001$.

crop (61–92% of cases) in all states except North Dakota (40%) (Fig. 5). Soybean, which usually requires no fertilizer N (Salvagiotti et al., 2008), was the first-year crop in 15% of the cases in the Dakotas, Minnesota, and Iowa, 7% in Nebraska, and 3% in Wisconsin. These cases were spatially distributed across much of the region except for the western halves of the Dakotas and Nebraska, indicating that a substantial, widespread proportion of growers may be underutilizing the large first-year N supply following alfalfa. This analysis cannot determine why soybean was planted following alfalfa, but we suspect that it is related to soybean market price, timing of alfalfa termination (late-spring or early summer termination), growing season length, and water use requirement of soybean vs. other crop types (Copeland et al., 1993). Future research should identify the conditions where soybean following alfalfa is economically and environmentally viable.

Spatial distributions for small grains and minor crops tended to be similar in North Dakota and Minnesota, whereas the areas of production did not overlap consistently in Nebraska, South Dakota, and Wisconsin (Fig. 4). Small grains, but not minor crops, followed alfalfa in the eastern halves of South Dakota and Nebraska and southern third of Wisconsin. Small grains were the first-year crop grown most frequently in the Dakotas (29% of cases) and Minnesota and Nebraska (10%), and minor crops most frequently in North Dakota (8%; Fig. 5). Most minor crops in North Dakota likely were sunflower (*Helianthus annuus* L.), sugarbeet (*Beta vulgaris* L.), and potato, because these were the minor crops with the largest area in these states (USDA-NASS, 2013a). Southeastern South Dakota and eastern Wisconsin had the highest spatial densities of small grains, which indicates that these areas may benefit from future research and education on alfalfa N credits to small grains (Fig. 4).

Alfalfa Phase Length. Phase length (2 to ≥5 yr) was significantly related to the type of first-year crop following alfalfa in 2011 in each state (Fig. 5), with the largest differences in North Dakota and Minnesota. In North Dakota, the longest alfalfa phases were more frequently followed by soybean and corn, whereas shorter phases were more frequently followed by small grains or minor crops. In Minnesota, the frequency of small

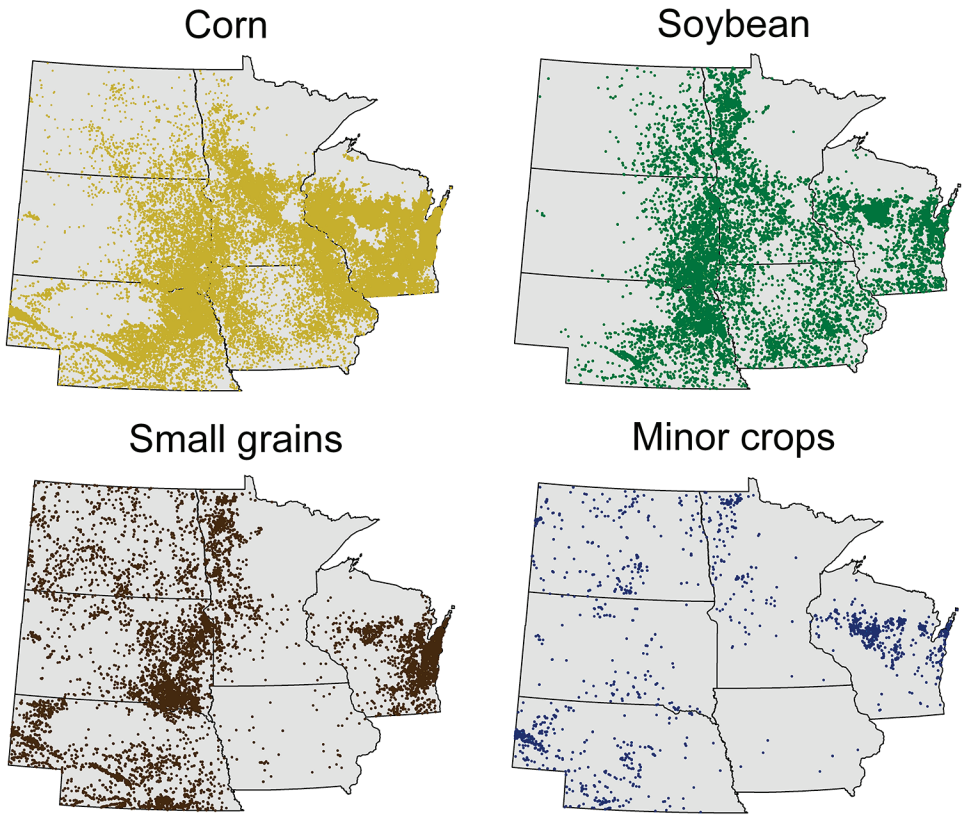


Fig. 4. Five-year (2008–2012) footprint of corn, soybean, small grains, and minor crops grown as the first crop after alfalfa termination, determined from the adjusted vector (described in text) USDA-National Agricultural Statistics Service Cropland Data Layers (2006–2012). Polygon borders are enlarged to enhance visibility.

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grains following 4-yr-long alfalfa phases was 31% compared to 7% frequency for the other phase lengths. There were smaller differences in the remaining four states, with small grains being slightly more frequent after longer alfalfa phases (i.e., 4 or ≥5 yr) in South Dakota, Nebraska, and Iowa, and soybean being more frequent after shorter phases in Nebraska. In Wisconsin, the frequency of minor crops as the first-year crop increased by 5% points when following 2-yr-long phases compared to all longer alfalfa phases, but there was high correspondence of areas with shorter phases followed by small grains and minor crops (Fig. 4). This pattern contrasts with that in the other states, where small grains and minor crops tended to follow longer alfalfa phases.

Soil Textural Class. The first-year crop type also changed with soil textural class (Fig. 5). In the Dakotas, corn frequency was highest for coarse-textured soils; small grains were more frequent for medium- and fine-textured soils. A higher frequency of corn on coarse-textured soils was unexpected because these soils typically have low water holding capacity and long-term trials in South Dakota indicate that when soil moisture is limited, the yield of first-year corn following alfalfa can be lower than corn in other rotations (Pikul et al., 2005). We speculate that the higher frequency of corn on coarse-textured soils was due to availability of irrigation. Field research for first-year corn following alfalfa on coarse-textured soils showed that it usually requires fertilizer N to maximize economic return (Yost et al., 2014c). This indicates that significant losses of mineralized N from alfalfa may be occurring even with a crop that has high N uptake potential. Crops with lower N uptake potential than corn, such as small grains and soybean, may further increase N loss under these conditions. In Nebraska, soybean frequency as the first-year crop increased and small grains decreased on medium- and fine-textured soils (Fig. 5). Crop type was less related to soil textural class in Minnesota, Iowa, and Wisconsin. Minnesota and Iowa had higher corn and lower soybean frequencies on medium-textured soils than other textures, and Minnesota also had slightly higher small grain and lower corn frequencies on coarse-textured soils than other textures. Wisconsin had slightly higher small grains and lower minor crop frequencies on medium- and fine-textured soils.

Year. First-year crop type was affected by the year in which it was produced in all states, although differences were small for Nebraska and Wisconsin (Fig. 5). Corn frequency decreased and minor crop increased in 2009 to 2011 in North Dakota. Corn frequency increased and small grains decreased from 2008 to 2012 in South Dakota; increasing corn frequency may be related to increasing corn grain prices during this time (Stern et al., 2012; USDA-NASS, 2013a). Corn was grown as the first-year crop less frequently in 2009 and 2010 in Minnesota and Iowa compared to other years; soybean replaced much of this corn area in Iowa and small grains replaced much in Minnesota. Market prices of the major and minor crops influence which crops are grown following alfalfa each year in this region, but this analysis does not include the temporal and spatial complexities in crop market prices and how they might influence grower decisions about which crops to grow. Hennessy (2006) investigated price-dependent and price-independent crop rotation structures for corn–soybean rotations in Iowa and found evidence for price dependencies

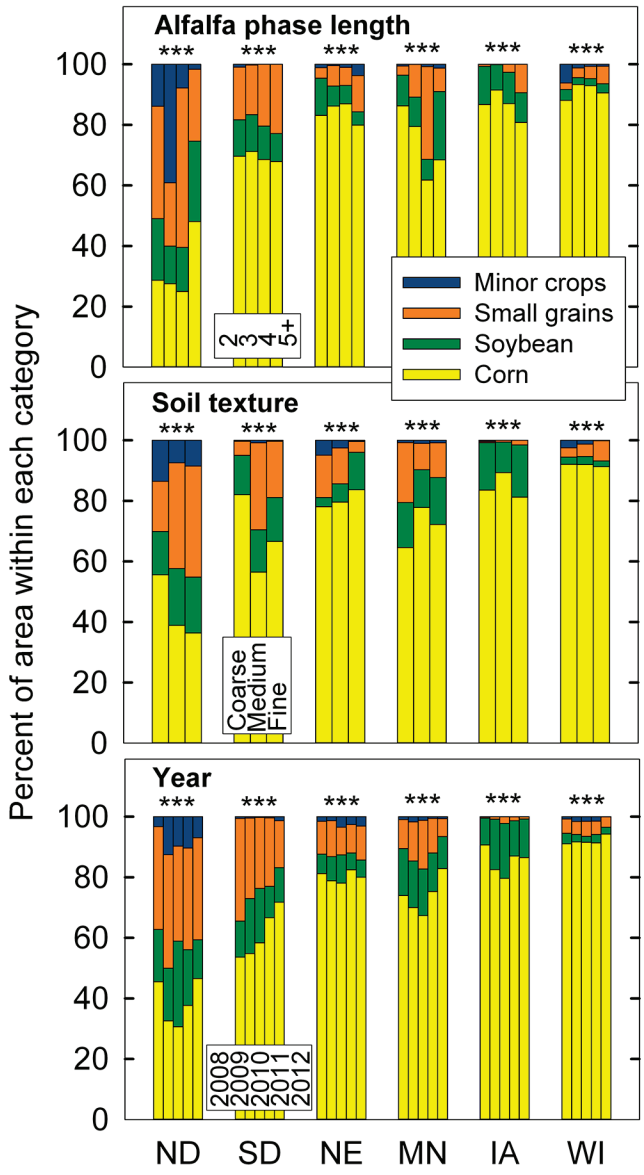


Fig. 5. The percent of the total area where the first-year crop following ≥2-yr-old alfalfa could be determined from the adjusted vector (described in text) USDA-National Agricultural Statistics Service Cropland Data Layers that was major and minor crops for each state by: (i) the length of the alfalfa phase in years (top); (ii) soil textural class (middle); and (iii) year when the indicated crops were grown (bottom). Differences in categorization among phase length, soil textural class, and year within states according to chi-squared tests were denoted with *** for $P \leq 0.001$.

(i.e., memories) of 1 yr for corn and 2 yr for soybean. Residual effects of soybean included a lower fertilizer N requirement and higher corn yield than continuous corn. This type of analysis could be expanded to include price structures for alfalfa–annual crop rotations.

Second-Year Crops following Alfalfa

Distributions of corn and soybean as second-year crops after alfalfa were similar to their first-year distributions, but fewer hectares were planted to corn and more to soybean (Fig. 6; Supplemental Fig. S6). Corn was the second-year crop grown in one-half to three-fourths of the cases in all states except North Dakota, where it was grown in about one-third of the cases (Fig. 7). Soybean was grown in one-fourth to one-third of the

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cases in each state except Wisconsin, where soybean frequency was only 14%. The high frequency of soybean distributed across most states indicates that many growers may not be utilizing the "free" N supply from alfalfa to the second-year crop, but perhaps are taking advantage of the soybean yield increase due to the rotation effect with corn (Crookston et al., 1991). Evaluation of the relative effects of residual N availability vs. the non-N rotation effect for second-year crops may provide the basis for making better decisions to improve economic returns.

Small grains as second-year crops were less common than as first-year crops, but spatial distributions of small grains as both crops were similar. Small grains were the second-year crop in 5% of the cases in all states except North Dakota, where they comprised one-fourth of the cases (Fig. 6). North Dakota also had the highest frequency of minor crops (8%). Alfalfa was the second-year crop in 5% of the cases across all states (Fig. 7), but it was more common within some areas, such as central and eastern Wisconsin and south-central and east-central Nebraska (Fig. 6). Because it is slow to establish, alfalfa as the second-year crop could lead to high nitrate losses if the N supply from the previous alfalfa phase continues to be high (Huggins et al., 2001).

Alfalfa Phase Length. Second-year crop types in 2012 were affected by alfalfa phase length in each state (Fig. 7). Soybean frequency as the second-year crop in North Dakota was higher when following alfalfa phases of ≥5 yr, and alfalfa frequency increased for 4-yr phases relative to other phases. In South Dakota, corn frequency increased from 38 to 53% when following 3-, 4-, and ≥5-yr alfalfa phases relative to 2-yr phases. Nebraska had a higher frequency of minor crops and a lower frequency of soybean for the longest phase length compared to shorter phases. Corn frequency decreased following longer alfalfa phases (4 and ≥5 yr) relative to shorter phases in Minnesota, but this may reflect the different geographic locations of the fields (Fig. 1). In Iowa, soybean followed 2-yr alfalfa

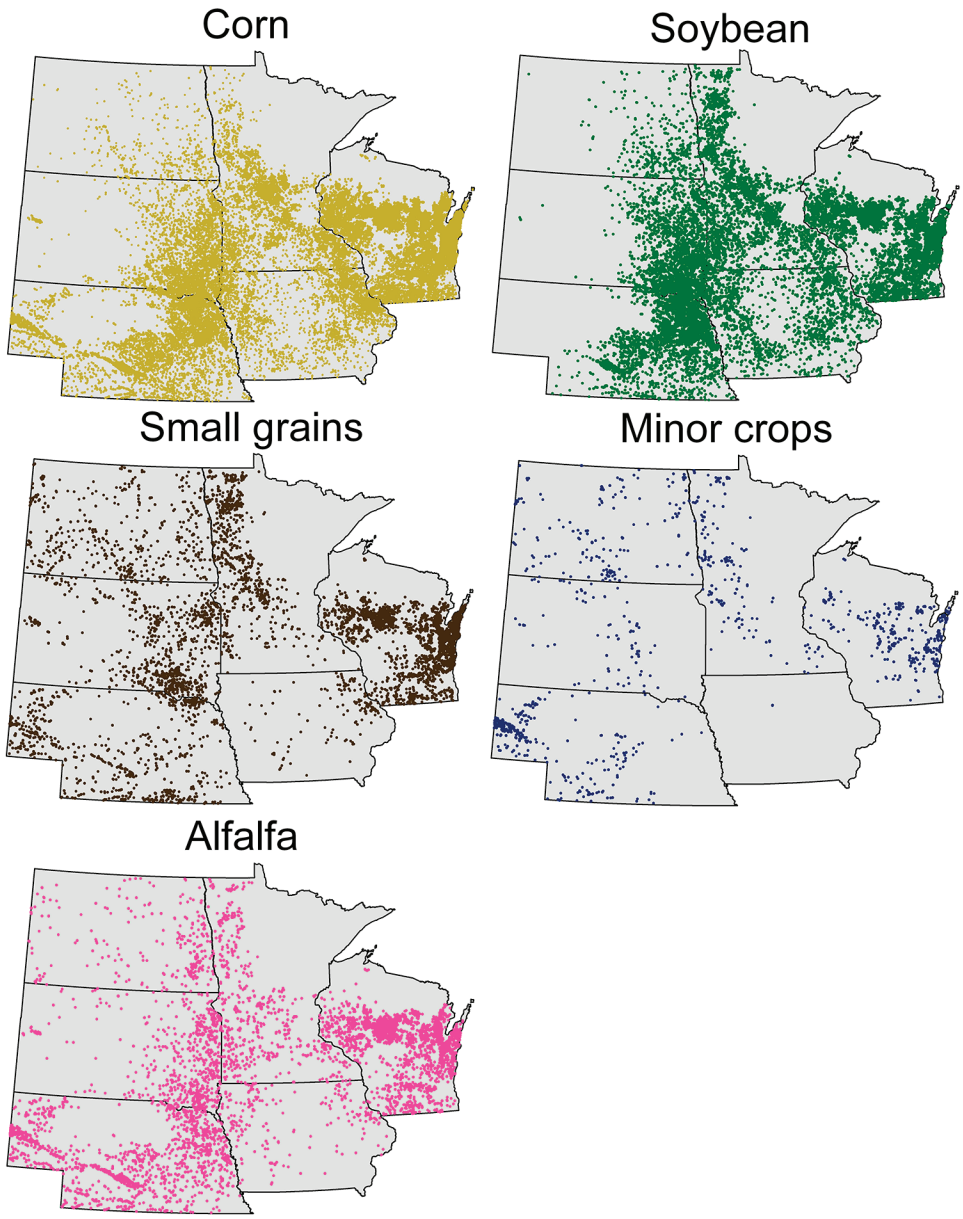


Fig. 6. Four-year (2009–2012) footprint of corn, soybean, small grains, minor crops, and alfalfa grown as the second crop after alfalfa termination, determined from the adjusted vector (described in text) USDA-National Agricultural Statistics Service Cropland Data Layers (2006–2012). Polygon borders are enlarged to enhance visibility.

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phases more frequently than longer phases, which were more frequently corn (Fig. 7). Increased soybean frequency following shorter alfalfa phases may be related to a perception by growers that the alfalfa N credit is higher after longer alfalfa phases. The frequency of alfalfa as the second-crop was higher following shorter alfalfa phases (2 and 3 yr) in Wisconsin, and there was a slightly lower frequency of corn for the shortest phase.

Soil Textural Class. As with the first-year crop, the second-year crop also was affected by soil textural class in each state (Fig. 7). In North Dakota, the frequency of minor crops increased and corn decreased as soil textural class changed from coarse to fine. In contrast, coarse-textured soils in South Dakota had higher corn and lower small grain frequencies than medium- and fine-textured soils. As described for first-year crops, the increased frequency of corn on coarse-textured soils may be related to increased availability of irrigation for these soils relative to other textural classes. As soils changed from coarse to fine in Nebraska, soybean frequency increased, whereas all remaining crop types decreased. The frequency of corn as the second-year crop increased relative to all remaining crop types on medium-textured soils in Minnesota and on coarse- or medium-textured soils in Iowa. Small grains frequency increased and minor crops decreased on fine-textured soil in Wisconsin.

Year. The type of second-year crop following alfalfa was affected by the year in which it was produced in each state (Fig. 7). In North Dakota, Nebraska, and Minnesota, corn was less frequently grown in 2010 and 2011 than other years. North Dakota had a large increase in alfalfa frequency in 2011 (13% points higher than other years) and soybean frequency decreased by 16% points from 2009 to 2012. In South Dakota, decreased frequency of small grains corresponded with increased soybean from 2009 to 2012. Higher minor crop and lower small grain frequencies occurred from 2009 to 2012 in Nebraska. Wisconsin had minor changes in all second-year crop types from year to year.

First- and Second-Year Crops following Alfalfa

The eight most common sequences of both the first- and second-year crop following alfalfa were various combinations of corn, soybean, small grains, and alfalfa; sequences other than these are referred to as "secondary crop sequences". These various sequences had both overlapping and distinct spatial distributions (Fig. 8). Corn–corn occurred in about one-fifth of the cases in the Dakotas, one-half of the cases in Nebraska, Minnesota, and Iowa, and about three-fourths of the cases in Wisconsin (Fig. 9). Corn–soybean was the second most frequent sequence following alfalfa in all states except North Dakota; this sequence occurred in about one-fourth of the cases (13–31%) across the five states.

The remaining six of eight common crop sequences occurred in 0 to 17% of the cases across states. Soybean–corn had a similar spatial distribution to corn–soybean, suggesting that selection of the first crop in these cases may depend on time of alfalfa termination (Fig. 8). The three common crop sequences with 1 or 2 yr of small grains were distributed mainly in central and eastern Wisconsin and the western half of the region. Most small grains and canning crops (included in minor crops) are short-season crops and may not utilize the alfalfa N supply as effectively as full-season crops like corn. Therefore, despite the agronomic and economic advantages of short-season crops, consideration should be given to the potential for nitrate leaching losses. Secondary crop sequences were most frequent in Minnesota (15% of the time) and North Dakota (34%).

The common and secondary sequences with alfalfa as the second-year crop represented 3 to 7% of the total area in this region. Of this area, the first-year crop was corn 14 to 31% of cases in the Dakotas, 76% of cases in Wisconsin, and 44 to 51% of cases in the remaining states. Soybean was the first-year crop 30 to 43% of cases in all states except Nebraska and Wisconsin (7–11% of cases), small grains were 33% of cases in the Dakotas and Nebraska, and minor crops were 1 to 9% of cases across states. Although sequences with alfalfa as the second-year crop comprise a low percentage of the total in this region, they represent opportunities for crop sequences that more fully utilize the ≥2 yr N contribution of terminated alfalfa.

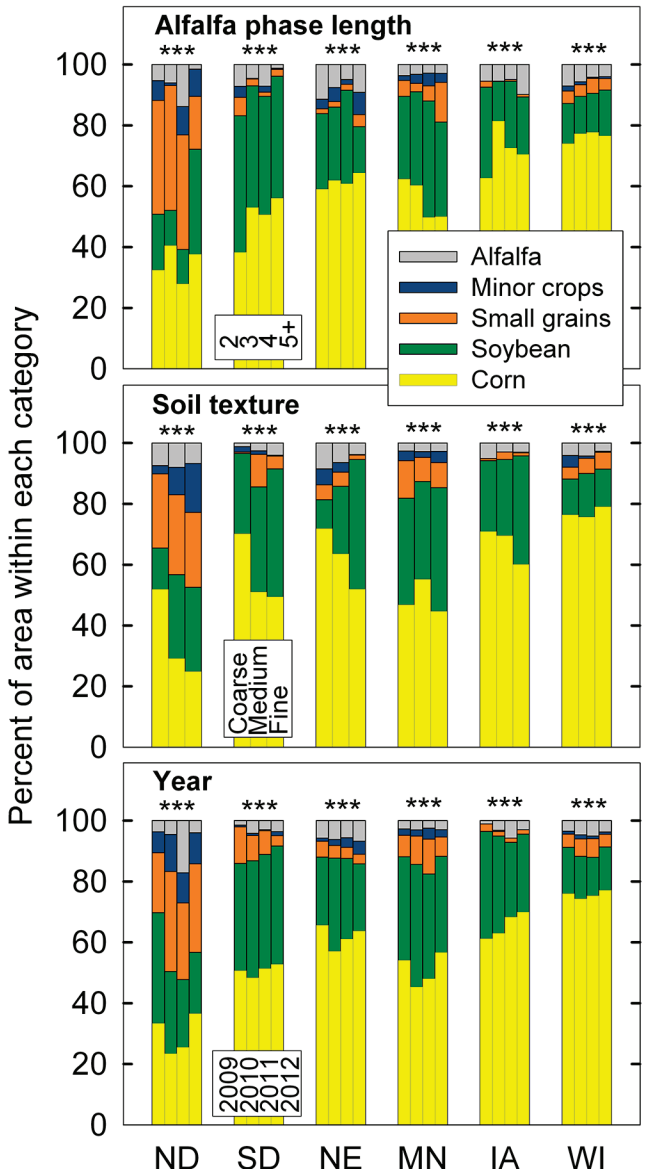


Fig. 7. The percent of the total area where the second-year crop following ≥2-yr-old alfalfa could be determined from the adjusted vector (described in text) USDA-National Agricultural Statistics Service Cropland Data Layers that was major and minor crops. For further description, see caption for Fig. 5.

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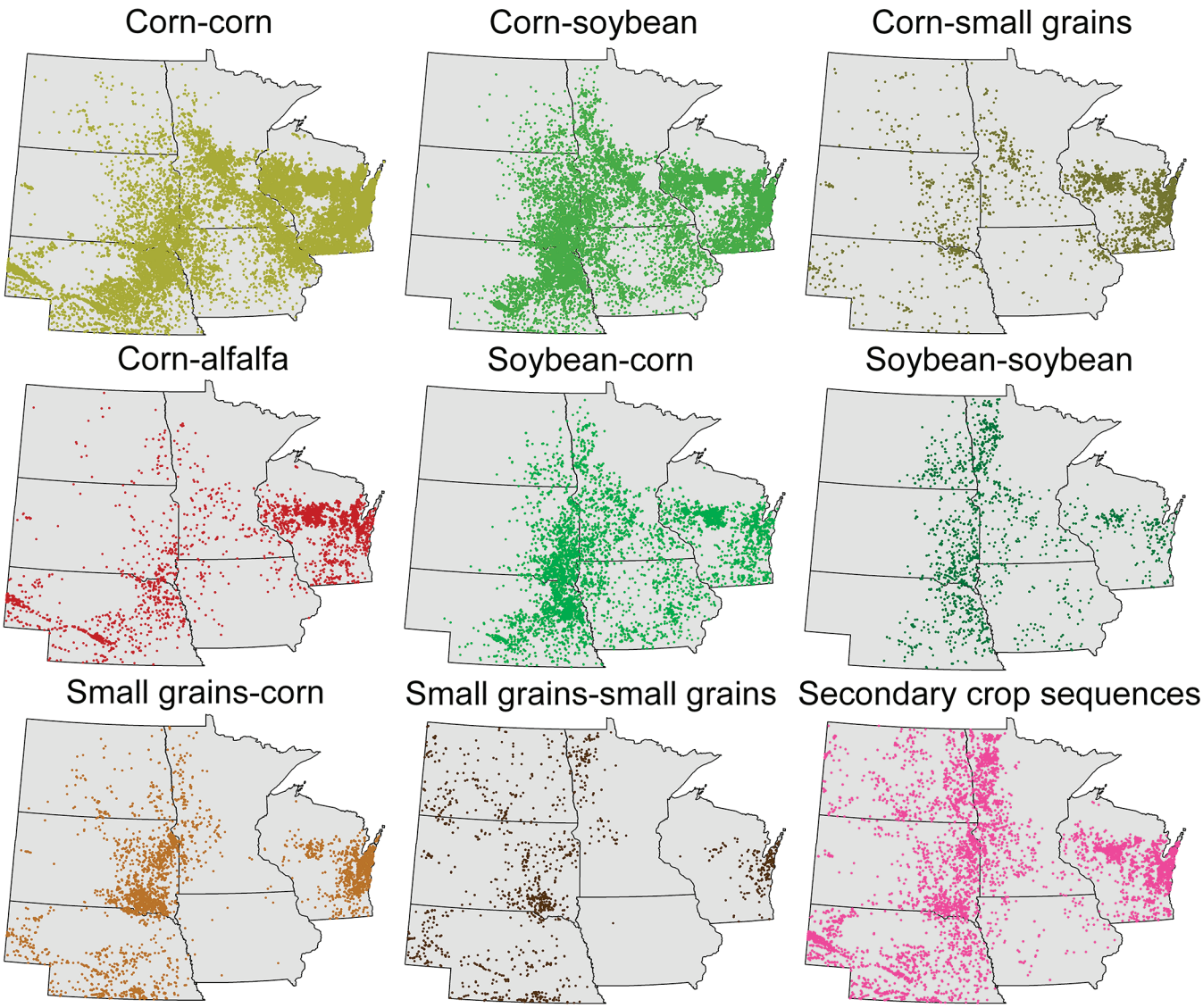


Fig. 8. Five-year (2008–2012) footprint of 2-yr crop sequences following alfalfa termination determined from the adjusted vector (described in text) USDA-National Agricultural Statistics Service Cropland Data Layers (2006–2012). Polygon borders are enlarged to enhance visibility.

Alfalfa Phase Length. Specific sequences of the first-year crop in 2011 and second-year crop in 2012 were affected by the preceding alfalfa phase length in each state (Fig. 9). In North Dakota, ≥5-yr-long alfalfa phases were followed less frequently by 2 yr of small grains and secondary crop sequences than shorter phases; this area was replaced mainly by corn–soybean and small grains–corn sequences. South Dakota had less corn–corn but no change in corn–soybean when following 2-yr-long alfalfa phases compared to longer phases; the opposite occurred in Nebraska. In Minnesota, corn–corn frequency increased by 16% points when following shorter alfalfa phases (2 and 3 yr) relative to longer phases (4 and ≥5 yr), and secondary crop sequence frequencies were variable among phases. Iowa had lower corn–corn and higher corn–soybean frequencies when following 2-yr phases than longer phases. In Wisconsin, corn–corn frequency increased following 3- and 4-yr alfalfa phases relative to other phase lengths, and secondary crop sequence frequency increased following 2-yr phases relative to other phases.

Soil Textural Class. In each state, soil textural class also affected the frequency of specific 2-yr crop sequences following alfalfa (Fig. 9). Corn–corn frequency was higher in the Dakotas on coarse-textured soils than on medium- and fine-textured soils. In Nebraska, corn–corn frequency decreased and corn–soybean increased as soil textural class changed from coarse to fine. Minnesota and Iowa had similar trends for corn–corn; its frequency was higher on medium-textured soils than other soil textural classes. In Wisconsin, secondary crop sequences were less and small grains–corn were more frequent as soil textural class changed from coarse to fine; otherwise crop sequences were relatively consistent across soil textural classes.

Year. The 2-yr crop sequences following alfalfa differed with year in each state, discussed here as the year of the second crop (Fig. 9). Corn–corn was less frequent in 2010 and 2011 than other years in North Dakota, Nebraska, Minnesota, and Iowa; much of the reduced corn–corn area in Minnesota and North Dakota was replaced by secondary crop sequences. In South Dakota, corn–soybean frequency increased and small grains–corn and small grains–small grains decreased from 2009 to 2012. In contrast, the frequency of secondary crop sequences increased from 2009 to 2012 in Nebraska. From 2009 to 2012 in Iowa, the frequency of corn–soybean decreased by 9% points and soybean–corn increased by 6% points. Wisconsin had a slightly

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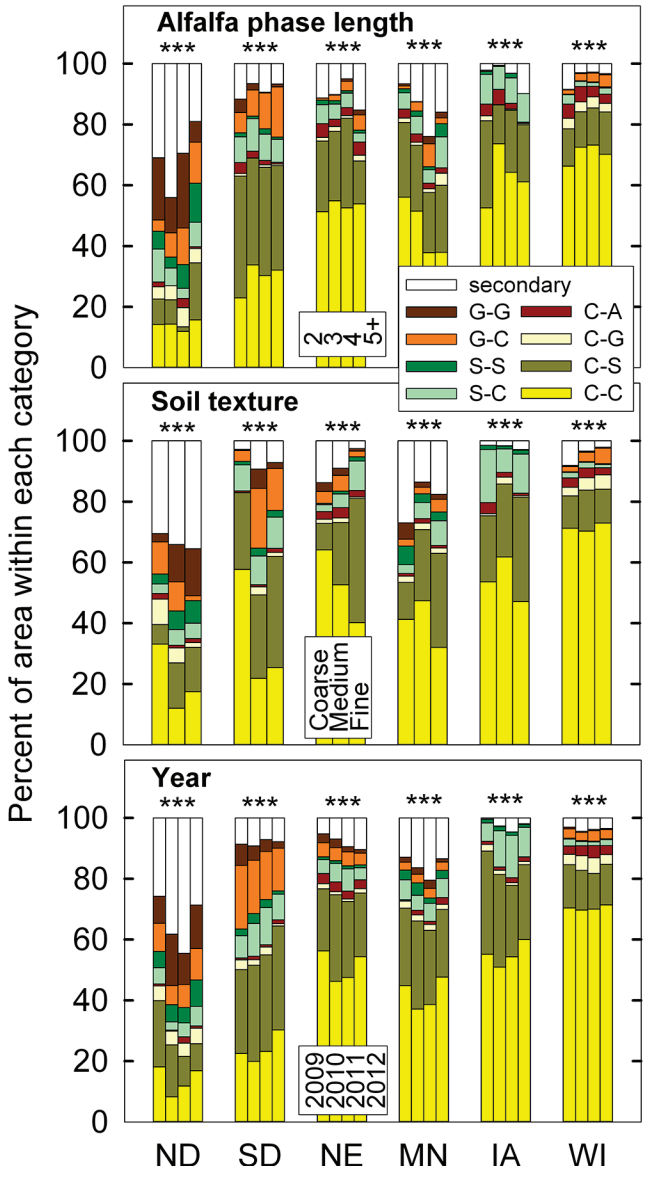


Fig. 9. The percent of the total area where both the first- and second-year crop following ≥2-yr-old alfalfa could be determined from the adjusted vector (described in text) USDA-National Agricultural Statistics Service Cropland Data Layers that was combinations of corn (C), soybean (S), small grains (G), alfalfa (A), or secondary combinations of these and minor crops. Year in the bottom figure represents the year when the second-year crop was grown. For further description, see caption for Fig. 5.

higher frequency of corn–small grains in 2010 to 2011 than other years, but was otherwise relatively consistent across years.

IMPLICATIONS

These are the first geographically-specific estimates describing the broad-scale crop rotation patterns of alfalfa with annual crops practiced by growers in the upper midwestern United States. Such spatial descriptions of alfalfa stand length and the two subsequent crops should improve estimates of site-specific economic and environmental benefits of alfalfa in crop rotations, aid in planning of fertilizer need assessments for alfalfa and the crops that follow, and help focus the development of educational programming and future research on crop rotation practices that maximize net return to alfalfa production and utilize the large N supply following alfalfa. Furthermore, these data may help improve water quality and soil erosion modeling at regional and watershed scales, promote more in-depth investigation of N cycling and loss when alfalfa is followed by crops other than corn, and support calculation of locally relevant crop production costs. The methodology we developed also may prove useful for examining rotation patterns of other annual and perennial crops. Future work should seek to identify and understand the complex effects of environmental, economical, and sociological factors on crop rotation patterns over large production areas.

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REFERENCES

Barnett, K. 2006. Economics of alfalfa and corn silage rotations. Univ. of Wisconsin Ext., Madison, WI. http://fyi.uwex.edu/forage/files/2014/01/Alf-CornSil-RotationCOP.pdf (accessed 4 June 2014).

Bélanger, G., Y. Castonguay, A. Bertrand, C. Dhont, P. Rochette, L. Couture et al. 2006. Winter damage to perennial forage crops in eastern Canada: Causes, mitigation, and prediction. Can. J. Plant Sci. 86:33–47. doi:10.4141/P04-171

Bullock, D.G. 1992. Crop rotation. 1992. Crit. Rev. Plant Sci. 11:309–326. doi:10.1080/07352689209382349

Copeland, P.J., R.R. Allmaras, R.K. Crookston, and W.W. Nelson. 1993. Corn-soybean rotation effects on soil water depletion. Agron. J. 85:203–210 doi:10.2134/agronj1993.00021962008500020008x

Cosgrove, D.R., and M. Barrett. 1987. Effects of weed control in established alfalfa (*Medicago sativa*) on forage yield and quality. Weed Sci. 35:564–567.

Coulter, J.A., T.A. Delbridge, R.P. King, D.L. Allan, and C.C. Sheaffer. 2013. Productivity, economics, and soil quality in the Minnesota variable-input cropping systems trial. Crop Manage. www.crops.org/publications/cm/pdfs/12/1/2013-0429-03-RS (accessed 4 June 2014). doi:10.1094/CM-2013-0429-03-RS

Crookston, R.K., J.E. Kurle, P.J. Copeland, J.H. Ford, and W.E. Lueschen. 1991. Rotational cropping sequence affects yield of corn and soybean. Agron. J. 83:108–113. doi:10.2134/agronj1991.00021962008300010026x

DeFauw, S.L., R.P. Larkin, P.J. English, J.M. Halloran, and A.K. Hoshide. 2012. Geospatial evaluations of potato productions systems in Maine. Am. J. Potato Res. 89:471–488. doi:10.1007/s12230-012-9271-2

Entz, M.H., W.J. Bullied, D.A. Forster, R. Gulden, and J.K. Vessey. 2001. Extraction of subsoil nitrogen by alfalfa, alfalfa-wheat and perennial grass systems. Agron. J. 93:495–503. doi:10.2134/agronj2001.933495x

Entz, M.H., W.J. Bullied, and F. Katepa-Mupondwa. 1995. Rotational benefits of forage crops in Canadian prairie cropping systems. J. Prod. Agric. 8:521–529. doi:10.2134/jpa1995.0521

Hamza, M.A., and W.K. Anderson. 2005. Soil compaction in cropping systems: A review of the nature, causes and possible solutions. Soil Tillage Res. 82:121–145. doi:10.1016/j.still.2004.08.009

Hennessy, D.A. 2006. On monoculture and the structure of crop rotations. Am. J. Agric. Econ. 88:900–914. doi:10.1111/j.1467-8276.2006.00905.x

Huggins, D.R., G.W. Randall, and M.P. Russelle. 2001. Subsurface drain losses of water and nitrate following conversion of perennials to row crops. Agron. J. 93:477–486. doi:10.2134/agronj2001.933477x

Jeffrey, S.R., S. Mooney, and M.H. Entz. 1993. An economic analysis of including alfalfa in Manitoba cereal-legume rotations. Can. J. Plant Sci. 73:216.

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Kanwar, R.S., R.M. Cruse, M. Ghaffarzadeh, A. Bakhsh, D.L. Karlen, and T.B. Bailey. 2005. Corn-soybean and alternative cropping systems effects on NO_3–N leaching losses in subsurface drainage water. Appl. Eng. Agric. 21:181–188. doi:10.13031/2013.18151

Kelling, K.A., P.E. Speth, K. Kilian, T. Wood, and M. Mlynarek. 2002. Direct comparison of alfalfa nitrogen credits to corn and wheat. In: K.A. Kelling, editor, Proceedings of the Wisconsin Fertilizer, Aglime, and Pest Management Conference, Madison, WI. 15–17 Jan. 2002. Univ. of Wisconsin Ext., Madison. http://dev.soils.wisc.edu/extension/wcmc/2002proceedings/Kelling-2Conf-2002.pdf (accessed 4 June 2014).

Kelner, D.J., J.K. Vessey, and M.H. Entz. 1997. The nitrogen dynamics of 1-, 2-, and 3-year stands of alfalfa in a cropping system. Agric. Ecosys. Environ. 64:1–10. doi:/10.1016/j.bbr.2011.03.031.

MacEwan, D. 2012. Estimating crop rotations as dynamic cycles using georeferenced field data. Ph.D. thesis. Univ. of California, Davis.

Malhi, S.S., R. Lemke, and J.J. Schoenau. 2010. Influence of time and method of alfalfa stand termination on yield, seed quality, N uptake, soil properties and greenhouse gas emissions under different N fertility regimes. Nutr. Cycling Agroecosyst. 86:17–38. doi:10.1007/s10705-009-9271-x

Mallarino, A.P., and E. Ortiz-Torres. 2006. A long-term look at crop rotation effects on corn yield and response to nitrogen fertilization. In: B.A. Pringnitz, editor, Proceedings of the Integrated Crop Management Conference, Ames, IA. 29–30 Nov. 2006. Vol. 5. Iowa State Univ. Ext., Ames. p. 198–206.

Meek, B.D., D.L. Carter, D.T. Westermann, and R.E. Peckenpaugh. 1994. Root-zone mineral nitrogen changes as affected by crop sequence and tillage. Soil Sci. Soc. Am. J. 58:1464–1469. doi:10.2136/sssaj1994.03615995005800050027x

Olmstead, J., and E.C. Brummer. 2008. Benefits and barriers to perennial forage crops in Iowa corn and soybean rotations. Renewable Agric. Food Syst. 23:97–107. doi: 10.1017/S1742170507001937.

Ominski, P.D., M.H. Entz, and N. Kenkel. 1999. Weed suppression by *Medicago sativa* in subsequent cereal crops: A comparative survey. Weed Sci. 47:282–290.

Pikul, J.L., Jr., L. Hammack, and W.E. Riedell. 2005. Corn yield, nitrogen use, and corn rootworm infestation of rotations in the northern Corn Belt. Agron. J. 97:854–863. doi:10.2134/agronj2004.0263

Plourde, J.D., B.C. Pijanowski, and B.K. Pekin. 2013. Evidence for increased monoculture cropping in the central United States. Agric. Ecosyst. Environ. 165:50–59. doi:10.1016/j.agee.2012.11.011

Porter, P.M., D.R. Huggins, C.A. Perillo, S.R. Quiring, and R.K. Crookston. 2003. Organic and other management strategies with two- and four-year crop rotations in Minnesota. Agron. J. 95:233–244. doi:10.2134/agronj2003.0233

Raimbault, B.A., and T.J. Vyn. 1991. Crop rotation and tillage effects on corn growth and soil structural stability. Agron. J. 83:979–985. doi:10.2134/agronj1991.00021962008300060011x

Randall, G.W., D.R. Huggins, M.P. Russelle, D.J. Fuchs, W.W. Nelson, and J.L. Anderson. 1997. Nitrate losses through subsurface tile drainage in Conservation Reserve Program, alfalfa and row crop systems. J. Environ. Qual. 26:1240–1247. doi:10.2134/jeq1997.00472425002600050007x

Robbins, C.W., and D.L. Carter. 1980. Nitrate-nitrogen leached below the root zone during and following alfalfa. J. Environ. Qual. 9:447–450. doi:10.2134/jeq1980.00472425000900030026x

Russell, A.E., D.A. Laird, and A.P. Mallarino. 2006. Nitrogen fertilization and cropping system impacts on soil quality in midwestern Mollisols. Soil Sci. Soc. Am. J. 70:249–255. doi:10.2136/sssaj2005.0058

Salvagiotti, F., K.G. Cassman, J.E. Specht, D.T. Walters, A. Weiss, and A. Dobermann. 2008. Nitrogen uptake, fixation and response to fertilizer N in soybeans: A review. Field Crops Res. 108:1–13. doi:10.1016/j.fcr.2008.03.001

SAS Institute. 2006. The SAS system for Windows. Version 9.2. SAS Inst., Cary, NC.

Soil Survey Staff. 2011. Soil Survey Geographic (SSURGO) database. NRCS, Washington, DC. www.nrcs.usda.gov/wps/portal/nrcs/detail/national/soils/?cid=nrcs142p2_053631 (accessed 4 June 2014).

Stanger, T.F., and J.G. Lauer. 2008. Corn grain yield response to crop rotation and nitrogen over 35 years. Agron. J. 100:643–650. doi:10.2134/agronj2007.0280

Stern, A.J., P.C. Doraiswamy, and E.R. Hunt, Jr. 2012. Changes of crop rotation in Iowa determined from the United States Department of Agriculture, National Agriculture Statistics Service cropland data layer product. J. Appl. Remote Sens. 6:063590. doi:10.1117/1.JRS.6.063590

Stokes, M.E., C.S. Davis, and G.G. Koch. 2012. Categorical data analysis using SAS. 3rd ed. SAS Inst., Cary, NC.

Undersander, D., and K. Barnett. 2008. Value of short rotations for alfalfa profitability. Univ. of Wisconsin Ext., Madison. www.uwex.edu/ces/forage/pubs/short_rotations_for_alfalfa.pdf (accessed 4 June 2014).

Undersander, D., D. Cosgrove, E. Cullen, C. Grau, M.E. Rice, M. Renz et al. 2011. Alfalfa management guide. ASA, CSSA, and SSSA, Madison, WI.

USDA-National Agricultural Statistic Service. 2013a. Data and statistics-Quick Stats. USDA-NASS, Washington, DC. www.nass.usda.gov/Quick_Stats/ (accessed 4 June 2014).

USDA-National Agricultural Statistic Service. 2013b. Research and Development Division-Cropland-FAQ'S. USDA-NASS, Washington, DC. www.nass.usda.gov/research/Cropland/sarsfaqs2.html (accessed 4 June 2014).

USDA-National Agricultural Statistics Service Cropland Data Layer. 2006–2012. Published crop-specific data layer. USDA-NASS, Washington, DC. http://nassgeodata.gmu.edu/CropScape/ (accessed 4 June 2014).

Vough, L.R., and G.C. Marten. 1971. Influence of soil moisture and ambient temperature on yield and quality of alfalfa forage. Agron. J. 63:40–42. doi:10.2134/agronj1971.00021962006300010014x

Westermann, D.T., and S.E. Crothers. 1993. Nitrogen fertilization of wheat no-till planted in alfalfa stubble. J. Prod. Agric. 6:404–408. doi:10.2134/jpa1993.0404

Yost, M.A., J.A. Coulter, M.P. Russelle, and M.A. Davenport. 2014a. Opportunities exist to improve alfalfa and manure nitrogen crediting in corn following alfalfa. Agron J. 106 (in press). doi:10.2134/agronj14.0212

Yost, M.A., T.F. Morris, M.P. Russelle, and J.A. Coulter. 2014b. Second-year corn after alfalfa often requires no fertilizer nitrogen. Agron. J. 106:659–669. doi:10.2134/agronj2013.0362

Yost, M.A., M.P. Russelle, and J.A. Coulter. 2014c. Field-specific fertilizer nitrogen requirements for first-year corn following alfalfa. Agron. J. 106:645–658. doi:10.2134/agronj2013.0416

Zentner, R.P., C.A. Campbell, S.A. Brandt, K.E. Bowren, and E.D. Spratt. 1986. Economics of crop rotations in western Canada. In: A.E. Slinkard and D.B. Fowler, editors, Wheat production in Canada: A review. Proceedings Canada Wheat Production Symposium, Saskatoon, SK. 3–5 Mar. 1986. Div. of Ext. and Community Relations, Univ. of Saskatchewan, Saskatoon, SK, Canada. p. 254–317.

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Carbon-sink potential of continuous alfalfa agriculture lowered by short-term nitrous oxide emission events

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Alfalfa is the most widely grown forage crop worldwide and is thought to be a significant carbon sink due to high productivity, extensive root systems, and nitrogen-fixation. However, these conditions may increase nitrous oxide (N_2O) emissions thus lowering the climate change mitigation potential. We used a suite of long-term automated instrumentation and satellite imagery to quantify patterns and drivers of greenhouse gas fluxes in a continuous alfalfa agroecosystem in California. We show that this continuous alfalfa system was a large N_2O source (624 ± 28 mg N_2O m^2 y^{-1}), offsetting the ecosystem carbon (carbon dioxide (CO_2) and methane (CH_4)) sink by up to 14% annually. Short-term N_2O emissions events (i.e., hot moments) accounted for ≤1% of measurements but up to 57% of annual emissions. Seasonal and daily trends in rainfall and irrigation were the primary drivers of hot moments of N_2O emissions. Significant coherence between satellite-derived photosynthetic activity and N_2O fluxes suggested plant activity was an important driver of background emissions. Combined data show annual N_2O emissions can significantly lower the carbon-sink potential of continuous alfalfa agriculture.

Alfalfa (*Medicago sativa*), a nitrogen (N) fixing species, is the most widely grown perennial forage crop worldwide and the largest crop by land area in the Western United States[1,2]. Alfalfa is traditionally used as cattle feed and growth in alfalfa land area is largely driven by increasing global feed demand for dairy and other livestock production[3]. Soil N inputs from symbiotic N fixation[4] help support plant growth but may also be a source of nitrous oxide (N_2O) emissions from both nitrification and denitrification[5]. From a carbon (C) accounting perspective, alfalfa has been referred to as a climate-friendly feedstock due to its soil C sequestration potential as a deep-rooting, perennial plant and reduced N fertilizer inputs[6]. However, few studies have combined carbon dioxide (CO_2), methane (CH_4), and N_2O fluxes in the total net annual CO_2-equivalent (CO_2e) budgets of alfalfa agroecosystems. Continuous measurements are needed to assess the greenhouse gas emissions and net C balance of continuous alfalfa ecosystems as these are likely to differ from other agriculture practices that incorporate alfalfa in short-term rotations[7–9].

The biogeochemical processes that drive N_2O production are notorious for being temporally dynamic and characterized by hot moments of emissions, defined as short periods in time with fluxes significantly larger than the mean[5,10,11]. Thus short-term or infrequent sampling is likely to underestimate the role of hot moments in annual N_2O fluxes[12]. Alfalfa typically has a high water demand and is often irrigated throughout the growing season to maintain productivity[13]. Short periods of anaerobiosis following irrigation or rainfall events combined with soil N inputs can create ideal conditions for hot moments of N_2O production. Acidic conditions may exacerbate the effect as N_2O reductase is inhibited at low pH[5,14]. Oxygen (O_2) availability is an important control on N_2O production via nitrification and anaerobic denitrification[5]. Nitrous oxide production can also be

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limited by temperature, substrate C, nitrate (NO_3^-), or ammonium (NH_4^+) availability[15]. In soils, these variables are likely regulated by nonlinear asynchronous processes across temporal scales[5,16], requiring high frequency measurements to effectively characterize the controls on N_2O hot moments, and determine drivers of background (i.e., non-hot moment) N_2O fluxes.

The global warming potential of alfalfa agriculture is also affected by carbon dioxide (CO_2) and methane (CH_4) fluxes. Both CO_2 and CH_4 fluxes may be characterized by hot moments of soil emissions. Increased CO_2 respiration often occurs following soil rewetting[17–20] and these pulses can contribute a significant fraction of the annual CO_2 release, particularly in water-limited systems[19,21]. Heterotrophic respiration is thought to be directly regulated by substrate availability, primarily plant photosynthate[22], which can also stimulate the production and emissions of N_2O and CH_4[23,24]. For example, root exudates are well-known labile soil C sources that can prime microbial activity and associated pulses in soil respiration[25]. Up to 20% of C fixed by photosynthesis is released by root exudation that may occur as pulsed inputs[26,27]. Changes in plant productivity within and across years may also regulate greenhouse gas fluxes through impacts on other photosynthetic inputs such as plant litter[28,29]. Alfalfa is generally a net CH_4 sink via microbial CH_4 oxidation under well-drained conditions[6,30,31], but high rainfall events and irrigation can produce anaerobic conditions that can stimulate hot moments of methanogenesis[32]. Even with the potential for periodic CH_4 emissions and CO_2 pulses, long-term eddy covariance measurements of CO_2 and CH_4 suggest that alfalfa cropping systems can be net C sinks at an ecosystem scale[6,31]. However, continuous N_2O measurements are needed to determine the total CO_2e of soils emissions from alfalfa.

With the increasing agricultural demand for alfalfa, continuous long-term measurements of greenhouse gas fluxes are needed to better quantify the net climate impacts of alfalfa agroecosystems. It is also critical to determine the drivers of greenhouse gas emissions to better manage alfalfa for emissions reduction. We used a combined suite of automated flux chambers, continuous environmental sensing, eddy covariance, and satellite imagery of photosynthetic activity to determine patterns and associated controls of CO_2, N_2O, and CH_4 fluxes over four complete years in irrigated alfalfa. We used continuous cavity ring-down spectroscopy (CRDS) and automated chambers to collect over 103,000 individual N_2O, CH_4, and CO_2 flux measurements which were coupled with soil O_2, moisture, and temperature sensors installed across the soil profile and a year-long intensive weekly sampling campaign for soil gas (CO_2, N_2O, and CH_4), mineral N, and soil pH. We tested the hypothesis that the combination of mineral N availability and low redox conditions are the primary drivers of hot moments of N_2O emissions and that hot moments offset a significant portion of the net CO_2e sink. We predicted that low redox conditions would occur during irrigation and high rainfall events, particularly during warm periods as the solubility of O_2 decreases with increasing temperature[33]. We also hypothesized that background patterns in N_2O emissions would follow patterns in plant activity indicative of the potential impact of plants on C or substrate availability.

Results and discussion

Annual soil N_2O budgets and ecosystem CO_2e balance

Annual mean N_2O fluxes were 624.4 ± 26.8 mg N_2O m^{-2} yr^{-1} (Table 1, range: 247.0 ± 5.7 to 901.9 ± 74.5 mg N_2O m^{-2} yr^{-1}) and were similar to or greater than other N_2O flux estimates from alfalfa systems[7,34–37]. However, few studies report flux measurements from irrigated, continuous alfalfa monocultures[36,37], which make up the majority of alfalfa ecosystems in the Western United States[2,7,13,38]. Annual soil N_2O emissions were highest in site years 2 and 3 (Table 1, $p < 0.001$) and lowest in site year 4 ($p < 0.001$). The use of N-fixing crops as a means to reduce N fertilizer inputs to agroecosystems is expected to decrease overall N_2O agricultural emissions[39]. However, the mean N_2O fluxes observed here (4.0 ± 0.2 kg N-N_2O ha^{-1} y^{-1}) were equal to or higher than rates from fertilized agricultural ecosystems[40,41]. This suggests net N_2O emissions from irrigated alfalfa may not always be reduced relative to other agricultural ecosystems receiving inorganic N inputs, particularly on relatively C-rich soils.

Soil N_2O fluxes reduced the annual net CO_2e sink (sum of eddy covariance NEE and chamber N_2O and CH_4; Table 1) by up to 14% (mean: 8 ± 0.4%). The ecosystem was a consistent net CO_2e sink (mean: −450.4 ± 121.9 g CO_2e m^{-2} y^{-1}) when estimated using eddy covariance NEE observations and chamber observations of N_2O and CH_4 (Table 1). Annual global warming potential (GWP) values were significantly greater in years 3 and 4 than years 1 and 2, driven by significant increases in net ecosystem exchange (NEE) and lower N_2O fluxes in year 4 (Table 1). Annual CH_4 fluxes were a consistent CO_2e sink (mean: −1.5 ± 0.1 g CO_2e m^{-2} y^{-1}) but were always less than 0.5% of the annual net GWP.

The importance of N_2O hot moments

Inter- and intra-annual variability in N_2O fluxes were largely driven by differences in the magnitude and frequency of hot moments of N_2O production. Hot moments represented only 0.2 to 1.1% of annual N_2O measurements but contributed up to 57% (mean: 44.4 ± 6.3%) of total N_2O emissions (Table 2), highlighting the importance of continuous measurements for capturing high emission events and that continuous background fluxes (i.e., lower than hot moments) still represent a significant portion of the annual budget. The magnitude of hot moments decreased with stand age, and the contribution of hot moments to the annual flux also decreased over time (Fig. 1c, Table 2, $p < 0.001$). The decrease in the magnitude of hot moments of N_2O emissions over time may be partially explained by increased alfalfa taproot development with stand age. Nitrous oxide fluxes are generally expected to increase with alfalfa stand age[36], driven by increasing organic matter and N inputs from more developed root systems. However, irrigation frequency is likely to decrease in more established stands or in systems supported by subsurface irrigation or a shallow water table[42–44], which could lower N_2O fluxes[45]. A well-developed taproot system can maintain access to a deep-water table to support plant water demands, reducing drought stress[46,47] and the need for irrigation events that stimulate hot moments of N_2O emissions. The decreased contribution and magnitude of N_2O hot moments did not consistently correspond to decreases in annual emissions (Table 2). This may be due to increases in N_2O emissions associated with the accumulation and mineralization of residual alfalfa-derived organic matter[36]. Here we found that reduced irrigation frequency drove the observed decreases in hot moment emissions with stand age. However, these emissions reductions were partially offset by background (i.e., lower than hot moment) increases in N_2O production, which could have been derived from greater soil C and N availability.

Drivers of soil N_2O emissions

Acidic soil conditions were maintained throughout the year (Fig. 2c), creating a favorable pH environment for incomplete denitrification following decreases in soil O_2 availability[48]. These soils were relatively C-rich (5% soil C from 0–30 cm)[49], which may have also contributed to the higher observed N_2O emissions here[50], but newly mineralized alfalfa roots and shoots were likely an important soil NO_3^- source[51] and substrate for denitrification. We found that hot moments of N_2O production occurred following rapid increases in moisture and decreases in soil O_2 in warm surface soils; lower soil temperatures in winter appeared to limit hot moments of N_2O emission following rain events (Fig. 2). Summer hourly mean N_2O fluxes peaked in late afternoon (Fig. 3c, $p = 0.06$), within hours after the onset of irrigation events. However, short periods of irrigation did not always correspond to increased soil moisture at depths below 10 cm (Fig. 2). This could

Table 1 | Annual greenhouse gas emissions

Year	N_2O flux (mg N_2O m^{-2} y^{-1})	N_2O GWP (g CO_2e m^{-2} y^{-1})	CH_4 flux (mg CH_4 m^{-2} y^{-1})	CH_4 GWP (g CO_2e m^{-2} y^{-1})	Chamber CO_2 flux (g CO_2 m^{-2} y^{-1})	NEE (g CO_2 m^{-2} y^{-1})	Total CO_2e (g CO_2e m^{-2} y^{-1})	Eddy R_{eco} (g CO_2 m^{-2} y^{-1})	Eddy GPP (g CO_2 m^{-2} y^{-1})
1 (2017–2018)	610.5 ± 68.1 a	181.9 ± 20.3 a	−44.0 ± 2.2 ab	−1.2 ± 0.1 ab	5869.5 ± 31.4 a	−1757 ± 85 a	−1576.3 ± 105.4 a	6485 ± 25 a	8242 ± 96 a
2 (2018–2019)	901.9 ± 74.5 b	268.8 ± 22.2 b	−31.6 ± 2.5 a	−0.9 ± 0.1 a	4135.0 ± 25.4 d	−1989 ± 86 a	−1721.1 ± 108.3 a	6141 ± 22 b	8129 ± 96 a
3 (2019–2020)	777.1 ± 52.0 ab	231.6 ± 15.5 ab	−60.6 ± 2.8 b	−1.7 ± 0.1 b	5217.3 ± 23.9 b	−2942 ± 101 b	−2712.1 ± 116.6 b	6513 ± 27 a	9455 ± 113 b
4 (2020–2021)	263.6. ± 5.6 c	78.6 ± 1.7 c	−78.2 ± 8.8 c	−2.2 ± 0.2 c	4565.2 ± 26.5 c	−2632 ± 93 b	−2555.6 ± 94.9 b	6521 ± 24 a	9153 ± 103 b
All	624.4 ± 27.8	186.1 ± 8.3	−53.5 ± 2.5	−1.5 ± 0.1	4925.9 ± 13.5	−2330 ± 46	−2115.4 ± 54.4	6451 ± 12	8745 ± 51

Mean (± standard error) annual chamber nitrous oxide (N_2O), methane (CH_4), and carbon dioxide (CO_2) fluxes, 100-year global warming potential (GWP) of N_2O and CH_4 in CO_2-equivalence (CO_2e), eddy covariance annual mean net ecosystem exchange (NEE), and annual field-scale CO_2e emissions (combination of chamber N_2O and CH_4 fluxes and eddy covariance NEE) by site year. Net ecosystem exchange (NEE) was derived from ecosystem respiration (R_{eco}) and gross primary productivity (GPP) eddy-covariance measurements. Letters denote statistically significant differences among annual values ($p < 0.01$) with statistical results reported from one-way repeated measures ANOVAs.

Table 2 | N_2O fluxes

Year	Annual mean (mg N_2O m^{-2} y^{-1})	Flux (*n*)	Hot moment flux (*n*)	Hot moment mean (mg N_2O m^{-2} d^{-1})	Hot moments removed mean (mg N_2O m^{-2} y^{-1})	Hot moments % of total flux
1 (2017–2018)	610.5 ± 68.1	25,252	48	496.1 ± 66.8	263.4 ± 9.9	56.8%
2 (2018–2019)	901.9 ± 74.5	25,169	74	456.6 ± 43.0	402.4 ± 13.7	55.3%
3 (2019–2020)	777.1 ± 52.0	26,261	55	363.1 ± 46.2	485.7 ± 10.4	37.5%
4 (2020–2021)	263.6 ± 5.6	25,336	273	19.8 ± 0.7	180.39 ± 2.6	31.6%
All years	624.4 ± 27.8	103,013	201	401.1 ± 26.9	346.9 ± 4.7	44.4%

Mean (± standard error) annual nitrous oxide (N_2O) fluxes by site year, number of measurements, number of outlier measurements, outlier mean (± standard error) N_2O fluxes, mean N_2O fluxes (± standard error) without hot moments included, and contribution of hot moments to total mean flux. Hot moments were calculated separately for each year and in aggregate for the total dataset (All years).

indicate that the majority of N_2O production during hot moments occurred near the soil surface.

Soil N_2O fluxes were significantly greater in the summer and lowest in the fall (Fig. 3c, $p < 0.001$). Seasonal and diel trends in soil N_2O fluxes further emphasized the importance of soil moisture changes from irrigation and rainfall events. Mean hourly N_2O fluxes during summer periods, when most irrigation events occurred, were consistently greater than any other period (Fig. 3c, $p < 0.001$). Overall, daily mean N_2O fluxes were positively correlated with weekly soil atmosphere N_2O concentrations across depths, suggesting N_2O production across the soil profile contributed to background soil N_2O emissions (Supplementary Information, Fig. S1, 10 cm $R^2 = 0.60$, $p < 0.001$, 30 cm $R^2 = 0.53$, $p < 0.001$, 50 cm $R^2 = 0.45$, $p < 0.001$). Temporal patterns in soil moisture, soil temperature, and bulk soil O_2 concentrations covaried across all depths and were significantly related to patterns in net N_2O fluxes on a daily timescale (Fig. S2, $p < 0.05$). Primary interactions between N_2O and moisture, temperature, and O_2 suggested that changes in N_2O fluxes were generally in phase but lagged changes in these variables at daily and weekly timescales (Supplementary Information, Fig. S2, $p < 0.05$). At weekly and monthly timescales, N_2O fluxes were predominantly associated with soil temperature and moisture at 10 and 30 cm depths (Supplementary Information, Fig. S2, $p < 0.05$). Wavelet coherence analyses suggested that short-term, hot moments of N_2O emissions were stimulated by changes in moisture and O_2 concentrations in surface soils, as well as sustained acidic soil conditions. Acidic soil pH (Fig. 3) and lagged responses of temperature and moisture were the predominant controls at longer timescales (Supplementary Information, Fig. S2, $p < 0.05$).

Continuous low-magnitude N_2O production was an increasing fraction of total N_2O emissions over time (Table 2). In contrast to hot moments, consistent low magnitude N_2O fluxes were regulated by plant activity, soil moisture, and soil temperature throughout the soil profile. Increases in background (low magnitude) N_2O emissions were positively correlated with periods of high gross primary productivity (GPP), measured with satellite observations of near-infrared reflectance of vegetation (NIRv, Supplementary Information, Fig. S3, $p < 0.05$)[28]. Alfalfa releases a small proportion of its symbiotically-fixed N as NH_4^+ to the soil[52–54], and decreases in photosynthate supply to root nodules and exudates following shoot harvest may also limit C substrate availability to nitrifiers and denitrifiers[55]. While no relationships were observed between soil NO_3^- or NH_4^+ and N_2O emissions during our weekly sampling campaign (Fig. 2b, Supplementary Information), observed coherence at a daily timescale between NIRv and N_2O suggested plant-derived C or NH_4^+ availability may regulate low magnitude N_2O emissions. Plants likely shifted C and N allocation to new plant growth immediately after cutting, leading to lower soil N_2O emissions. Emissions increased over the growing season, possibly due to greater root exudation as aboveground plant biomass re-established.

Soil CH_4 emissions

Soils were a small consistent net sink of CH_4, accounting for only 0.06% of the total net C based-CO_2e uptake over the four year period. Annual mean soil CH_4 fluxes were −53.5 ± 2.5 mg CH_4 m^{-2} y^{-1} (Table 1, range: −78.2 ± 8.8 to −31.6 ± 2.5 mg CH_4 m^{-2} yr^{-1}). The net CH_4 sink was significantly greater in site year 4 than all other years (Table 1, $p < 0.001$). Sinks measured here were larger than others alfalfa ecosystem estimates[10,31,56], likely from the lower detection limit of the CRDS and automated chambers. In contrast to expectations, decreases in bulk soil O_2 concentrations did not appear to drive significant increases in net CH_4 production or decreases in the CH_4 sink (Fig. 1). Extended periods of soil anaerobiosis may be required to stimulate net CH_4 production[12,57], and this was not observed during the four year measurement period. We did observe a substantial increase in soil CH_4 concentrations (but not surface fluxes) shortly following the largest decrease in soil O_2 concentrations in March and April 2019 (Fig. 1, Supplementary Information, Fig. S8). Elevated soil moisture may have limited gas diffusion. Slower diffusion together with methanotrophic consumption near the soil surface likely regulated net soil CH_4 efflux during this period[58,59]. We also observed significant variability in hourly mean diel CH_4 fluxes (Fig. 3d), but this

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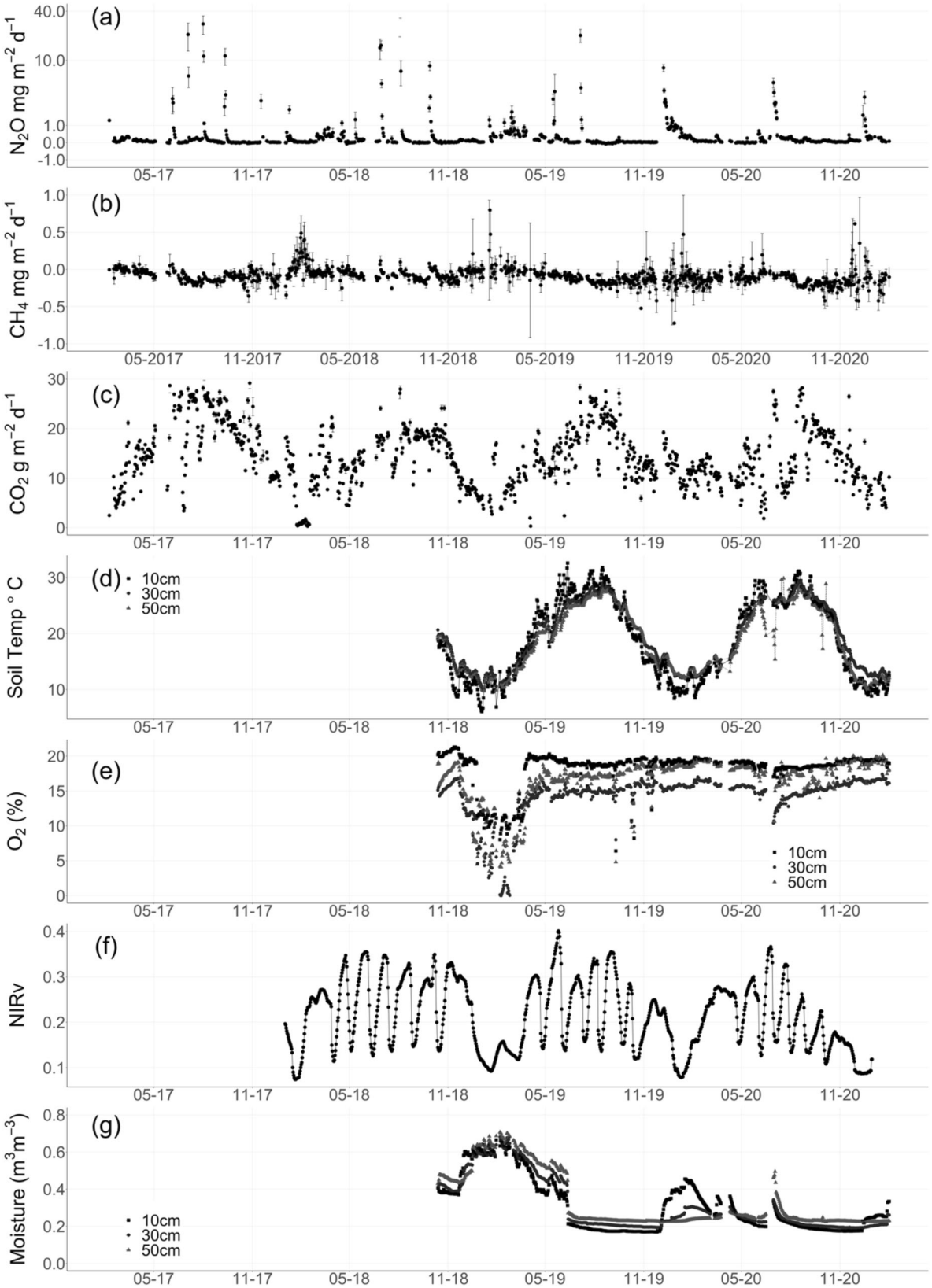


Fig. 1 | Greenhouse gas fluxes, soil sensing, and satellite imagery. Daily mean (± standard error) (**a**) carbon dioxide (g CO_2 m^{-2} d^{-1}), **b** methane (mg CH_4 m^{-2} d^{-1}), and **c** nitrous oxide (mg N_2O m^{-2} d^{-1}) fluxes (n = approximately 80 per day, with a total of 108,638, 103,013, and 102,997 flux measurements of CO_2, N_2O, and CH_4, respectively). Black circles represent mean daily flux measurements. Daily mean (± standard error) (**d**) soil temperature (°C), **e** soil oxygen (O_2), **f** daily near-infrared reflectance of vegetation (NIRv), and (**g**) volumetric soil moisture (m^3 m^{-3}) over the soil sensor measurement period and available daily satellite imagery (n = 96 measurements per day except for NIRv). For (**d**) soil temperature, (**e**) O_2, and (**g**) moisture, depth values are labeled as squares (10 cm), circles (30 cm), and triangles (50 cm).

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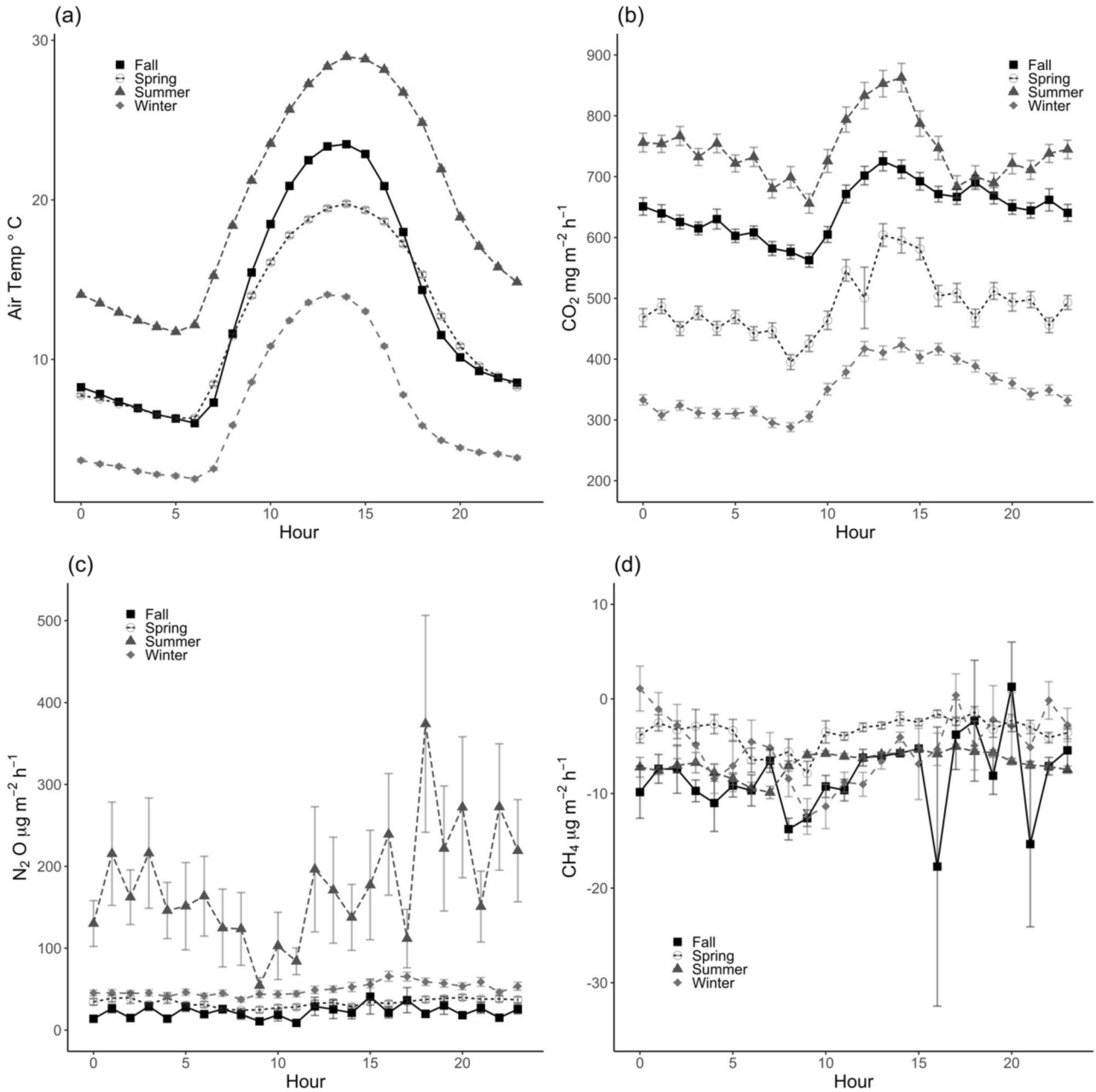


Fig. 2 | Diel greenhouse gas fluxes. Hourly mean (± standard error) (a) air temperature (°C), (**b**) carbon dioxide (CO_2)fluxes (mg CO_2 m^{-2} h^{-1}), (**c**) methane (CH_4) fluxes (µg CH_4 m^{-2} h^{-1}), and (**d**) nitrous oxide (N_2O) fluxes (µg N_2O m^{-2} h^{-1}), grouped by season (Fall = squares, Spring = open circles, Summer = triangles, and Winter = diamonds) over the entire measurement period (Fall: $n \geq 1220$ measurements per hour, Spring: $n \geq 848$ measurements per hour, Summer: $n \geq 956$ measurements per hour, Winter: $n \geq 1060$ measurements per hour).

variability was not significantly correlated with any measured soil characteristics.

Methane fluxes varied in response to temperature across depths and timescales and temperature was the strongest control on net CH_4 consumption (Supplementary Information, Fig. S4, $p < 0.05$). Decreases in soil moisture stimulated net CH_4 consumption (Supplementary Information, Fig. S4, $p < 0.05$), likely due to increased diffusivity[60,61] and O_2 availability. Periods of CH_4 uptake were highest in the late summer, occurring when soils were the driest throughout the soil profile (Fig. 1a, c). Lower soil moisture across the soil profile also generally corresponded to higher rates of CH_4 uptake and lower overall soil moisture increased CH_4 uptake with stand age, except for site year 2 (Table 1). Sustained CH_4 consumption combined with observed trends in N cycling suggest that CH_4 oxidation by nitrifiers or nitrification by methanotrophs[62–65] could be regulating non-CO_2 greenhouse gas production and consumption under oxic conditions.

Agroecosystem CO_2 balance

Soil CO_2 emissions were greater than other alfalfa ecosystems[6], likely driven by a combination of high plant productivity, relatively high soil C content[49], and warm temperatures throughout the growing season. Chamber CO_2 fluxes, which here represent combined soil and root respiration, averaged 4925.9 ± 13.5 g CO_2 m^{-2} yr^{-1} and were lower than ecosystem respiration (R_{eco}) estimates (6451 ± 12 g CO_2 m^{-2} yr^{-1}) from the nearby eddy covariance observations (Table 1). Soil CO_2 fluxes closely followed seasonal patterns in soil temperature, with similar trends in soil temperature observed across depths (Fig. 1a, b). Surprisingly, soil CO_2 fluxes did not vary significantly with NIRv on

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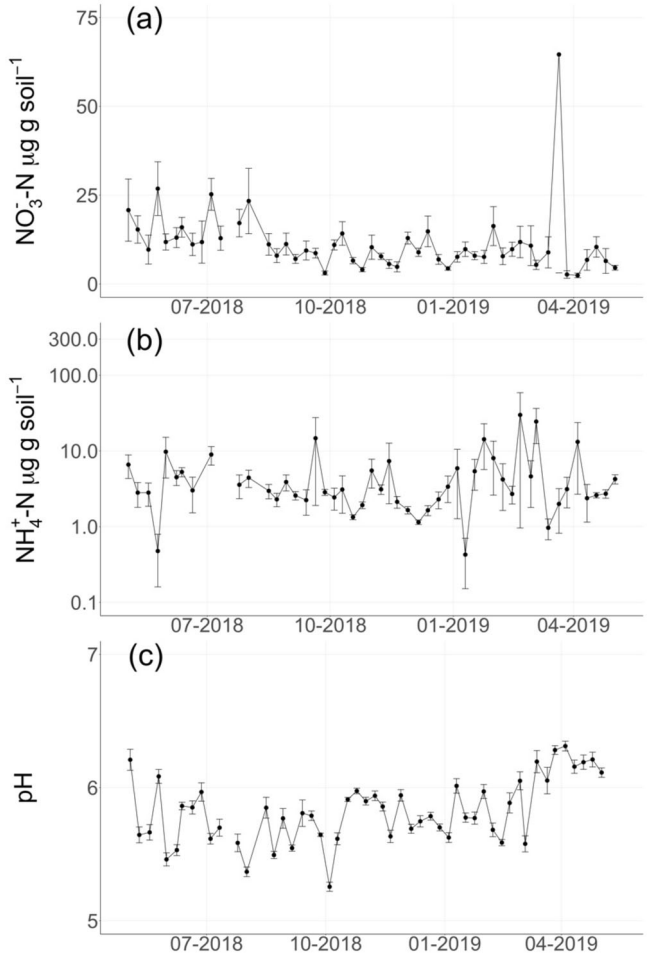


Fig. 3 | Weekly soil nitrogen and pH. Weekly mean (± standard error) (**a**) soil nitrate (µg NO_3^--N g soil^{-1}), **b** soil ammonium (µg NH_4^+-N g soil^{-1}), and **c** soil pH ($n = 10$ per week for 52 weeks). Manual soil measurements (0–10 cm depth) were conducted weekly from May 2018–May 2019.

a daily scale (Supplementary Information, Fig. S3, $p < 0.05$). Soil CO_2 fluxes and NIRv covaried on weekly, monthly, and annual timescales highlighting the importance of plant harvesting and phenology in regulating soil respiration[28].

To quantify for C removed from the field, we used mean annual yields of 595 ± 137 g C m^{-2} y^{-1} or 2,072 ± 502 g CO_2 m^{-2} y^{-1} [31]. This is equivalent to 89% of NEE, with the remaining C (258.3 g CO_2 m^{-2} y^{-1} or 70.4 CO_2 m^{-2} y^{-1}) assumed to be stored as belowground biomass or soil C. With this number, the CO_2e of N_2O emissions would then offset 70% of the net CO_2 sink. The fate of harvested C was not considered in this study, which examined only ecosystem-scale fluxes. However, it should be noted that if conducting a life cycle analysis, harvested alfalfa is typically used as dairy or cattle feed, where alfalfa C is converted to a combination of both CO_2 and CH_4[66].

We observed significant differences in NIRv following alfalfa cutting events (Fig. 1c) and mean annual NIRv decreased significantly across the measurement period (Table 3, $p < 0.01$). Lags observed between NIRv and soil CO_2 fluxes may represent a delayed response to photosynthate availability as plants likely reallocate new photosynthate to aboveground biomass production following harvest events[67]. Alfalfa in this region can be harvested up to seven times per year, where the majority of aboveground plant biomass is removed[28,31]. Cuttings corresponded to significant reductions in mean daily soil respiration values, although soil respiration values typically recovered

Table 3 | Moisture, rainfall, and NIRv

Year	Mean 0-50 cm Soil Moisture (%)	Rainfall (mm y^{-1})	NIRv
1 (2017-2018)	–	444 a	–
2 (2018-2019)	47.8 ± 7.8 b*	356 ab	0.23 ± 0.01 a
3 (2019-2020)	35.3 ± 17.1 a	447 a	0.21 ± 0.01 b
4 (2020-2021)	24.3 ± 4.3 c	176 b	0.19 ± 0.01 c
All	31.5 ± 14	331 ± 64	0.21 ± 0.01

Annual mean (± standard error) 0–50 cm soil moisture ($n = 96$ measurements per day for 763 total days), annual rainfall (mm y^{-1}), and mean (± standard error) annual near-infrared reflectance of vegetation (NIRv) by site year (e.g., January 27 to January 26, $n = 365$ per year).
*Site year 2 soil moisture values include 5 out of 12 months. Letters denote significant differences between annual values ($p < 0.01$) with statistical results reported from one-way repeated measures ANOVAs.

within 5 to 7 days (Fig. 1a). Periods of increased plant growth rates following harvests likely resulted in a shift in C allocation from below- to aboveground[68] and highlights the importance of substrate limitation on NEE[29]. If aboveground regrowth increases plant nutrient demands, it could induce a lagged response in belowground respiration driven by subsequent reallocation of photosynthate belowground followed by enhanced soil nutrient mining by microbial communities[69]. The observed lagged relationships between NIRv and ecosystem greenhouse gas fluxes may also represent delays between photosynthetic CO_2 uptake and root C exudation processes. Short-term increases in soil moisture content and associated decreases in O_2 availability throughout the year were also important controls on soil respiration (Supplementary Information, Fig. S5, $p < 0.05$). Soil temperature across depths was significantly associated with respiration rates across timescales.

This combination of automated chambers, eddy covariance, soil sensing, and satellite imagery used here provided a comprehensive dataset of multi-year, annual, ecosystem-scale fluxes from a continuous alfalfa agroecosystem. We were able to determine the importance of both short-term hot moments and background emissions on total greenhouse gas budgets and explore scale-emergent drivers of N_2O emissions. We found that N_2O emissions reduced the net CO_2e sink at the ecosystem-scale by up to 14% annually and offset 70% of the ecosystem C sink after accounting for harvest biomass removal (post-harvest fate of harvested alfalfa was not included in this calculation). As hypothesized, this was predominantly driven by rare hot moments of soil N_2O emissions supplied by elevated soil NO_3^- pools and acidic soil conditions and stimulated by irrigation and rainfall events. Hot moments were ≤1% of measurements but averaged 44.4 ± 6.3% of annual N_2O fluxes. Additionally, background fluxes were likely driven by sustained substrate availability that varied with moisture, temperature, and NIRv, a possible index of plant inputs to soil. Lagged relationships between NIRv, CO_2, and N_2O fluxes suggested that plant inputs were likely an important driver of soil CO_2 fluxes and background N_2O emissions. Our results show that N_2O emissions likely significantly lower the field-scale C sink potential of this globally important crop. Hot moments of N_2O emissions, typically underestimated with traditional measurement approaches, played an outsized role in annual ecosystem-scale greenhouse gas budgets, highlighting the importance of continuous measurement for accurate ecosystem-scale greenhouse gas accounting.

Methods

Site info

The study was conducted in the Sacramento-San Joaquin Delta region of California, USA (38.11°N, 121.5°W). The site was in conventional perennial alfalfa (>5 years) that was periodically flood-irrigated during the growing season. The site was located on highly degraded

peatland soils that have lost a significant proportion of their initial organic matter[49]. Alfalfa and corn are the dominant agricultural land uses in the region, with alfalfa representing 20% of agricultural land area (32,000 ha) in the Sacramento-San Joaquin Delta[70] and the largest crop by area in California (405,000 ha)[71]. Nearly 100% of alfalfa in California is irrigated, with flood irrigation being the most common practice[71]. The site had a Mediterranean climate with hot dry summers and cool wet winters. The region's historical mean annual temperature was 15.1 ± 6.3 °C and a mean annual rainfall averaging 326 ± 4 mm[23]. Site year (January 27 - January 26) rainfall data was collected from a nearby (<1 km) Ameriflux site[72]. Near-infrared reflectance of vegetation (NIRv), a metric for canopy photosynthetic activity[28], was calculated from daily 3 m resolution normalized difference vegetation index (NDVI) and near-infrared radiation (NIR) was collected from Planet Labs satellite imagery[73–75]. Near-infrared reflectance of vegetation was also used as a proxy for plant inputs to soils given that up to 20% of C fixed by photosynthesis is released by root exudation[26,27].

Ryde is the major soil series found under alfalfa in the region, and is widespread across the Sacramento San Joaquin-Delta and along the central coast of California[76]. Ryde soils belong to the fine-loamy, mixed, superactive, thermic Cumulic Endoaquolls taxonomic class and are very deep, poorly drained soils formed in alluvium from mixed rock sources and decomposed vegetative matter[76]. Total soil C concentrations (mean ± standard error) were 5.26 ± 0.02% at 0–15 cm, 5.00 ± 0.15% at 15–30 cm, and 1.99 ± 0.09% at 30–60 cm[49]. Total soil *N* concentrations were 0.38 ± 0.003% at 0–15 cm, 0.35 ± 0.01% at 15–30 cm, and 0.16 ± 0.01% at 30–60 cm[49].

Automated chamber measurements

Surface fluxes of N_2O, CH_4, and CO_2 were measured continuously from January 2017 to February 2021 using an automated chamber system. The system consisted of nine opaque, automated gas flux chambers (eosAC, Eosense, Nova Scotia, Canada) connected to a multiplexer (eosMX, Eosense, Nova Scotia, Canada). The multiplexer allowed for dynamically signaled chamber deployment and routed gases to a cavity ring-down spectrometer (Picarro G2508, Santa Clara, CA, USA). Chambers were measured sequentially over a 10-min sampling period with a 1.5-min flushing period before and after each measurement.

Chambers were deployed in a 10 × 10 m grid design, with each chamber approximately 5 m from other chambers. Extended 15 cm soil collars were utilized to maintain measurement collection and ensure chambers were not inundated during irrigation or high rainfall events. Chambers were randomly assigned to either plant rows ($n = 5$) or inter-plant areas of bare soil ($n = 4$). Chambers remained in their original positions throughout the field campaign, except for short periods (<3 days) during field management activities (e.g., harvest, winter grazing). Foliage near chambers were minimally trimmed as needed between harvests if it inhibited chamber closure.

To determine chamber volume, chamber collar heights were measured approximately weekly and interpolated between measurements to account for changes in chamber height over time. Chamber volumes were also used to calculate the minimum detectable flux of 0.002 nmol N_2O m^{-2} s^{-1}, 0.06 nmol CO_2 m^{-2} s^{-1}, and 0.002 nmol CH_4 m^{-2} s^{-1} [77]. The minimum detectable fluxes reported here are conservative estimates, as the actual chamber volume was always smaller than the maximum theoretical volume used to calculate these values.

Flux calculations and analyses were first performed using Eosense eosAnalyze-AC v. 3.7.7 software, then data quality assessment and control were subsequently performed in R (RStudio, v.1.1.4633)[78]. Fluxes were removed from the final dataset if they were associated with erroneous spectrometer cavity temperature or pressure readings or if any gas concentrations were negative, corresponding to instrument malfunction. Fluxes were also removed if the chamber deployment period was less than 9 min or greater than 11 min, indicative of chamber malfunction. Calculated linear and exponential fluxes were compared using estimate uncertainty to estimate ratios, and in cases where both the linear and exponential models produced high uncertainty, the individual flux was eliminated from the dataset. Data filtering removed 2.1% of flux measurement periods, generating a final dataset of 108,638, 103,013, and 102,997 simultaneous flux measurements of CO_2, N_2O, and CH_4, respectively. Following data filtering, all statistical analyses were performed using JMP Pro 15 (SAS Institute Inc., Cary, NC). Differences in site year, hourly, and seasonal mean flux values were analyzed with one-way ANOVAs followed by post-hoc Tukey tests. Values reported in the text are means ± standard errors unless otherwise noted.

To quantify site-level CO_2 uptake[49] and calculate site-level global warming potential (GWP) we utilized annual net ecosystem exchange (NEE) estimates from a nearby (<1 km) Ameriflux tower[72] in alfalfa grown with identical management practices and soil type. Here we used the eddy covariance technique[79] to capture continuous, long-term exchange of CO_2, CH_4, H_2O, and energy fluxes between the landscape and the atmosphere, along with measurements of environmental drivers[80]. Fluxes were measured at a frequency of 20 Hz using open-path infrared gas analyzers (LI-7500 for CO_2 and H_2O, LI-7700 for CH_4, LiCOR Inc., Lincoln, NE, USA) that were calibrated at least every 6 months. Sonic anemometers measured sonic temperature and three-dimensional wind speed at 20 Hz (WindMaster Pro 1590, Gill Instruments Ltd, Lymington, Hampshire, England). To convert N_2O and CH_4 flux measurements to CO_2e, we used the IPCC AR5 100-year GWP values of 28 CO_2e for CH_4 and 298 CO_2e for N_2O[81].

Quantifying hot moments of greenhouse gas emissions

This large, continuous dataset allowed us to quantify N_2O hot moments and their impact on total N_2O emissions. Following data filtering, the quantity and magnitude of hot moment measurements and their impact on annual flux estimates were determined. We defined hot moments as flux measurements with values greater than four standard deviations from the mean[12], as statistically 99.9% of the population should fall within four standard deviations of the mean. Yearly mean flux values were then calculated for only hot moment fluxes, the entire flux dataset, and the flux dataset with hot moment observations removed to determine the impact of outlier fluxes on annual greenhouse gas emissions. Given our large and continuous dataset, we could also compare mean fluxes with and without high flux events[12,82] to better quantify the importance of hot moments.

Weekly soil measurements

Weekly soil samples (0–15 cm depth, $n = 10$ $week^{-1}$) were randomly collected with a 6 cm diameter soil auger within 30 m of the chamber array from April 2018 to May 2019. Soil samples were analyzed for gravimetric soil moisture, soil pH, and 2 M potassium chloride (KCl) extractable nitrate (NO_3^-) plus nitrite (NO_2^-) and ammonium (NH_4^+). For KCl extracts, we utilized a 5:1 ratio of 2 M KCl volume to oven dry equivalent (ODE) soil that were shaken for 1 h and subsequently filtered with Whatman Grade 1 filter paper[83]. The KCl extracts were then analyzed colorimetrically for NH_4^+ and NO_3^- using an AQ300 analyzer (Seal Instruments, Mequon, WI). Soil moisture was determined gravimetrically by drying 10 g of field-fresh soil to a constant weight at 105 °C. Soil pH was measured in a slurry of 10 g of field-fresh soil in 10 mL of distilled deionized water[84].

Soil sensor measurements

Two sets of soil sensors were installed from September 2018-February 2021 at depths of 10 cm, 30 cm, and 50 cm. This included SO-110 oxygen (O_2) and soil temperature sensors (Apogee Instruments,

Logan, UT) and CS616 moisture sensors (Campbell Scientific, Logan, UT) connected to a CR1000 datalogger (Campbell Scientific, Logan, UT) storing data at 15 min intervals. Sensors remained installed throughout the year. Erroneous data corresponding to sensor malfunction were removed from the dataset, which included 1.7% of soil moisture measurements and 3.4% of soil O_2 measurements. In total, there were 73 of 839 days missing during the soil sensor measurement period.

Weekly soil depth gas samples

Two replicate soil gas samples were taken for CO_2, CH_4, and N_2O at 10 cm, 30 cm, and 50 cm depths weekly from September 2018 to December 2019. Instrument grade stainless steel 1/8" tubing (Restek, Bellefonte, PA) was installed in parallel to the soil sensors above, with approximately 15 cm of tubing installed with multiple sampling holes parallel to the soil surface. Sampling septa (Restek, Bellefonte, PA) were installed in 1/8" Swagelok union (Swagelok, Solon, OH) permanently connected to the stainless-steel tubing. Septa were changed monthly. Gas samples were collected weekly with 30 ml BD syringes after first clearing the tubing dead volume. Short periods of soil inundation following extensive rainfall (March-April 2019) made it impossible to collect gas samples from some depths. Samples were stored in over-pressurized 20 ml glass vials with thick septa (Geomicrobial Technologies, Oechelata, OK) until manual sample injection analysis on a Shimadzu GC-34 (Shimadzu Corp., Tokyo, Japan). Generalized pairwise regression analyses were used to explore the relationships between measured soil atmosphere CO_2, CH_4, and N_2O concentrations and surface soil CO_2, CH_4, and N_2O fluxes.

Wavelet coherence analysis

Wavelet coherence analysis was used to identify interactions between soil greenhouse gas fluxes, NIRv, and the soil variables (O_2, moisture, and temperature at 10, 30, and 50 cm) measured[12,85,86]. Wavelet coherence is a tool for comparing time series and is used to determine significance, causality and scale-emergent interactions between variables[16,80,87]. Wavelet coherence measures the cross-correlation between time series and allowed us to explore relationships between greenhouse gas fluxes and potential controls of NIRv, O_2, moisture, and temperature at daily, monthly, and annual timescales. Wavelet coherence is derived from two time series as a function of decomposed frequency (Wave.xy) and the wavelet power spectrum (Power.x, Power.y) of each individual time series:

$$\text{Coherence} = \frac{|\text{Wave}.xy|^2}{\text{Power}.x \cdot \text{Power}.y} \quad (1)$$

This approach allows for continuous wavelet-based analysis of univariate and bivariate time series, facilitating comparisons of time series data across scales, leads, and lags[86,88]. Missing data were replaced with zeroes to compute an unbiased estimator of the wavelet variance for time series with missing observations[86,89]. Statistical significance (p-value) was computed using 1000 Monte Carlo simulations. All wavelet decomposition and coherence calculations were conducted using the WaveletComp 1.1 R package[88].

Reporting summary

Further information on research design is available in the Nature Portfolio Reporting Summary linked to this article.

Data availability

The daily mean greenhouse gas fluxes (chamber CO_2, CH_4, N_2O, and eddy covariance CO_2), satellite-derived vegetation indices (NIRv), soil gas concentrations, and soil O_2, temperature, and moisture sensor data generated in this study and used to create the figures have been deposited the Dryad database: https://doi.org/10.6078/D1ZQ53.

Code availability

The corresponding R code used in this study have been deposited in the Dryad database: https://doi.org/10.6078/D1ZQ53.

References

1. Yang, S. et al. Alfalfa benefits from Medicago truncatula: The RCT1 gene from M. truncatula confers broad-spectrum resistance to anthracnose in alfalfa. *Proc. Natl Acad. Sci. USA* **105**, 12164–12169 (2008).
2. Ottman, M. et al. Long term trends and the future of the alfalfa and forage industry. *Proc. 2013 Western Alfalfa & Forage Symposium, Reno, NV, 11-13, December, 2013. UC Cooperative Extension, Plant Sciences Department, University of California, Davis, CA 95616*. 11–13 (2013).
3. Wang, Q., Hansen, J. & Xu, F. China's emerging dairy markets and potential impacts on U.S. alfalfa and dairy product exports. *Clim. Change 2013 Phys. Sci. Basis* **53**, 1–30 (2013).
4. Peterson, T. A. & Russelle, M. P. Alfalfa and the nitrogen cycle in the Corn Belt. *J. Soil Water Conserv.* **46**, 229 LP–229235 (1991).
5. Butterbach-Bahl, K., Baggs, E. M., Dannenmann, M., Kiese, R. & Zechmeister-Boltenstern, S. Nitrous oxide emissions from soils: how well do we understand the processes and their controls? *Philos. Trans. R. Soc. Lond. B Biol. Sci.* **368**, 20130122 (2013).
6. Alberti, G. et al. Changes in CO2 emissions after crop conversion from continuous maize to alfalfa. *Agric. Ecosyst. Environ.* **136**, 139–147 (2010).
7. Tenuta, M., Amiro, B. D., Gao, X., Wagner-Riddle, C. & Gervais, M. Agricultural management practices and environmental drivers of nitrous oxide emissions over a decade for an annual and an annual-perennial crop rotation. *Agric. For. Meteorol.* **276–277**, 107636 (2019).
8. Drury, C. F. et al. Diverse rotations impact microbial processes, seasonality and overall nitrous oxide emissions from soils. *Soil Sci. Soc. Am. J.* **85**, 1448–1464 (2021).
9. Johnson, J. M. F., Weyers, S. L., Archer, D. W. & Barbour, N. W. Nitrous oxide, methane emission, and yield-scaled emission from organically and conventionally managed systems. *Soil Sci. Soc. Am. J.* **76**, 1347–1357 (2012).
10. Savage, K., Phillips, R. & Davidson, E. High temporal frequency measurements of greenhouse gas emissions from soils. *Biogeosciences* **11**, 2709–2720 (2014).
11. Firestone, M. K. & Davidson, E. A. Microbiologial basis of NO and N2O production and consumption in soil. *Exch. Trace Gas. Terr. Ecosyst. Atmos.* 7–21 https://doi.org/10.1017/CBO9781107415324.004 (1989).
12. Anthony, T. L. & Silver, W. L. Hot moments drive extreme nitrous oxide and methane emissions from agricultural peatlands. *Glob. Chang. Biol.* 15802. https://doi.org/10.1111/gcb.15802 (2021).
13. Bauder, J. W., Jacobsen, J. S. & Lanier, W. T. Alfalfa emergence and survival response to irrigation water quality and soil series. *Soil Sci. Soc. Am. J.* **56**, 890–896 (1992).
14. Davidson, E. A., Keller, M., Erickson, H. E., Verchot, L. V. & Veldkamp, E. Testing a conceptual model of soil emissions of nitrous and nitric oxides. *BioScience* **50**, 667 (2000).
15. Giles, M., Morley, N., Baggs, E. M. & Daniell, T. J. Soil nitrate reducing processes - Drivers, mechanisms for spatial variation, and significance for nitrous oxide production. *Front. Microbiol.* **3**, 1–16 (2012).
16. Sturtevant, C. et al. Identifying scale-emergent, nonlinear, asynchronous processes of wetland methane exchange. *J. Geophys. Res. Biogeosci.* 188–204. https://doi.org/10.1002/2015JG003054. Received (2016).

17. Borken, W. & Matzner, E. Reappraisal of drying and wetting effects on C and N mineralization and fluxes in soils. *Glob. Chang. Biol.* **15**, 808–824 (2009).
18. Canarini, A., Kiær, L. P. & Dijkstra, F. A. Soil carbon loss regulated by drought intensity and available substrate: a meta-analysis. *Soil Biol. Biochem.* **112**, 90–99 (2017).
19. Kim, D. G., Vargas, R., Bond-Lamberty, B. & Turetsky, M. R. Effects of soil rewetting and thawing on soil gas fluxes: a review of current literature and suggestions for future research. *Biogeosciences* **9**, 2459–2483 (2012).
20. Barnard, R. L., Blazewicz, S. J. & Firestone, M. K. Rewetting of soil: revisiting the origin of soil CO2 emissions. *Soil Biol. Biochem.* **147**, 107819 (2020).
21. Leon, E. et al. Hot spots, hot moments, and spatio-temporal controls on soil CO2efflux in a water-limited ecosystem. *Soil Biol. Biochem.* **77**, 12–21 (2014).
22. Davidson, E. A., Janssens, I. A. & Lou, Y. On the variability of respiration in terrestrial ecosystems: moving beyond Q10. *Glob. Chang. Biol.* **12**, 154–164 (2006).
23. Hatala, J. A. et al. Greenhouse gas (CO2, CH4, H2O) fluxes from drained and flooded agricultural peatlands in the Sacramento-San Joaquin Delta. *Agric. Ecosyst. Environ.* **150**, 1–18 (2012).
24. Keane, B. J. et al. Greenhouse gas emissions from the energy crop oilseed rape (Brassica napus); the role of photosynthetically active radiation in diurnal N2O flux variation. *GCB Bioenergy* **10**, 306–319 (2018).
25. Panchal, P., Preece, C., Peñuelas, J. & Giri, J. Soil carbon sequestration by root exudates. *Trends Plant Sci.* **27**, 749–757 (2022).
26. Guyonnet, J. P., Cantarel, A. A. M., Simon, L. & Haichar, F. E. Z. Root exudation rate as functional trait involved in plant nutrient-use strategy classification. *Ecol. Evol.* **8**, 8573–8581 (2018).
27. Haichar, F. et al. Plant host habitat and root exudates shape soil bacterial community structure. *ISME J.* **2**, 1221–1230 (2008).
28. Baldocchi, D. D. et al. Outgoing near-infrared radiation from vegetation scales with canopy photosynthesis across a spectrum of function, structure, physiological capacity, and weather. *J. Geophys. Res. Biogeosci.* **125**, e2019JG005534 (2020).
29. Oikawa, P. Y. et al. Evaluation of a hierarchy of models reveals importance of substrate limitation for predicting carbon dioxide and methane exchange in restored wetlands. *J. Geophys. Res. Biogeosci.* **122**, 145–167 (2017).
30. Serrano-Silva, N., Sarria-Guzmàn, Y., Dendooven, L. & Luna-Guido, M. Methanogenesis and methanotrophy in soil: a review. *Pedosphere* **24**, 291–307 (2014).
31. Hemes, K. S. et al. Assessing the carbon and climate benefit of restoring degraded agricultural peat soils to managed wetlands. *Agric. For. Meteorol.* **268**, 202–214 (2019).
32. Sapkota, A., Haghverdi, A., Avila, C. C. E. & Ying, S. C. Irrigation and greenhouse gas emissions: a review of field-based studies. *Soil Syst.* **4**, 20 (2020).
33. Speight, J. G. 5 - Sources of water pollution. in *Natural Water Remediation* (ed. Speight, J. G.) 165–198 (Butterworth-Heinemann, 2020). https://doi.org/10.1016/B978-0-12-803810-9.00005-X.
34. Rochette, P. et al. Emissions of N_2O from alfalfa and soybean crops in Eastern Canada. *Soil Sci. Soc. Am. J.* **68**, 493–506 (2004).
35. Wagner-Riddle, C., Thurtell, G. W., Kidd, G. K., Beauchamp, E. G. & Sweetman, R. Estimates of nitrous oxide emissions from agricultural fields over 28 months. *Can. J. Soil Sci.* **77**, 135–144 (1997).
36. Burger, M., Haden, V. R., Chen, H., Six, J. & Horwath, W. R. Stand age affects emissions of N2O in flood-irrigated alfalfa: a comparison of field measurements, DNDC model simulations and IPCC Tier 1 estimates. *Nutr. Cycl. Agroecosyst.* **106**, 335–345 (2016).
37. Mosier, A. R., Halvorson, A. D., Peterson, G. A., Robertson, G. P. & Sherrod, L. Measurement of net global warming potential in three agroecosystems. *Nutr. Cycl. Agroecosyst.* **72**, 67–76 (2005).
38. Deng, J. et al. Changes in irrigation practices likely mitigate nitrous oxide emissions from California cropland. *Glob. Biogeochem. Cycles* **32**, 1514–1527 (2018).
39. Syakila, A. & Kroeze, C. The global nitrous oxide budget revisited. *Greenh. Gas Meas. Manag.* **1**, 17–26 (2011).
40. Robertson, G. P., Paul, E. A. & Harwood, R. R. Greenhouse gases in intensive agriculture: contributions of individual gases to the radiative forcing of the atmosphere. *Science* **289**, 1922–1925 (2000).
41. Snyder, C. S., Bruulsema, T. W., Jensen, T. L. & Fixen, P. E. Review of greenhouse gas emissions from crop production systems and fertilizer management effects. *Agric. Ecosyst. Environ.* **133**, 247–266 (2009).
42. Shouse, P. J., Ayars, J. E. & Šimůnek, J. Simulating root water uptake from a shallow saline groundwater resource. *Agric. Water Manag.* **98**, 784–790 (2011).
43. Kandelous, M. M. et al. Evaluation of subsurface drip irrigation design and management parameters for alfalfa. *Agric. Water Manag.* **109**, 81–93 (2012).
44. Noory, H., Liaghat, A. M., Chaichi, M. R. & Parsinejad, M. Effects of water table management on soil salinity and alfalfa yield in a semi-arid climate. *Irrig. Sci.* **27**, 401–407 (2009).
45. Orchard, V. A. & Cook, F. J. Relationship between soil respiration and soil moisture. *Soil Biol. Biochem.* **15**, 447–453 (1983).
46. Moran, J. F. et al. Drought induces oxidative stress in pea plants. *Planta* **194**, 346–352 (1994).
47. Tang, L. et al. Overexpression of GsZFP1 enhances salt and drought tolerance in transgenic alfalfa (Medicago sativa L.). *Plant Physiol. Biochem.* **71**, 22–30 (2013).
48. Shaaban, M. et al. Reduction in soil N2O emissions by pH manipulation and enhanced nosZ gene transcription under different water regimes. *Environm. Poll.* **235**, 625–631 (2018).
49. Anthony, T. L. & Silver, W. L. Mineralogical associations with soil carbon in managed wetland soils. *Glob. Chang Biol.* **26**, 6555–6567 (2020).
50. Krichels, A. H. & Yang, W. H. Dynamic controls on field-scale soil nitrous oxide hot spots and hot moments across a microtopographic gradient. *J. Geophys. Res. Biogeosci.* **124**, 3618–3634 (2019).
51. Kavdır, Y., Rasse, D. P. & Smucker, A. J. M. Specific contributions of decaying alfalfa roots to nitrate leaching in a Kalamazoo loam soil. *Agric. Ecosys. Environ.* **109**, 97–106 (2005).
52. Burity, H. A., Ta, T. C., Faris, M. A. & Coulman, B. E. Estimation of nitrogen fixation and transfer from alfalfa to associated grasses in mixed swards under field conditions. *Plant Soil* **114**, 249–255 (1989).
53. Thilakarathna, M. S., McElroy, M. S., Chapagain, T., Papadopoulos, Y. A. & Raizada, M. N. Belowground nitrogen transfer from legumes to non-legumes under managed herbaceous cropping systems. A review. *Agron. Sustain. Dev.* **36**, 1–16 (2016).
54. Brophy, L. S. & Heichel, G. H. Nitrogen release from roots of alfalfa and soybean grown in sand culture. *Plant Soil* **116**, 77–84 (1989).
55. Erice, G. et al. Photosynthesis, N2 fixation and taproot reserves during the cutting regrowth cycle of alfalfa under elevated CO2 and temperature. *J. Plant Physiol.* **168**, 2007–2014 (2011).
56. Ning, J. et al. Optimizing alfalfa productivity and persistence versus greenhouse gases fluxes in a continental arid region. *PeerJ* **2020**, 1–19 (2020).
57. Conrad, R. Soil microorganisms as controllers of atmospheric trace gases (H2, CO, CH4, OCS, N2O, and NO). *Microbiol. Rev.* **60**, 609–640 (1996).
58. Kammann, C., Hepp, S., Lenhart, K. & Müller, C. Stimulation of methane consumption by endogenous CH4 production in aerobic grassland soil. *Soil Biol. Biochem.* **41**, 622–629 (2009).

59. Bender, M. & Conrad, R. Methane oxidation activity in various soils and freshwater sediments: Occurrence, characteristics, vertical profiles, and distribution on grain size fractions. *J. Geophys. Res.* **99**, 16531 (1994).
60. Min, K. et al. Differential effects of wetting and drying on soil CO2 concentration and flux in near-surface vs. deep soil layers. *Biogeochemistry* **7**, 255–269 (2020).
61. Von Fischer, J. C., Butters, G., Duchateau, P. C., Thelwell, R. J. & Siller, R. In situ measures of methanotroph activity in upland soils: A reaction diffusion model and field observation of water stress. *J. Geophys. Res. Biogeosci.* **114**, 1–12 (2009).
62. O'neill, J. G. & Wilkinson, J. F. Oxidation of ammonia by methane-oxidizing bacteria and the effects of ammonia on methane oxidation. *Microbiology* **100**, 407–412 (1977).
63. Yoshinari, T. Nitrite and nitrous oxide production by Methylosinus trichosporium. *Can. J. Microbiol.* **31**, 139–144 (1985).
64. Jones, R. D. & Morita, R. Y. Methane oxidation by Nitrosococcus oceanus and Nitrosomonas europaea. *Appl. Environ. Microbiol.* **45**, 401–410 (1983).
65. Ward, B. B. Kinetic studies on ammonia and methane oxidation by Nitrosococcus oceanus. *Arch. Microbiol.* **147**, 126–133 (1987).
66. Hassanat, F., Gervais, R., Massé, D. I., Petit, H. V. & Benchaar, C. Methane production, nutrient digestion, ruminal fermentation, N balance, and milk production of cows fed timothy silage- or alfalfa silage-based diets. *J. Dairy Sci.* **97**, 6463–6474 (2014).
67. Schmitt, A., Pausch, J. & Kuzyakov, Y. C and N allocation in soil under ryegrass and alfalfa estimated by 13C and 15N labelling. *Plant Soil* **368**, 581–590 (2013).
68. Schmitt, A., Pausch, J. & Kuzyakov, Y. Effect of clipping and shading on C allocation and fluxes in soil under ryegrass and alfalfa estimated by 14C labelling. *Appl. Soil Ecol.* **64**, 228–236 (2013).
69. Lambers, H., Raven, J. A., Shaver, G. R. & Smith, S. E. Plant nutrient-acquisition strategies change with soil age. *Trends Ecol. Evol.* **23**, 95–103 (2008).
70. The Delta Protection Commission. The State of Delta Agriculture: Economic Impact, Conservation and Trends. (2020).
71. Putnam, D. H., Summers, C. G. Orloff, S. B. Alfalfa production systems in California. in *Irrigated alfalfa management for Mediterranean and Desert zones* (University of California Agriculture and Natural Resources, 2007).
72. Camilo, R.-S., Szutu, D., Baldocchi, D. & Hemes, K. meriFlux BASE US-Bi2 Bouldin Island corn, Ver. 13-5, AmeriFlux AMP, (Dataset). https://doi.org/10.17190/AMF/1419513 (2021).
73. PlanetTeam. Planet Application Program Interface: In *Space for Life on Earth*. https://api.planet.com (2021).
74. Houborg, R. & McCabe, M. F. High-Resolution NDVI from planet's constellation of earth observing nano-satellites: a new data source for precision agriculture. *Remote Sens.* **8**, 768 (2016).
75. Kong, J. et al. Matching high resolution satellite data and flux tower footprints improves their agreement in photosynthesis estimates. *Agric. For. Meteorol.* **316**, 108878 (2022).
76. Soil Survey Staff. Natural Resources Conservation Service, United States Department of Agriculture. *Official Soil Series Descriptions*. (2020). Available at: https://www.nrcs.usda.gov/resources/data-and-reports/web-soil-survey#citation. Accessed [June/08/2020].
77. Nickerson, N. Evaluating gas emission measurements using Minimum Detectable Flux (MDF). *White Paper* (2016).
78. O'Connell, C. S., Ruan, L. & Silver, W. L. Drought drives rapid shifts in tropical rainforest soil biogeochemistry and greenhouse gas emissions. *Nat. Commun.* **9**, 1348 (2018).
79. Baldocchi, D. D., Hicks, B. B. & Meyers, T. P. Measuring biosphere-atmosphere exchanges of biologically related gases with micrometeorological methods. *Ecology* **69**, 1331–1340 (1988).
80. Eichelmann, E. et al. The effect of land cover type and structure on evapotranspiration from agricultural and wetland sites in the Sacramento/San Joaquin River Delta, California. *Agric. For. Meteorol.* **256–257**, 179–195 (2018).
81. Myhre, G. et al. Anthropogenic and natural radiative forcing. *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* 659–740 https://doi.org/10.1017/CBO9781107415324.018 (2013).
82. Benhadi-Marín, J. A conceptual framework to deal with outliers in ecology. *Biodivers. Conserv.* **27**, 3295–3300 (2018).
83. Hart, S. C., Stark, J. M., Davidson, E. A. & Firestone, M. K. Nitrogen mineralization, immobilization, and nitrification. in *Methods of Soil Analysis, Part 2. Microbial and Biochemical Properties* (eds. Weaver, R. W., Angle, J. S. & Bottomley, P. S.) 985–1018 (Soil Science Society of America, 1994).
84. McLean, E. O. Soil pH and Lime Requirement. in *Page, A.L., Ed., Methods of Soil Analysis. Part 2. Chemical and Microbiological Properties, American Society of Agronomy, Soil Science Society of America, Madison*, 199–224 (1982).
85. Liu, P. C. Wavelet spectrum analysis and ocean wind waves. in *Wavelets in Geophysics* (eds. Foufoula-Georgiou, E. & Kumar, P. B. T.-W. A. and I. A.) vol. **4** 151–166 (Academic Press, 1994).
86. Wood, T. E., Detto, M. & Silver, W. L. Sensitivity of soil respiration to variability in soil moisture and temperature in a humid tropical forest. *PLoS One* **8**, e80965 (2013).
87. Rodríguez-Murillo, J. C. & Filella, M. Significance and causality in continuous wavelet and wavelet coherence spectra applied to hydrological time series. *Hydrology* **7**, 82 (2020).
88. Rösch, A. & Schmidbauer, H. WaveletComp: Computational Wavelet Analysis. R package version 1.1. 1–38 (2018).
89. Mondal, D. & Percival, D. B. Wavelet variance analysis for gappy time series. *Ann. Inst. Stat. Math.* **62**, 943–966 (2010).

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Author contributions

T.L.A. wrote the original draft and created the visualizations, W.L.S. and D.D.B. conducted reviews and editing of the original draft, T.L.A. and W.L.S. conceptualized the paper, T.L.A., W.L.S., D.D.B., J.G.V., and D.J.S. contributed to the methodology and data investigation.

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The authors declare no competing interests.

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Power Profiler

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How clean is the electricity you use?

In the United States, electricity is generated in many different ways, with a wide variation in environmental impact. Electricity generation from the combustion of fossil fuels contributes toward unhealthy air quality, acid rain, and global climate change.

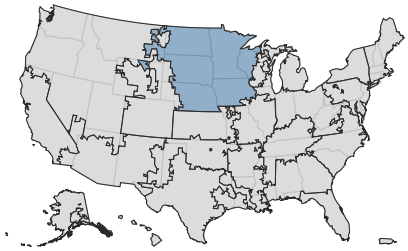
Many electricity customers can choose their provider of electricity or can purchase green power from their utility. In fact, you might now have the option of choosing cleaner, more environmentally-friendly sources of energy.

To compare the fuel mix (i.e., resource mix) and air emission rates of the electricity in your region to the national average and to determine the air emissions that result from electricity use in your home or business, either select the appropriate eGRID subregion or enter your ZIP code to determine the appropriate eGRID subregion.

Power Profiler does not provide information about the environmental attributes of electric power generated by individual companies. For company-specific information, access EPA's eGRID database <https://epa.gov/egrid>.

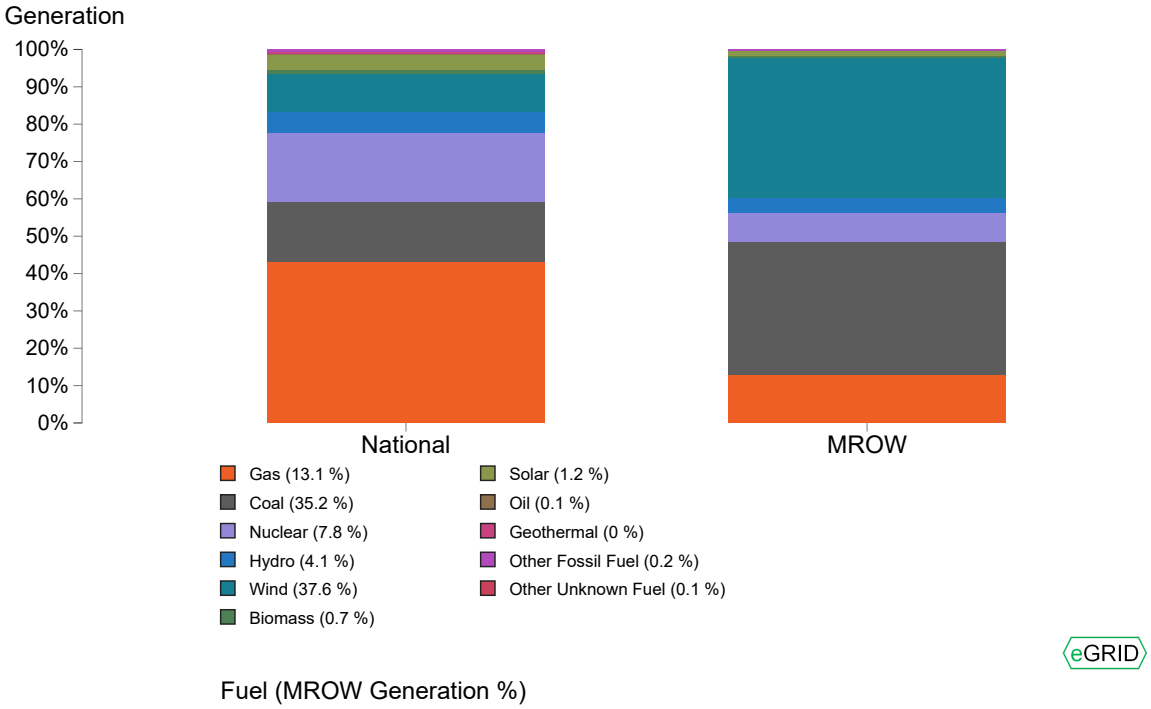
MROW Emission Rates

CO2: 920.1 lbs/MWh SO2: 0.896 lbs/MWh NOx: 0.711 lbs/MWh



Fuel Mix

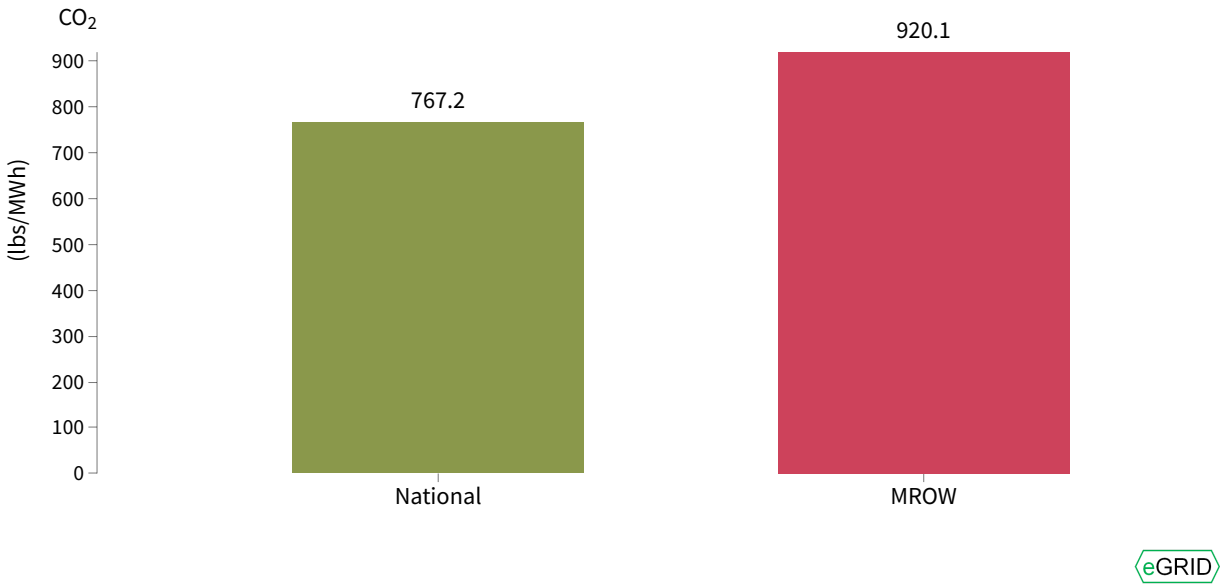
This chart compares fuel mix (%) of sources used to generate electricity in the selected eGRID subregion <https://www.epa.gov/system/files/images/2024-05/egrid-subregion-map.png> to the national fuel mix (%).



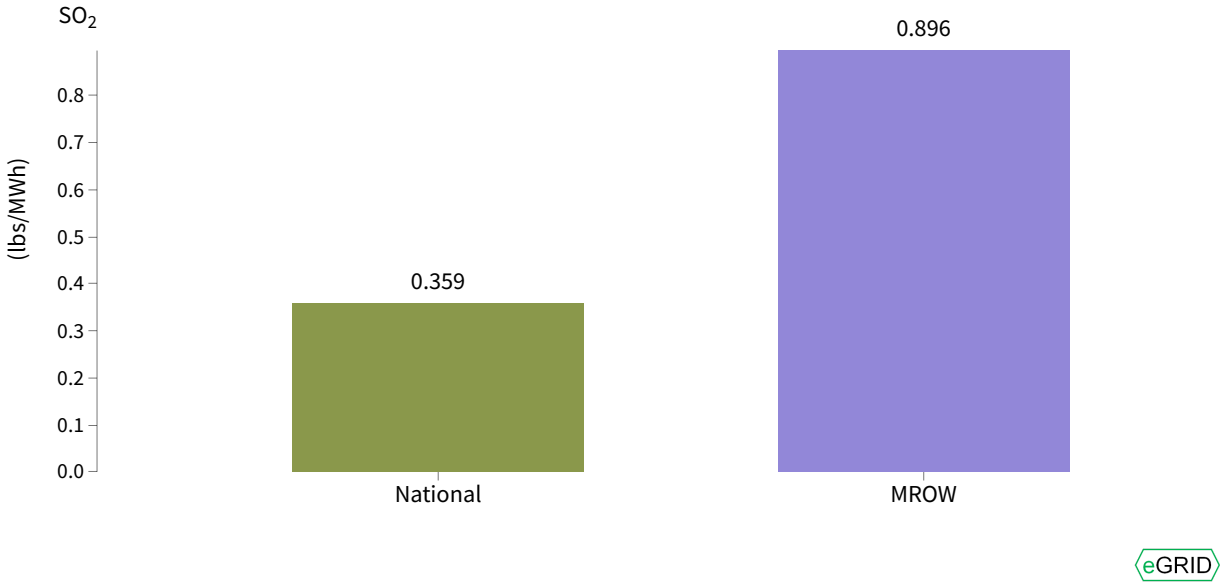
eGRID

Fuel (MROW Generation %)

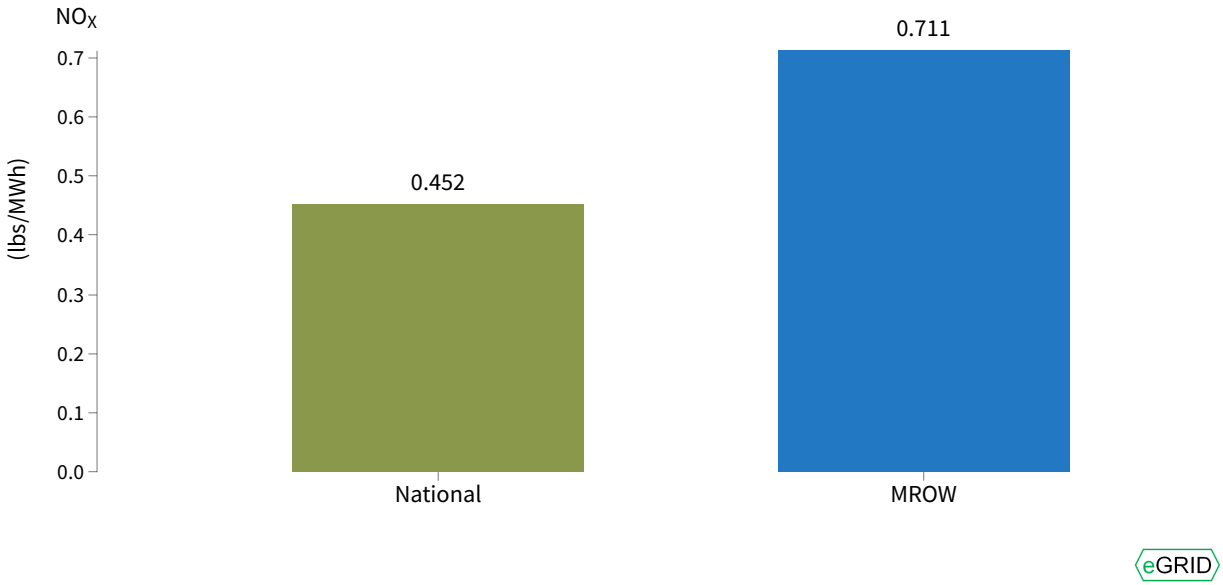
Emission Rates



eGRID



eGRID


NOX
(lbs/MWh)
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
0.452
0.711
National
MROW
eGRID

Contact Us About eGRID <https://epa.gov/egrid/forms/contact-us-about-egrid> to ask a question, provide feedback, or report a problem.

Last updated on October 1, 2025

RMI

Roadmap for Distributed Green Ammonia in Minnesota



Report / June 2024

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RMI is an independent nonprofit, founded in 1982 as Rocky Mountain Institute, that transforms global energy systems through market-driven solutions to align with a 1.5°C future and secure a clean, prosperous, zero-carbon future for all. We work in the world's most critical geographies and engage businesses, policymakers, communities, and NGOs to identify and scale energy system interventions that will cut climate pollution at least 50 percent by 2030. RMI has offices in Basalt and Boulder, Colorado; New York City; Oakland, California; Washington, D.C.; Abuja, Nigeria; and Beijing.

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Introduction

Ammonia (NH_3) accounts for over 1% of global greenhouse gas (GHG) emissions, and with a production scale of around 185 million tons per annum (tpa), it is an essential commodity in fertilizer production and contributor to climate change.[1] Ammonia production is currently concentrated in low-cost natural gas and coal regions such as the US Gulf, China, and Russia. Present-day ammonia supply chains involve complex, multistep processes spanning thousands of miles, as production is often far removed from consumption. During periods of low fossil fuel prices and efficient transportation by ship, pipeline, and truck, the existing supply chain structure adequately ensures fertilizer production, purchase, and application in the quantities needed. However, the stability of such supply chains and low pricing are not guaranteed. Geopolitical factors and extreme weather events have exposed the vulnerabilities of the current centralized system and fossil fuel dependence of existing supply chains, all of which directly affect fertilizer consumers.

Russia's invasion of Ukraine highlighted several weaknesses of highly centralized fertilizer supply chains and natural gas–based production processes. The war disrupted both ammonia and natural gas production, resulting in limited supply and elevated prices. Reduced supply of natural gas from Russia led to high-priced domestic natural gas feedstocks in Europe and the United States. Because natural gas is a primary feedstock for ammonia production, high natural gas prices drove ammonia to cost points producers could not justify, reducing ammonia supply by 70% in Europe and more than tripling prices in the immediate aftermath of the Russian invasion to over \$1,600/tNH_3 from the historic market average of \$516/tNH_3 in the United States.[2]

The compounding challenges of high carbon intensity, centralized production, and feedstock price variability suggest the need for a complementary ammonia production system that is founded on a low-carbon, decentralized processes — that is, distributed green ammonia (DGA) deployed near consumption centers.



In the United States, Minnesota is a prime candidate for initiating the inaugural wave of distributed ammonia projects. The state is a major consumer of fertilizer, yet Minnesota's agricultural sector faces higher fertilizer costs compared with the national average due to higher transportation costs. This underscores the urgency and potential positive impact of localized ammonia production. Minnesota has also demonstrated robust policy backing with dedicated grants for localized fertilizer production, setting the stage for innovative ventures in the ammonia sector. With these factors in alignment, Minnesota stands poised to spearhead the advancement of distributed ammonia projects, heralding a paradigm shift in the Midwest and, potentially, in other regions of the United States.

This roadmap for advancing DGA in Minnesota focuses on the decarbonization of ammonia production and the direct application of ammonia as a fertilizer in the state. There are significant emissions associated with the use of fertilizers, but that issue is beyond the scope of this report. This roadmap includes an evaluation of business models, techno-economic dynamics, and necessary policy frameworks essential for translating these aspirations into actionable projects in Minnesota, a state that well understands the benefits of local, carbon-free fertilizer production. Key analytical elements include:

- Assessment of the enabling environment of Minnesota, including a high-level market analysis, demand profile, emissions intensity, renewable energy capacity and potential, techno-economic analysis, and available policy support

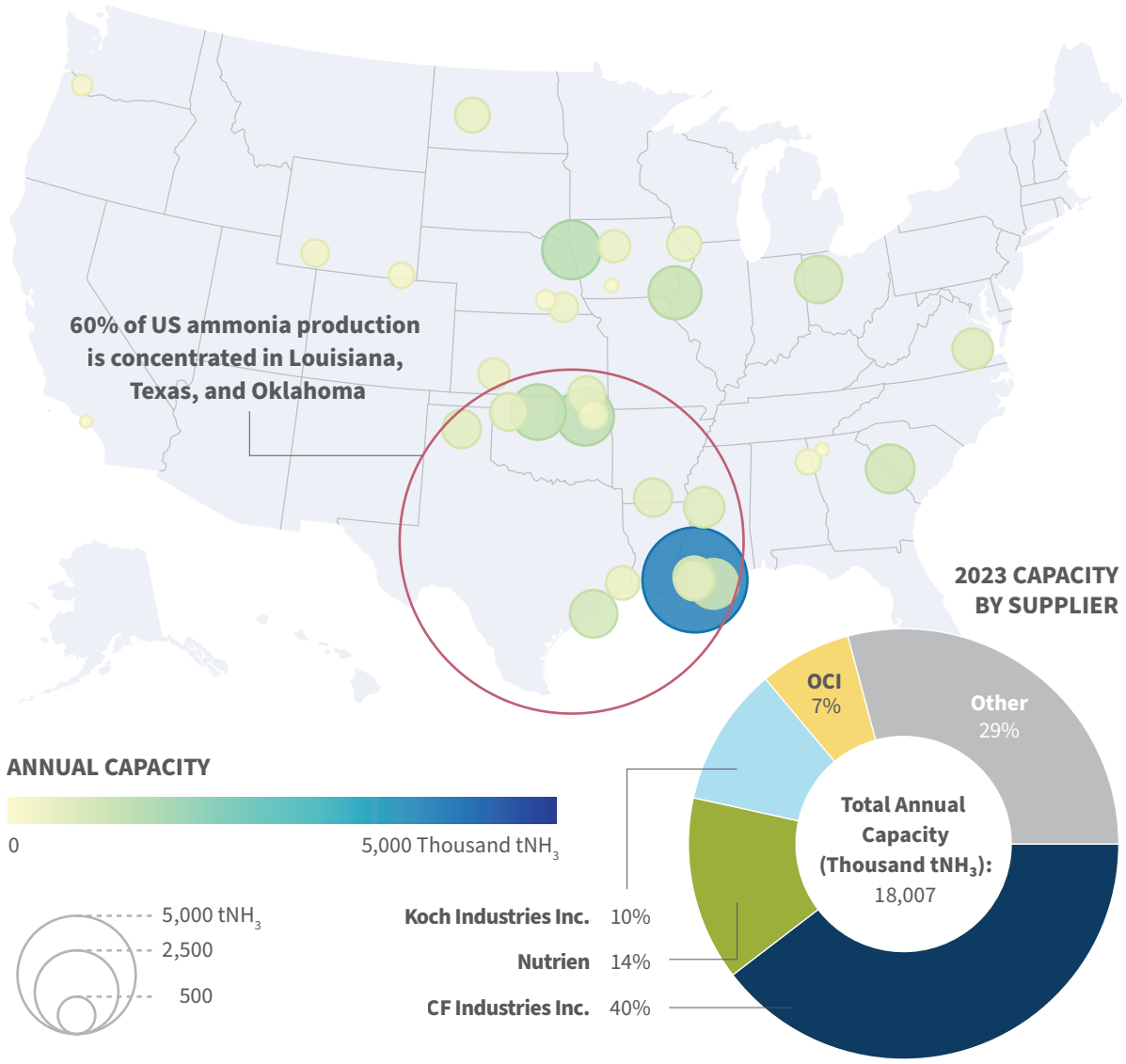
- Engagement with key stakeholders in Minnesota's low-carbon fertilizer space, including state agencies, financial institutions, nonprofit organizations, project developers, and original equipment manufacturers (OEMs), through bilateral conversations and focus-group discussions

- Formulation of targets and a suggested implementation strategy for DGA through emissions reduction goals, business model proposals, and policy recommendations

The US Fertilizer Market

In the United States, domestic production of ammonia is dominated by 17 manufacturers and is geographically centralized within the Gulf Coast region due to the strategic access to natural gas reserves and well-established pipeline infrastructure. Three major ammonia producers, CF Industries, Nutrien, and Koch Industries, provide 64% of the entire domestic ammonia supply, with the majority of their ammonia manufacturing plants concentrated in Louisiana, Oklahoma, and Texas (see Exhibit 1).[3]

Exhibit 1 Ammonia Production Capacity Profile by Location and Company



RMI Graphic. Source: RMI analysis; Nutrien, **https://nutrien-prod-asset.s3.us-east-2.amazonaws.com/s3fs-public/uploads/2024-01/Nutrien_2023Fact%20Book_Update_12624.pdf**

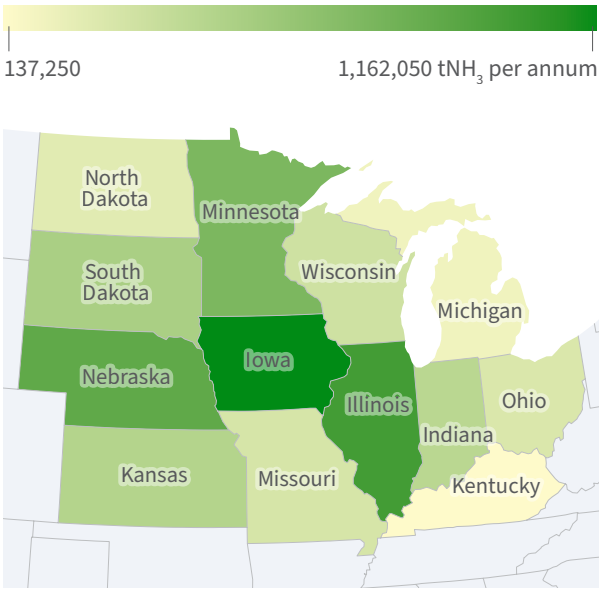
With approximately 80% of US ammonia consumption going to agricultural fertilizers, farms in the Midwest represent the primary consumption hub, with corn driving roughly 50% of all US agricultural ammonia demand. Minnesota is the fourth highest-consuming state of ammonia fertilizer, driving over 10% of market demand, yet no ammonia production facilities are located in the state (see Exhibit 2).

Minnesota, along with many other Midwestern states, relies on ammonia transported from the Gulf through a complex network encompassing pipelines, barges, railways, and trucks, facilitated by market intermediaries ranging from logistics and distribution entities to wholesalers, agricultural retailers, integrated distributors, and cooperatives (see Exhibit 3).

The existing market structure, while serving as the backbone of fertilizer distribution in Minnesota and the broader Midwest region, falls short in ensuring consistent stability regarding both fertilizer prices and volumes of fertilizer.

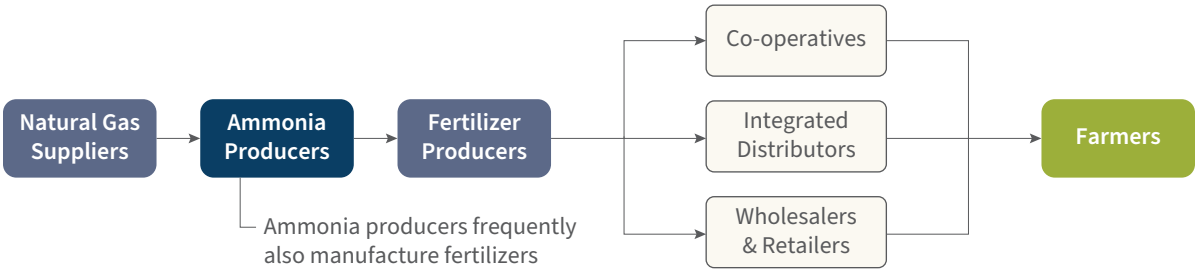
Exhibit 2

Ammonia Demand in the US Midwest for Corn Crops



RMI Graphic. Source: RMI analysis; USDA, **https://downloads.usda.library.cornell.edu/usda-esmis/files/j098zb09z/0z70b374s/w9506686w/acrg0622.pdf**

Exhibit 3 Illustrative Fertilizer Market Structure



RMI Graphic. Source: RMI adaption from DOE, **https://liftoff.energy.gov/wp-content/uploads/2023/12/20230921-Pathways-to-Commercial-Liftoff-Chemicals-Refining.pdf**

Distributed Green Ammonia Opportunity

DGA can address the challenges of the current fertilizer market. DGA shortens supply chains so that production is located more closely to ammonia consumption and shifts feedstocks away from natural gas–based feedstocks toward renewable electricity, increasing certainty of supply and price stability for consumers.

Technology Profile of Distributed Green Ammonia

A new wave of technology that efficiently and economically produces ammonia at scales far smaller than traditional ammonia plants creates an opportunity to shift fertilizer production toward a distributed business model. Conventional ammonia synthesis processes have seen significant cost reductions in scaling up production volumes. Consequently, most units are sized to produce 100,000 to more than 1 million tpa.

New production processes, deriving from the Haber-Bosch (HB) process,[i] employ technology with different operational and design advantages that forgo the need to upsize plants to reduce production costs. Regional-scale systems slightly modify the traditional integrated ammonia synthesis plant to optimize for production up to 100,000 tpa, whereas single-farm systems rely on novel, modular containerized style units for easily replicable construction and standardizable mass production, best for production scales up to 3,500 tpa (see Exhibit 4, next page). These new ammonia production technologies can be specifically tailored to meet the needs of off-takers. They are well suited for the demand of a single, large US farm, which needs at most 3,500 tpa,[ii] and up to the scale of an agricultural cooperative, which needs between 3,500 and 100,000 tpa.

Commercial maturity for these newer ammonia production systems is low, but technological maturity is generally high, depending on the specific process considered. Although there are alternative ammonia production methods that have yet to achieve full technology readiness levels (TRLs), this report focuses primarily on TRL 9 technologies that are derived from the Haber-Bosch process.

Deployment of DGA projects is necessary to take full advantage of learning curves, especially for modular systems, as cost-effectiveness is achieved with increased technology installation. Developing DGA projects will only reinforce cost reduction and technological de-risking, creating a positive feedback loop of falling costs. Projects must overcome the challenges associated with first-of-a-kind project development, but once projects get off the ground, DGA can offer broad benefits to consumers, local communities, developers, and financiers over incumbent ammonia production technology and business models.

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i Haber-Bosch refers to the conventional, industrial ammonia synthesis process where hydrogen and nitrogen are combined at a high pressure and high temperature.

ii The 3,500 tpa amount is based on stakeholder engagement and average use volume.

Exhibit 4 Different Scales of Ammonia Production, with Examples of Current Green Ammonia Projects



H2F

Iberdrola and Fertiberia in Puertollano, Spain

- 100 MW solar PV, 5 MW battery storage, 20 MW PEM electrolysis, and 11 high-pressure hydrogen storage tanks
- In operation since 2022, H2F produces **17,000 mtpa of green ammonia** at its neighboring plant

NEOM Green Hydrogen Complex

NEOM, ACWA Power and Air Products in Saudi Arabia

- 4 GW of solar power, 650 mtpd of hydrogen, saving over 3 million tpa of CO_2
- In construction and scheduled to come online in 2025, producing **1.2 million tpa of green ammonia**

RMI Graphic. Source: RMI analysis; Fertiberia, **https://www.fertiberia.com/en/greenammonia/h2f-project/;** Air Products, **https://www.airproducts.com/energy-transition/neom-green-hydrogen-complex**

Active players in the green ammonia landscape

For small-scale systems, the Haber-Bosch technology is modified and improved so that it can be better integrated with renewable energy systems and operate at a single-farm level through containerized and low-maintenance devices. TRL levels vary across OEMs (between 3 and 9), but these systems can be differentiated into three categories:

1. Miniaturized Haber-Bosch, a process that optimizes the synthesis loop for small-scale production
2. Enhanced Haber-Bosch synthesis, a process that involves improved and more efficient synthesis at lower pressure and lower capital expenditures (capex) than traditional Haber-Bosch through reactor and catalyst modifications
3. Novel and alternative ammonia synthesis methods, which include less proven methods such as electrochemical and nonthermal plasma ammonia production

In the miniaturized Haber-Bosch space, Talus Renewables is demonstrating proof of concept with its recent commercial 15-year offtake agreement with the Kenya Nut Company, an agribusiness based in Nairobi, Kenya.[4]

Regional-scale systems feature minimal modifications to the Haber-Bosch process to allow for low capital expenditures and/or low-pressure synthesis at a smaller scale than conventional industrial-scale plants. These modifications are often in the form of design improvements, increased flexibility, catalyst innovation, or solid oxide electrolyzer integration into the Haber-Bosch synthesis. The TRL levels are usually higher, ranging from 6 to 9, with some projects expected to reach final investment decision this year. An initial effort in that direction is represented by ReMo Energy, a DGA OEM, which signed a memorandum of understanding for offtake with the logistics company Trammo for a 20,000 tpa facility to be built in Illinois.[5] In the ammonia technology space, incumbent Topsoe is designing regional-scale solid oxide–based modular plants of 100 megawatts (MW), the equivalent of 100,000 tpa, in collaboration with First Ammonia.[6]

Although not exactly DGA, larger-scale green ammonia projects, with production profiles similar to those of conventional centralized plants, are also underway. In Africa, Stamicarbon is developing a 300,000 tpa green ammonium nitrate plant in Angola and a 200,000 tpa renewable power-to-fertilizer plant in Kenya.[7] In the United States, Atlas Agro, a leading green ammonia project developer, has announced the Pacific Fertilizer Plant in Richland, Washington, with a production capacity of 700,000 tpa of nitrogen fertilizers.[8] This project relies on green ammonia synthesis technology from KBR, another incumbent OEM.

Fertilizer Market Dynamics and Distributed Green Ammonia Advantages

Cyclical downturns in commodity markets for ammonia-based fertilizers are exacerbated by the significant influence of supply and demand shocks on market participants. This phenomenon is particularly pronounced due to the high level of global integration in these markets. These challenges primarily manifest in price volatility and disruptions in supply chains, leading to adverse effects on farmers. DGA can act as a direct hedge to these challenges while providing a series of additional co-benefits in local investment and renewable energy integration.

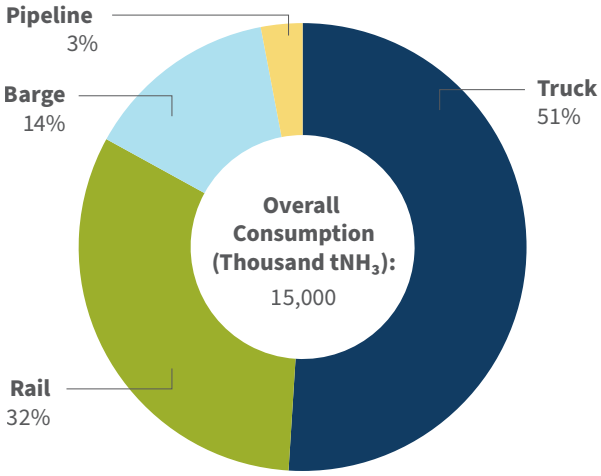
From supply chain disruption to simplification

Multistep transport processes to deliver traditionally produced ammonia to users expose supply chains to weather or labor disruptions and increase pass-through costs. In the United States, ammonia is primarily transported by pipelines, trucks, railways, and barges (see Exhibit 5 for volume shares, next page), yet these modes of transportation are not always reliable. Railway strikes in 2022 threatened to halt the transport of ammonia via rail, which is the mode of transport for over 32% of ammonia.[9] Droughts in the Mississippi River, a core connector between fertilizer producers in the Gulf and consumers in the Midwest, hindered the transport of ammonia to farms in fall 2023 via barge, which accounts for 14% of overall ammonia transportation.[10] During the past decade, unintended stoppages and malfunctions among barges have increased by 700%.[11] Historically, weather patterns such as prolonged cold spells have resulted in production shutdowns due to high natural gas costs from increased home heating demands.

Logistics costs vary depending on factors such as such as the point of origin, the chosen mode of transportation, and the frequency of loading and unloading. Collectively, extended transportation routes, pass-through costs associated with multistep supply chains, and the utilization of high-cost transportation methods such as trucking can contribute to substantial expenses in the distribution of ammonia from the Gulf to the Midwest, often escalating logistics costs to well over $300/tNH$_3$.[12]

With distributed ammonia production, fertilizer supply chains shift from spanning thousands of miles with multimodal transport to being "within the backyard" of farming communities, leading to more reliable supply and significant cost reductions. Simplifying supply chain logistics can shield consumers from the geopolitical instability and unpredictable transportation that can impact fertilizer supply.

Exhibit 5 **Ammonia Transportation Modes and Volumes**



RMI Graphic. Source: RMI analysis; Fertilizer Institute, **https://www.tfi.org/wp-content/uploads/2024/03/TFI-fertilizer-logistics-and-transportation.pdf**; US Geological Survey, **https://pubs.usgs.gov/periodicals/mcs2024/mcs2024-nitrogen.pdf**

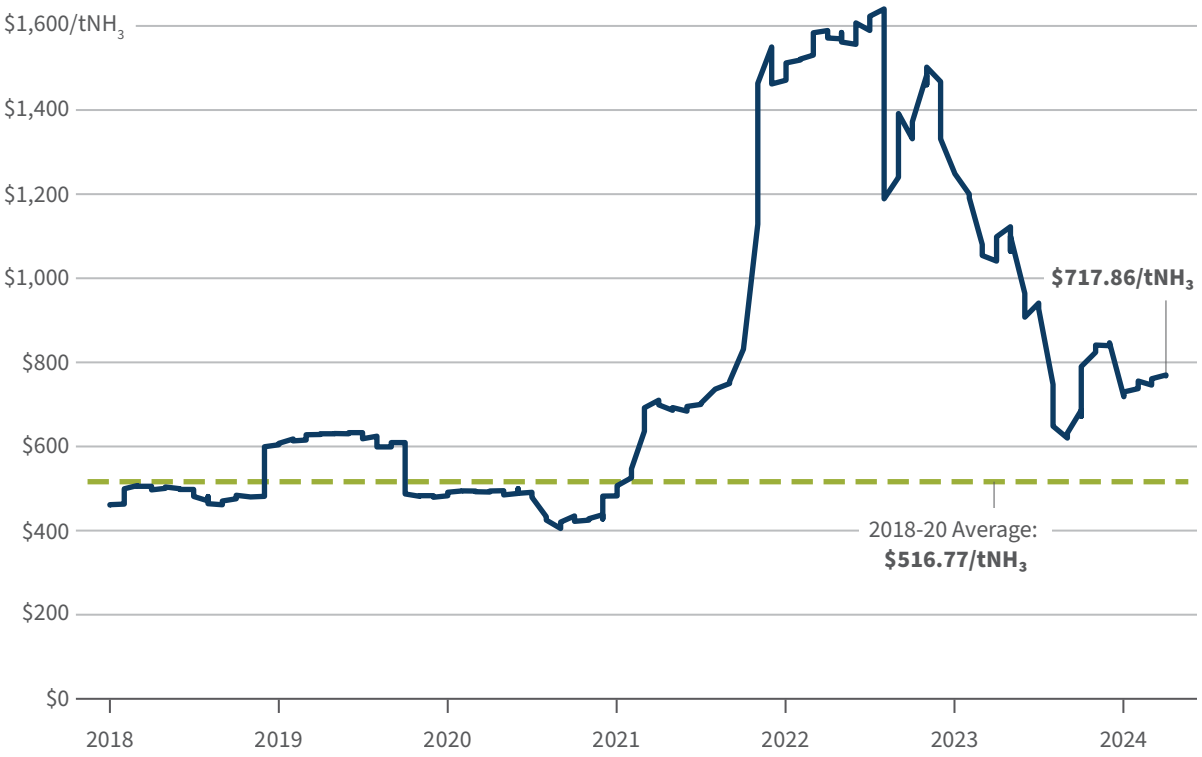
With the logistical challenges of fertilizer procurement lessened, the uncertainty of predicting how much ammonia will be available and of long lead times is also reduced. Localizing production also helps limit supply chain pass-through costs by streamlining distribution. This not only maximizes cost reduction but also minimizes the opportunity for supply chain disruptions to add unexpected costs and for intermediaries to inflate costs along the way.

From price volatility to stability

Imports and international pricing dynamics of ammonia significantly influence the pricing of ammonia in the US market. The United States produces most of the ammonia it consumes but still imports about 10% of its ammonia, mainly from Trinidad and Tobago or Canada. Domestic ammonia production prices rose only slightly with recent natural gas price volatility related to the Russian invasion of Ukraine, but in 2022 market prices rose three times over the market average from 2018 to 2020, reaching upward of $1,600/tNH$_3$ from $516/tNH$_3$. As of April 2024, despite the low natural gas prices, ammonia market prices were still 1.49 times higher (equivalent to $767/tNH$_3$) than the market average from 2018 to 2020 (see Exhibit 6, next page).

Because ammonia imports, especially lately, have been significantly higher priced than domestic ammonia, imports have had a price-setting effect on the US market. Typically, wholesale ammonia prices are not capped or predictable because contracts hinge on the fluctuating price of natural gas, with benchmarks such as the Cost and Freight (CFR) Tampa reflecting the average cost of ammonia production in the Gulf region (inclusive of transportation to its destination).

Exhibit 6 **Delivered Ammonia Market Prices in Iowa, US Midwest**



RMI Graphic. Source: RMI analysis; USDA, **https://mymarketnews.ams.usda.gov/viewReport/2863**

Minnesota farmers, like those in the rest of the Midwest, face considerable cost burdens due to ammonia's intricate supply chain dynamics and reliance on fossil fuels. Farmers' ability to procure fertilizer at the required volumes and prices is limited because they rely heavily on intermediaries to ensure timely availability during critical application seasons. However, the centralized nature of the supply chain necessitates farmers placing orders months in advance, demanding meticulous understanding of both local farming patterns and global production trends to ensure adequate supply.

This financial burden is reflected in the substantial decrease in net income for US farms when the price of ammonia increased after Russia's invasion of Ukraine, leading to widespread losses averaging $191 per acre through 2022.[13] Facing escalating expenses, some farmers may turn to synthetic fertilizer alternatives like manure, despite its labor-intensive application process and diminished nitrogen availability. This shift could impact crop yields, potentially driving up demand and market prices for agricultural products, thereby amplifying the broader economic repercussions stemming from fertilizer price volatility.

Producing ammonia with renewable energy will help stabilize fertilizer prices by decoupling ammonia production from natural gas price fluctuations and linking it with the set yearly cost of renewable electricity. This will reduce the current strain on farmers from constantly fluctuating and rising ammonia prices by ensuring that they can purchase fertilizer at more stable and affordable costs. Even with the shift to renewable-based ammonia, a future fertilizer market would not be isolated from price volatility given the seasonality of fertilizer demand, but green production can limit the severity of price volatility compared with production that relies on natural gas.

Distributed green ammonia co-benefits

Local investment

Moving fertilizer production to the Midwest could further benefit local economies by accelerating growth of renewable energy generation and creating green jobs in farming communities. Investments would spur a series of benefits, including the creation of a new specialized workforce of agronomists and technicians to operate distributed ammonia plants. This would provide the additional benefit of increasing investment in cooperative systems and ultimately increase the retention of dollars spent in local areas. Farmers and farming cooperatives (co-ops) will be the main beneficiaries of this transition, unlike in the current system where centralized producers define market dynamics.

Operational advantages for renewable electricity integration

New distributed ammonia production technologies will better enable integration with renewable electricity feedstocks. Conventional ammonia production technology must consistently maintain and operate high temperatures and pressures for the reaction of converting hydrogen and nitrogen into ammonia to occur. When these processes move away from the consistently supplied fossil feedstocks toward intermittently available renewable electricity, they require additional buffer in electricity supply through batteries or oversized renewables that increase costs and complexity. Newer, smaller-scale ammonia production processes are typically far more flexible in operation and can more readily adjust production to changes in renewable energy availability, providing opportunities for cost reduction and system simplification.

Project simplification and standardization

Once technological maturity is reached for distributed ammonia production, projects will have a lower financing risk and be more attractive to investors. Several distributed projects have been announced in recent years in the United States, involving companies such as ReMo Energy, Talus Renewables, First Ammonia, and Atlas Agro. Talus, in partnership with Landus Cooperative, opened the first plant in June 2024.

Deployment of DGA projects is necessary to prove the concept and the viability of the DGA pathway. Project developers and investors alike will appreciate the shorter construction periods; lower engineering, procurement, and construction (EPC) costs; and smaller amounts of capital required, making access to debt and equity financing a potentially easier ask. Once plants are operational, these systems may see less costly operation and maintenance costs alongside improved production resiliency given their more simplistic system design and technical improvements, which allow for lower pressure and lower temperature synthesis compared with conventional technology.

In addition, small-scale, containerized ammonia production facilities can be manufactured and installed much faster than large-scale ammonia plants (i.e., 1–3 years versus 3–10 years). The ability to go online sooner enables a faster return on investment, and the stackability of modular systems provides further benefits. Modular ammonia production systems can be installed in phases, allowing the farm or co-op to generate revenue as they gradually scale with a better understanding of offtake demand.

Many of these advantages give DGA business models a long-term economic edge compared with large-scale ammonia production processes. Nonetheless, key risks need to be addressed to effectively scale DGA.

Risks Related to Distributed Green Ammonia

Reshaping the fertilizer industry with a transition to DGA production requires the first wave of projects to access financing and establish early offtake contracts. This is particularly challenging for new players given the hesitancy of consumers to disrupt the status quo. Lack of product differentiation for green fertilizers and general perceptions of risk, cost premiums, and low commercial maturity create a challenge in getting these initial projects off the ground.

Heightened investment risk perception

First-of-a-kind distributed fertilizer projects involve a heightened perception of risk, a potential cost premium, and at times a lower TRL. This creates reluctance among capital providers and hesitation across off-takers to pivot to DGA production pathways. Both agricultural co-ops and lending institutions view the distributed pathway as high-risk because one has not yet been operated on a commercial scale. New ammonia reactors are only recently starting to being fully optimized and integrated into a unit with electrolyzers and powered by renewable electricity. Whole-system testing is important to validate OEMs' claims on a unit's ability to efficiently follow and operate at varying electricity loads in projects not connected to the grid.

Cost competitiveness

DGA's cost competitiveness is relative to changing fertilizer market prices, creating uncertainty about their economic advantage for off-takers. Fertilizer purchasers — notably agricultural co-ops and other market intermediaries — will benchmark DGA prices against ammonia market prices, and costs are a significant driver of buyer interest. Although DGA production costs in context of current fertilizer price spikes may appear competitive, buyers' expectations of price cyclicality may create hesitancy to commit to new fertilizer purchasing agreements. In other words, buyers may fear being locked into a price that appears competitive when market prices are high but that may not be the lowest price when market prices fall. Their concern stems from the ammonia market's typical cycle of price volatility and stability. Essentially, buyers are hedging against the risk of overpaying in the future as they anticipate prices of ammonia may become more stable as volatility factors are mitigated. By contrast, DGA producers expect their production cost to decrease in the long term. As production costs fall, DGA producers can increase their returns and see greater margins — even if market costs are higher or lower than the price contracted with off-takers.

Lack of targeted policy support

There is a critical need for policy that supports DGA deployment. The Inflation Reduction Act (IRA) has been instrumental in improving DGA economics, but other support programs that incentivize innovation, de-risk financing and investing, and provide supplementary financing to reduce burden on developers are still required. Leveraging existing tax credit structures where possible and engaging with existing support for co-ops, farmers, and stakeholders will be critical to enable early projects to secure offtake and illustrate the viability of the technology pathway. To help get early DGA projects with fertilizer applications off the ground, project developers should prioritize business models centered on economically strong agricultural co-ops in Midwestern states with robust policy support, such as Minnesota. Additionally, expanding buyer and investor education will provide greater clarity about the advantages of DGA, its costs, and its technological readiness. State and federal policy support should also be strengthened and expanded.

Developing Distributed Green Ammonia in Minnesota

Minnesota provides an ideal enabling environment for the first wave of DGA projects, owing to its supportive policy environment, strong renewable energy profile, and sizable demand for fertilizer demand. Minnesota is the fourth largest consumer of ammonia for agricultural use in the United States, with a current demand reaching 747,000 tpa for nitrogen fertilizers.[14,iii] Similar to other states in the Corn Belt such as North Dakota, Minnesota grapples with the intertwined challenges of price fluctuations and increased transportation expenses stemming from limited connectivity to the central ammonia pipeline distribution network. Moreover, Minnesota boasts abundant wind energy potential. These factors are further strengthened by the existence of grants incentivizing local production of green fertilizers by co-ops.

Current Landscape in Minnesota

Efforts to produce locally

Green ammonia projects are ramping up in the Midwest, and Minnesota is already positioning itself to tap into the opportunity to produce fertilizers closer to consumption. The state's dependence on external fertilizer sources has prompted a push for local production and decoupling ammonia synthesis from natural gas price fluctuations. In 2013, the University of Minnesota launched a first-of-its-kind green ammonia pilot program in Morris, in western Minnesota, to show the opportunity for distributed production.[15] This effort has gained momentum since the Russian invasion of Ukraine, which prompted other market actors to find opportunities in local low-carbon fertilizer production.

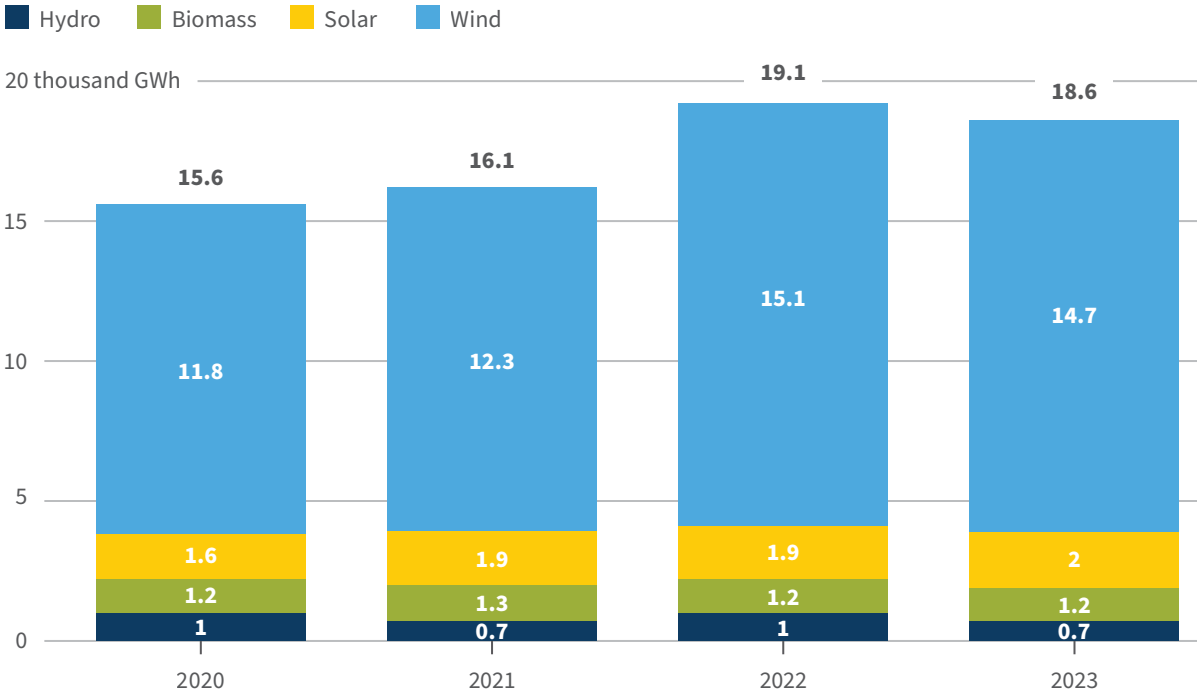
The Heartland Hydrogen Hub, a project funded by the US Department of Energy (DOE) that spans Minnesota, North Dakota, and South Dakota, is a more recent example of local production. As part of the hub, Xcel Energy is planning a large-scale urea plant that uses CO_2 offtake from ethanol refineries combined with green ammonia.[16] This project leverages Minnesota's ample sources of biogenic CO_2 from its ethanol refineries, as well as from several pulp and paper mills.

Similar projects have also been announced in North Dakota, which may look to Minnesota for customers given its large demand for nitrogen fertilizer. For example, NextEra plans to build a wind-powered $1.3 billion ammonia facility in Spiritwood.[17]

Minnesota provides an ideal enabling environment for the first wave of DGA projects, owing to its supportive policy environment, strong renewable energy profile, and sizable demand for fertilizer demand.

iii Requiring 911,000 tons of ammonia for production.

Exhibit 7 Cumulative Renewable Energy Generation in Minnesota, 2020–23



RMI Graphic. Source: US Energy Information Administration, **https://www.eia.gov/electricity/data/browser/#/topic/0?agg=2,1,0&fuel=9cdd&geo=g00004&sec=g&linechart=ELEC.GEN.WND-US-99.A~~~~~~~~~~~~~~~~&columnchart=ELEC.GEN.COW-US-99.A&map=ELEC.GEN.COW-US-99.A&freq=A&start=2018&end=2023&ctype=linechart&ltype=pin&rtype=s&pin=&rse=0&maptype=0**

Abundant renewable energy resources

Minnesota's efforts to produce green ammonia locally would not be possible without its excellent renewable energy profile (see Exhibit 7). In 2023, renewable energy accounted for 33% of Minnesota's electricity generation, with 54% of the state's total energy capacity coming from carbon-free sources including renewables, nuclear, and hydropower.[18]

Wind energy alone accounts for more than three-fourths of Minnesota's renewable generation. Most of Minnesota's utility-scale (1 MW or larger) wind farms are located in the southwestern part of the state where flat land is abundant.[19] This locality coincides with the majority of the state's farmland where direct-application ammonia fertilizer is typically utilized over urea.

In 2023, solar energy also provided almost 4% of Minnesota's total electricity generation, and hydropower accounted for more than 1% of the state's total electricity generation.[20] About 90% of the state's solar power came from utility-scale installations. Although there are nearly 30 utility-scale hydroelectric power plants in the state, most of the plants are small: The largest has a capacity of 76 MW.[21]

The state's utilization of multiple forms of alternative energy resources is ahead of many other states, and, largely thanks to the availability of high winds throughout Minnesota, there are still opportunities for further development to support additional endeavors such as clean fertilizer production.

Existing Policy Landscape

To understand how Minnesota can best support the deployment of DGA systems, it is essential first to understand the existing policy landscape at the federal and state levels.

Federal policy

In recent years, the federal government, through the US Department of Agriculture (USDA), has prioritized and financially supported domestic fertilizer production and deployment of renewable energy projects for farmers.[22] The DOE has made the development of clean hydrogen a priority in its strategy, and the IRA represented a key milestone in supporting electrolytic hydrogen and incentivizing green ammonia.[23]

The Biden administration set a target of reaching 100% carbon–free electricity by 2035 and net-zero GHG emissions by 2050.[24] The DOE's Industrial Decarbonization Roadmap establishes that decarbonizing fertilizer is connected to the generation of hydrogen from low-carbon energy, highlighting ammonia as a key use of clean hydrogen.[25] Besides the federal government's recognition of green ammonia as key to decarbonize fertilizer emissions to reach its national decarbonization goals, there is federal support for innovative fertilizer production pathways. The IRA includes clean electricity tax credits and a clean hydrogen production tax credit, described below.

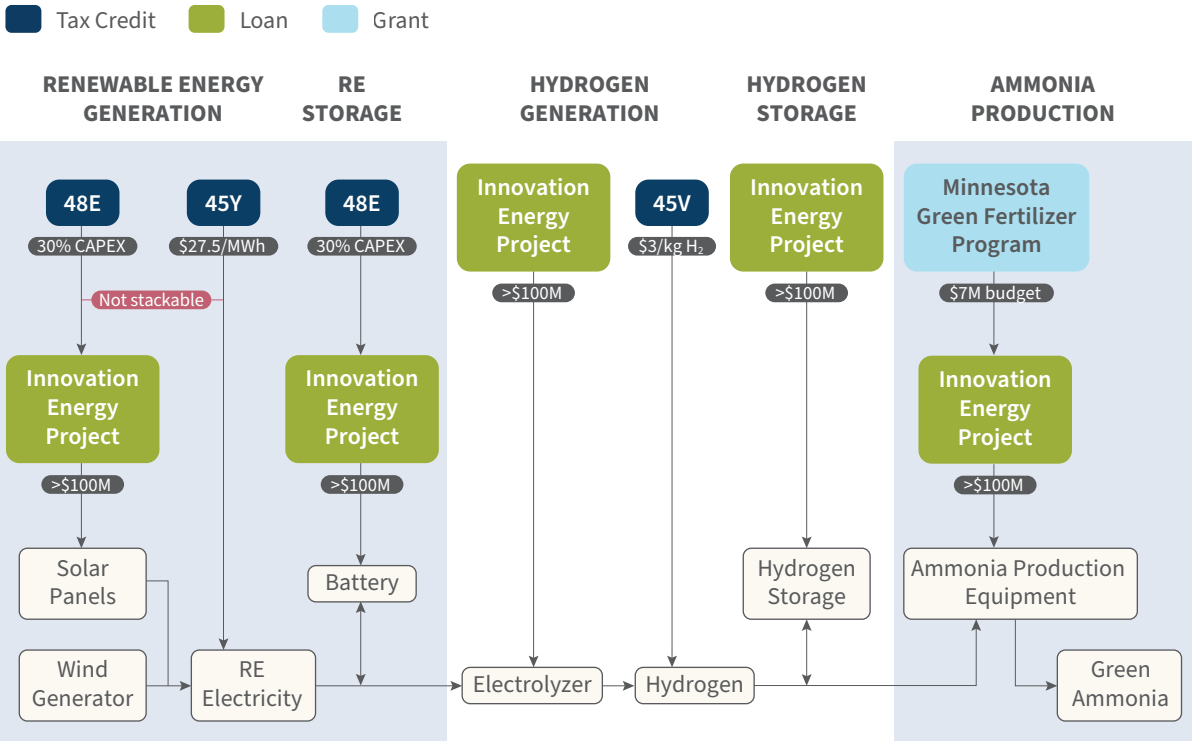
The Bipartisan Infrastructure Law created the DOE Regional Clean Hydrogen Hub program and allocated $7 billion to support the creation of hydrogen hubs.[26] The Heartland Hydrogen Hub, which includes Minnesota, was one of the seven hydrogen hubs selected,[27] with green fertilizer production mentioned as one of the main uses of hydrogen. In addition, DOE announced a $1 billion hydrogen demand program to design and implement demand-side incentives.[28]

The DOE's Loan Program Office (LPO) is another federal funding mechanism, with guaranteed loans through its Title 17 for innovative energy projects.[29] IRA provided an important boost to the LPO by appropriating $11.7 billion to issue new loans and increasing its existing loan program authority by $100 billion.[30] Although there is no minimum loan size, guarantees are usually $100 million and cannot exceed 80% of the anticipated project costs. Projects eligible under Title 17 must include a new or significantly improved technology not widely adopted in the United States.[31] They must demonstrate that the technology is used in three or fewer facilities and can catalyze the market by being employed in other commercial projects.

Exhibit 8 (next page) presents the main federal tax credits and LPO loan program across the value chain for green ammonia production, including renewable energy and electrolytic hydrogen generation and storage.

In recent years, the federal government has prioritized and financially supported domestic fertilizer production and deployment of renewable energy projects for farmers. The DOE has made the development of clean hydrogen a priority in its strategy, and the IRA represented a key milestone in supporting electrolytic hydrogen and incentivizing green ammonia.

Exhibit 8 Federal Tax Credits and LPO Loans for Which Green Ammonia Production Is Eligible



RMI Graphic. Source: RMI analysis; IRA Guidebook, **https://www.whitehouse.gov/wp-content/uploads/2022/12/Inflation-Reduction-Act-Guidebook.pdf**

Primary federal tax credits and financial support mechanisms that apply to green ammonia projects include:[32]

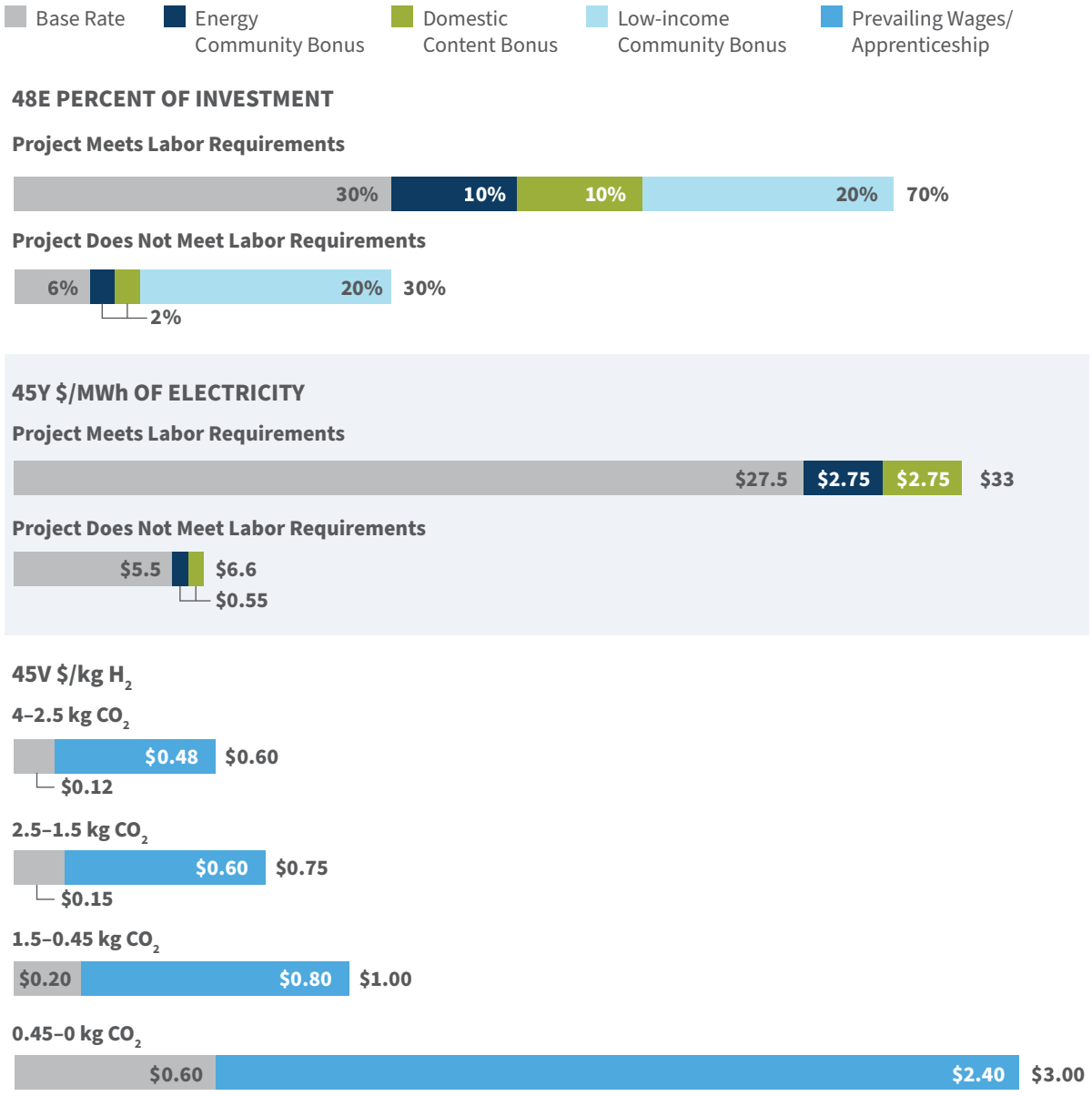
- **48E:** The 48E tax credit for clean electricity subsidizes 30% of the project's capital expenditure when prevailing and apprenticeship requirements are met. It can reach up to 70% with the domestic content, energy community, and low-community bonuses, as shown in Exhibit 9 (next page). The IRA also added stand-alone battery technologies under the scope of the tax credit.

- **45Y:** The production tax credit 45Y provides a base rate of $27.5/MW hour (MWh) when prevailing and apprenticeship requirements are met. Bonuses similar to those in the 48E tax credit are applicable to 45Y.

- **45V:** The 45V clean hydrogen production tax credit offers up to $3/kg of hydrogen produced with less than 0.45kg of carbon dioxide equivalent (CO_2e) per kilogram of hydrogen produced. Dedicated renewable projects producing hydrogen will be able to take advantage of this tax credit and stack it with either 45Y or 48E. The US Internal Revenue Service (IRS) published the 45V tax credit guidance in December 2023, opening a comment period that closed in March 2024. However, there is no official timeline for when the IRS will publish the final guidance, and it could be released as late as the end of 2024.

- **LPO innovative energy projects:** Technologies across the entire value chain for green ammonia production are eligible for the DOE LPO program, including renewable energy and green hydrogen generation and storage. The Haber-Bosch process is eligible as a technology to reduce GHG emissions from industrial applications such as ammonia production.

Exhibit 9 **Federal Tax Credits**



RMI Graphic. Source: RMI analysis; IRA Guidebook, **https://www.whitehouse.gov/wp-content/uploads/2022/12/Inflation-Reduction-Act-Guidebook.pdf**

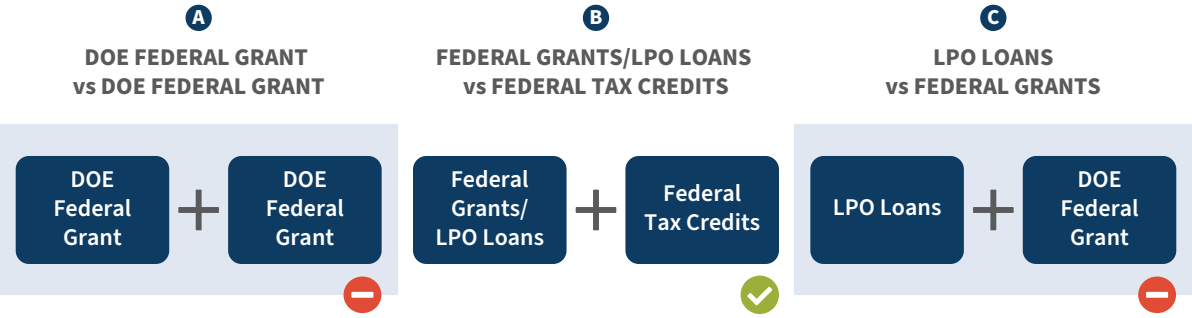
Several federal funding mechanisms are stackable, but there are some limitations based on the project's scope (see Exhibit 10, next page):

(a) Two federal grants cannot support the same project, scope of project, or budget.

(b) Federal tax credits are stackable with DOE federal grants and LPO loans.

(c) LPO loans are not stackable for projects that are expected to benefit directly or indirectly from another federal support program, such as grants.

Exhibit 10 Stackability Rules for Federal Fundings Mechanisms



RMI Graphic. Source: RMI analyses based on LPO's Title 17 Program, **https://www.energy.gov/lpo/title-17-clean-energy-financing; IRA Guidebook, https://www.whitehouse.gov/wp-content/uploads/2022/12/Inflation-Reduction-Act-Guidebook.pdf**

State policy

Minnesota has developed robust climate goals and targets. It set a goal of 100% carbon-free electricity by 2040. Its Climate Action Framework, published in 2022, aims to reduce the state's GHG emissions by 50% from 2005 levels in 2030 and achieve net-zero emissions by 2050.[33] Thanks to these efforts, GHG emissions from Minnesota's power sector have dropped by 40% over from 2012 to 2022.[34]

To reach the goal of achieving 100% clean electricity by 2040, Minnesota's Public Utilities Commission undertook a permitting reform for renewable energy projects. In December 2023, a working group proposed 12 reforms that could reduce permitting to nine months. The report was used to design a package that the Minnesota Legislature passed under the Energy Infrastructure Permitting Act in May 2024, which was waiting to be signed by the governor as of the publication of this report.[35]

Minnesota is also the only Corn Belt state with specific incentives for in-state green fertilizer production. Minnesota's Department of Agriculture is designing a $7 million green fertilizer grant program to reduce fertilizer emissions.[36] The grant's objective is to provide financial support to co-ops that invest in a green fertilizer production facility in Minnesota. Co-ops must have long-term offtake agreements to purchase the green fertilizer and obtain training in nutrient management best practices, in alignment with the state nitrogen fertilizer management plan.[37]

Momentum in Minnesota with a First Wave of Commercial Projects

DGA production is already competitive with large-scale green ammonia production and can be competitive with grey and blue ammonia production pathways under specific assumptions, especially concerning natural gas pricing. Minnesota has good renewable energy generation, which makes DGA projects there economically feasible. The development of technologies and standardization of production solutions will strengthen DGA's market position. Modeled scenarios relating to cost factors, learning rates, and system configurations provide insights into when and how much cost reductions should be expected. In the coming years, a reduction in the levelized cost of ammonia (LCOA) of 30% will be achieved, as the cost of electrolyzers and modular ammonia synthesis systems continue to decline.

Distributed Green Ammonia Cost Analysis

Cost factors

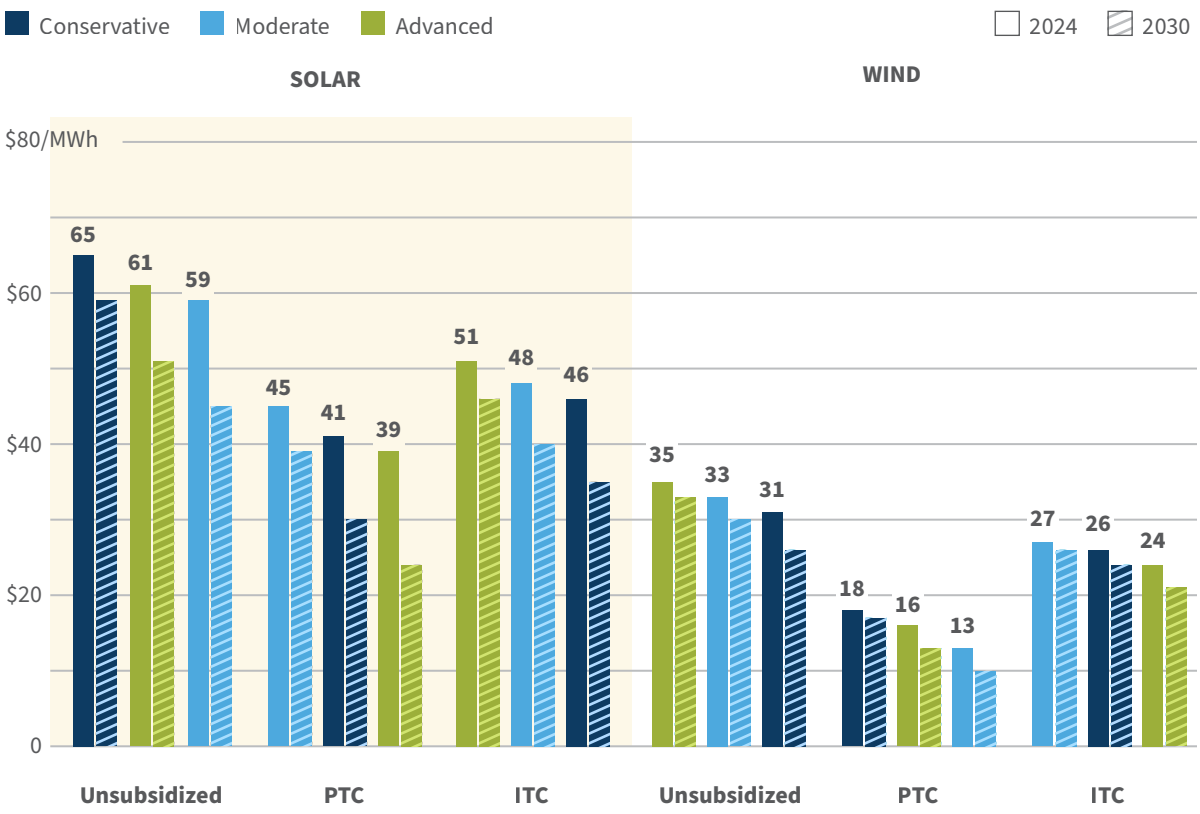
To calculate LCOA, the authors used a system optimization model they developed. This model designs an ammonia production system using various technical assumptions and market development scenarios. Such an approach makes it possible to determine the sensitivity of LCOA to changes in the main cost components — the cost of energy, the cost of hydrogen production, and the cost of nitrogen and ammonia production.

For a DGA project, energy is one of the primary cost factors, and it can vary within a wide range of 30%–80% of total LCOA, depending on the scenario. Whereas the cost of grey ammonia constantly fluctuates in response to natural gas price changes, the price of green ammonia is proportional to the cost of renewable energy (RE) available on-site.

Two power supply configurations were used in the analysis: behind the meter (BTM) and in front of the meter (FTM). In a BTM configuration, local RE generating and storing capacities are constructed to supply the ammonia plant. Energy supply and thus production rates depend on the wind and solar energy availability profiles in the plant location. By contrast, with an FTM configuration, energy is always available from the local energy grid. This decreases upfront project capital expenditures compared with a BTM alternative, because required feedstock production and storage capacities are lower.

A comparison between FTM and BTM energy supply configurations shows that FTM can provide a lower LCOA if energy cost is below $40/MWh, though this cost is below average market prices. It is important to highlight that Minnesota has favorable conditions for RE generation, especially for wind; see for levelized cost of energy (LCOE) modeling results. By 2030, the cost of solar energy will drop significantly, and therefore the consumption profile will shift toward higher solar energy utilization (see Exhibit 11, next page). Total cost reduction in this share of LCOA is expected to be 15% by 2030. Moreover, modeling results for a 10 ktpa and 50 ktpa (see Exhibit 12, page 24) production scales, demonstrate that flexible DGA systems allow for lower cost of energy compared with large-scale ammonia production (see Exhibit 13, page 25).

Exhibit 11 LCOE for Solar and Wind Energy Generation in Minnesota Considering Scenarios with an Investment Tax Credit (ITC), Production Tax Credit (PTC), and Unsubsidized Energy Generation

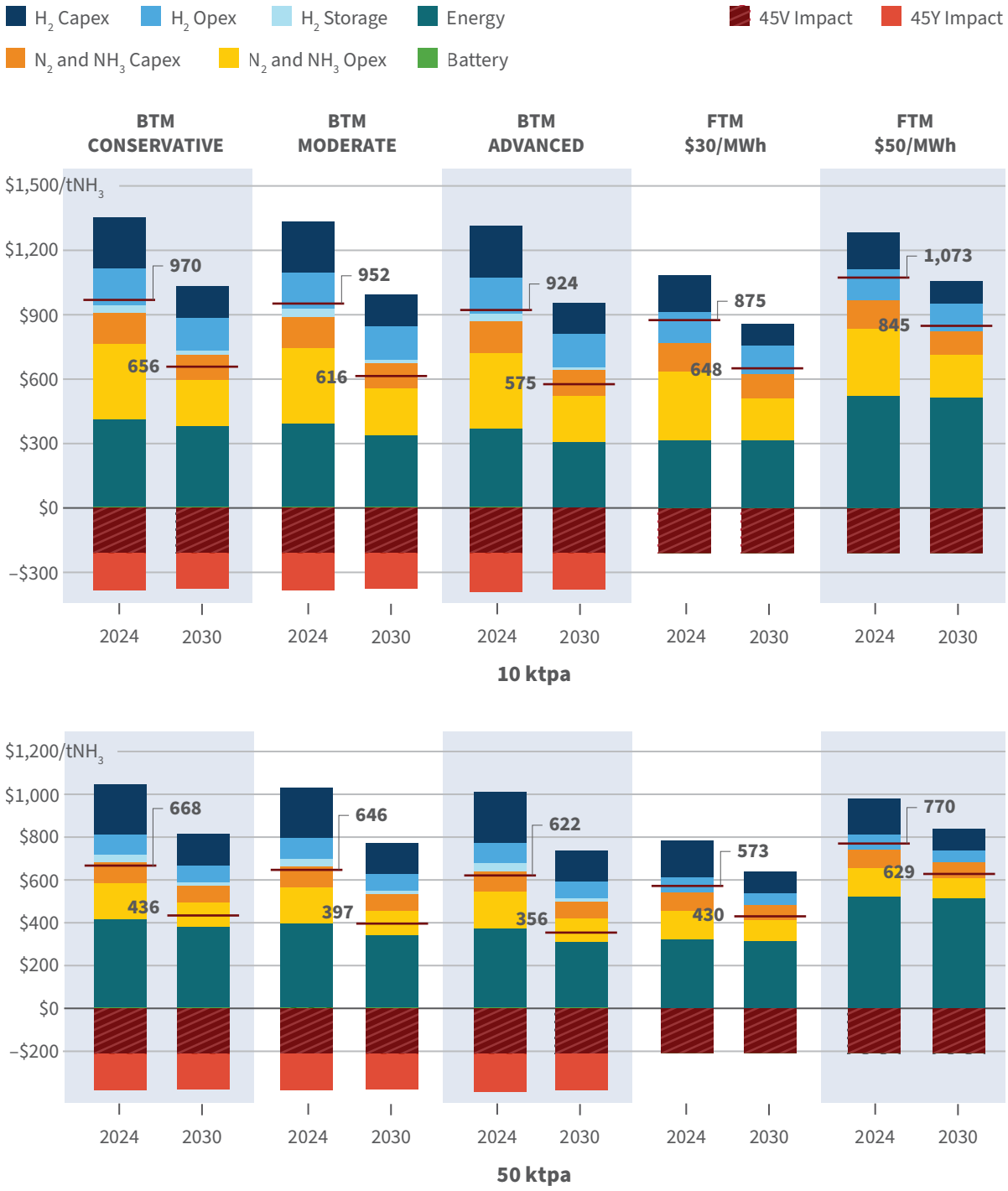


Note: LCOE calculation results. Three options of tax credit application were considered — unsubsidized energy generation, production tax credit (PTC), and investment tax credit (ITC). For each case three RE scenarios — conservative, moderate, and advanced (from left to right in each section of the exhibit) — from the Annual Technology Baseline (ATB) analysis by National Renewable Energy Laboratory (NREL) were used. Calculation was made for the most favorable locations in Minnesota. Bars are presented in pairs: The first bar represents 2024 results, and the second bar represents 2030 results. The DOE's Land-Based Wind Market Report: 2023 Edition states that an average unsubsidized LCOE of wind energy in the Midwest has reached the level of $32/MWh, based on data from already operational wind farms. As can be seen in the exhibit, this cost level nearly matches RMI's modeling result for 2024 using a moderate RE scenario from NREL ATB 2023.

RMI Graphic. Source: RMI analysis

Hydrogen costs can make up to 20% of a subsidized LCOA for a BTM configuration and are estimated to be around 3% for FTM projects, where energy is the major cost factor. Considering learning curves of electrolyzers and market dynamics, a 40% cost reduction in hydrogen is expected by 2030. Hydrogen expenses include capital expenditures and operating expenditures (opex) related to hydrogen production, operation, and maintenance, excluding energy costs. The dynamics of capital and operating expenditures associated with hydrogen show that the role of operating expenditures is most significant with small-scale production facilities, and that they decrease as ammonia production scales up. Hydrogen storage expenditures are relatively small across all analyzed scenarios. Analysis included deployment of pressurized canisters for DGA production and pipeline storage for large-scale systems, which is a cheaper option.

Exhibit 12 LCOA Modeling Results for Two DGA Production Scales

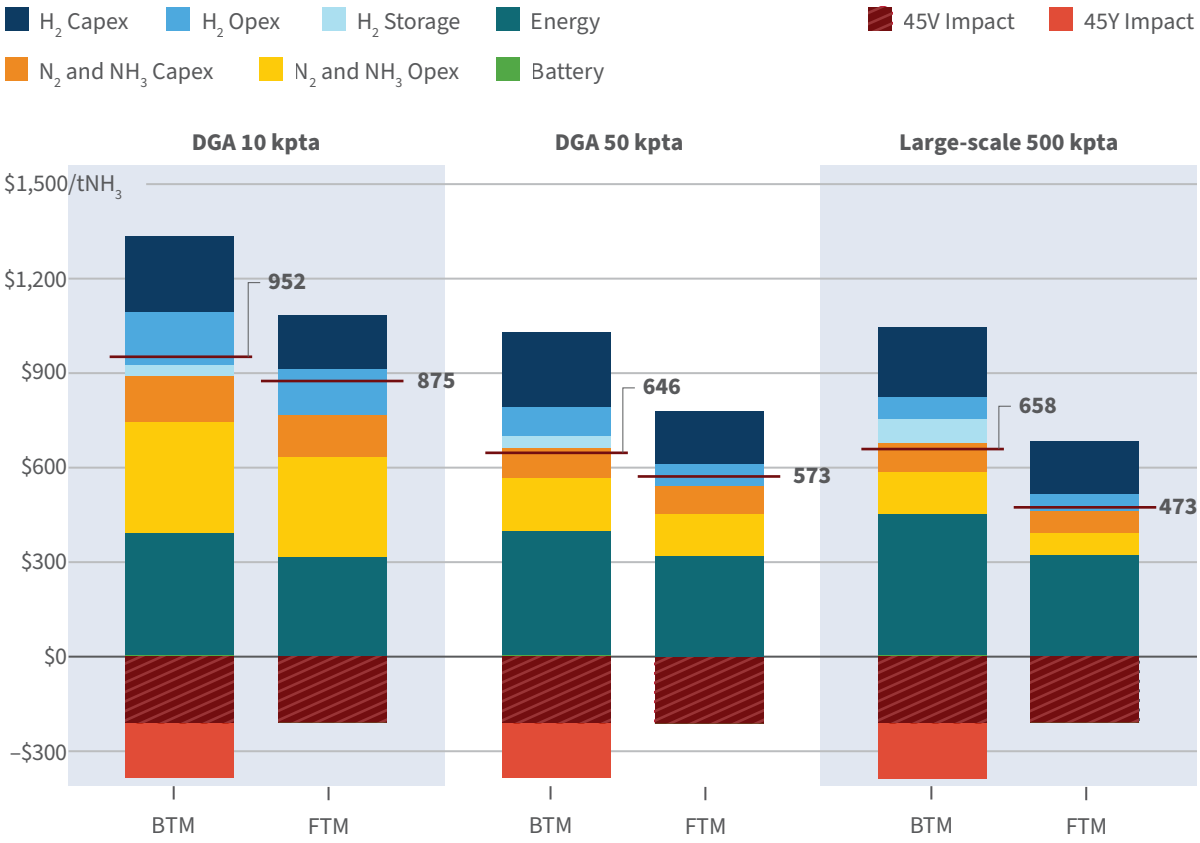


Note: The 10 kpta DGA comparison considers a BTM configuration with three RE scenarios from NREL ATB 2023, and a FTM configuration with two energy cost levels. Cost levels for 2024 and 2030 can be compared for each provided scenario. LCOA values are provided on top of the plot bars.

For the 50 ktpa DGA production scale, three RE scenarios for a BTM configuration and two energy cost levels for a FTM configuration are considered. Compared with a 10 kpta DGA, an increased ammonia production volume lowers the total LCOA by minimizing (1) opex related to hydrogen production, (2) capex related to nitrogen and ammonia production, and (3) opex related to nitrogen and ammonia production. Change of hydrogen-related capex and energy-related capex and opex is insignificant relative to the 10 ktpa production case.

RMI Graphic. Source: RMI analysis

Exhibit 13 Comparative Analysis of DGA and Large-scale Ammonia Production Pathways



Note: Green ammonia production is modeled using a moderate RE scenarios by NREL ATB 2023 and a $3/MWh FTM energy price for comparison. As can be seen, flexible DGA ammonia synthesis systems can allow a competitive LCOA level, compared with a large-scale electrified conventional Haber-Bosch system. With low energy costs, DGA systems become competitive with grey and blue production pathways. The analysis considered air separation units (ASU) to be deployed for DGA and pressure swing absorption units (PSA) to be used for industrial-scale production. DGA can benefit from flexibility and scalability of PSA systems because they are well matched with RE sources. Both ASU and Haber-Bosch reactors, by contrast, benefit from economy of scale.

RMI Graphic. Source: RMI analysis

Costs associated with nitrogen and ammonia production account for 50% of a subsidized LCOA. Share of these costs is lower for an FTM configuration than for a BTM configuration, and it further declines for large-scale systems. As the DGA market matures, a 30% cost reduction can be achieved in this cost factor by 2030. EPC costs can comprise a significant share of the project budget, especially in developing sectors like hydrogen production and novel ammonia synthesis systems. Considering EPC costs, modular and stackable DGA systems can benefit from standardized feedstock production solutions as technologies evolve.

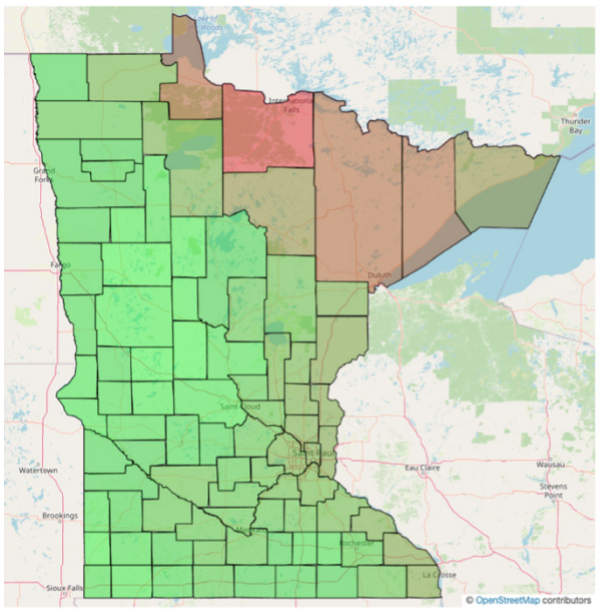
The last cost factor of LCOA is tax credits. Analysis considered 45V and 45Y tax credits, which were applied to hydrogen production and energy generation (for a BTM configuration) subparts of the ammonia production system. The 45Y incentives for RE generation include two available subsidy mechanisms: an investment tax credit (ITC) and a production tax credit (PTC). The financial calculation used the 45Y mechanism, which provides the lowest LCOE. As LCOA is calculated considering the whole service life of the ammonia plant, the total impact of the 45V hydrogen credit is lower relative to a credit value calculated over a single year.

Exhibit 14 shows LCOA distribution across Minnesota counties, reflecting the areas most favorable for DGA production. Locations with the cheapest energy allow for the lowest LCOA. The data used for the map doesn't include transportation costs, assuming that a DGA production facility is placed near end users.

Cost Dynamics and Competitive Position

Regular fluctuations in natural gas prices and geopolitical factors abruptly inflating ammonia market prices (to $1,600/tNH$_3$) indicate that DGA ammonia production is already a viable solution. Assuming highly favorable wind conditions, the western and central parts of Minnesota are the most feasible locations for BTM DGA projects. Today, with high natural gas prices, DGA production of 50 kilotons per annum (ktpa) can already be competitive with blue and grey pathways. By 2030, DGA production of 50 ktpa can reach cost parity with grey and blue ammonia pathways even considering moderate RE market forecasts and low natural gas prices (see Exhibit 15, next page).

Exhibit 14 A Map of LCOA for a BTM DGA Production Across Minnesota Counties



Note: Because a BTM DGA system in Minnesota would primarily use wind energy, DGA projects in central and western parts of the state, which have the most favorable wind conditions, would have the lowest production costs. A more accurate estimation of a particular production location would require consideration of other factors, such as permitting to construct required RE capacity and the suitability of ammonia for local soil.

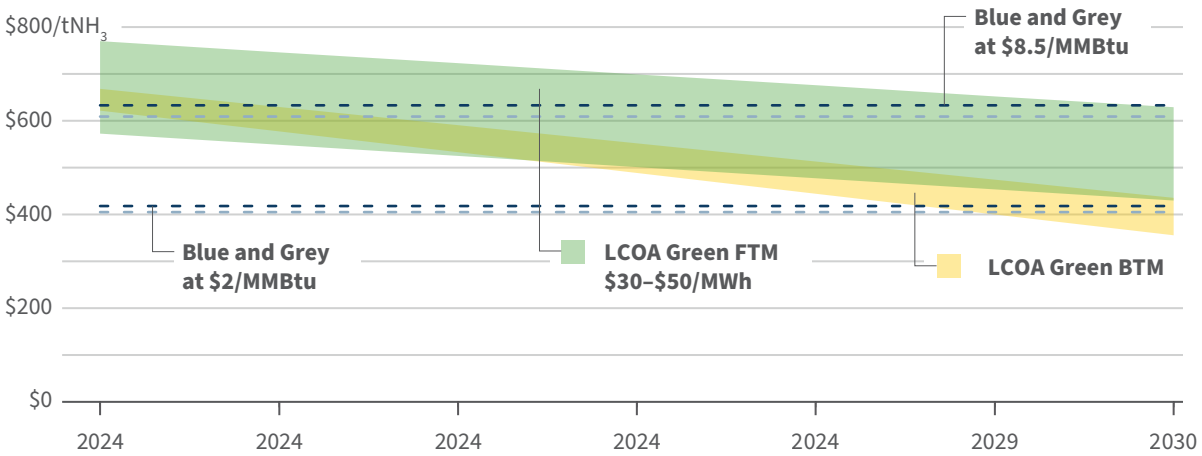
RMI Graphic. Source: RMI analysis

A 10 ktpa–scale system will be cost-competitive in a scenario with moderate and high natural gas prices. LCOA levels for centralized grey and blue production pathways are presented in Exhibit 16 (next page). Recognizing that levelized production costs and market costs are different, this comparison allows for the estimation of feasible ammonia price ranges and the value of a green premium. Importantly, the share of transportation expenses in these LCOA calculations was estimated to be around $180/tNH$_3$ (assuming ammonia delivery to Traverse County), while in unfavorable market conditions it can increase up to $300/tNH$_3$. A DGA production pathway implies ammonia production close to end-users, therefore transportation expenses were excluded.

Compared with DGA systems, large-scale blue and grey ammonia facilities can be profitable in high-cost environments. Even if the feedstock price increases from $2/million British thermal units (MMBtu) to $5/MMBtu (an increase of 2.5 times, see Exhibit 16), the feedstock cost for the hydrogen production increases by less than two times. This shows that grey and blue ammonia plants have a reduced sensitivity to feedstock pricing. As DGA will have to compete with these production pathways, lowering production cost, especially by targeting improved system efficiencies and securing low electricity prices, will be essential to remain competitive.

From 2024 to 2030, there will be a steady decline in the LCOA for both FTM and BTM DGA systems, as shown in Exhibit 15. Both become increasingly competitive with blue and gray ammonia over time. In fact, market development and commissioning of new projects will lead to a significant decrease of equipment costs in DGA.

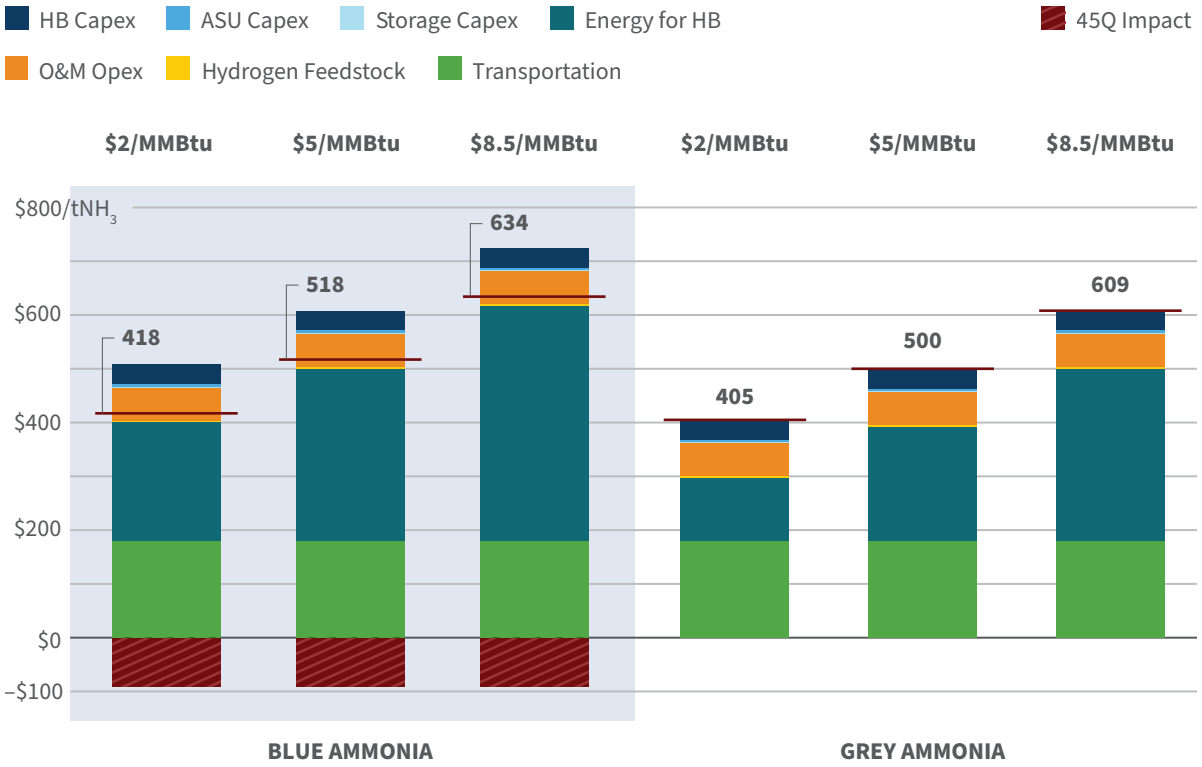
Exhibit 15 LCOA for FTM and BTM Green Ammonia Projects



Note: Projections of LCOA from 2024 to 2030 for BTM and FTM DGA systems at 50 ktpa in Minnesota compared with blue and grey ammonia production costs in the US Gulf. LCOA ranges for centralized blue and grey ammonia production are calculated with a natural gas price range of $2–$8.5/MMBtu.

RMI Graphic. Source: RMI analysis

Exhibit 16 LCOA for Blue and Grey Ammonia Production Considering Different Natural Gas Prices



Note: Delivered LCOA calculation results considering blue and grey centralized ammonia production in the Gulf using different market prices for natural gas prices from recent years: minimum ($2/MMBtu), average ($5/MMBtu), and maximum ($8.5/MMBtu). The capture rate for blue SMR is assumed at 85%. The application of 45Q incentive minimizes the cost difference between blue and grey ammonia. 45Q refers to the production tax credit based on the quantity of CO_2 captured and stored during the hydrogen synthesis process. The transportation cost assumes pipeline distribution from Louisiana to Iowa and distribution to demand centers in Minnesota by trucks.

RMI Graphic. Source: RMI analysis

This will result in an estimated 30% LCOA reduction for DGA ammonia pathways by 2030. With an estimated 20% learning curve effect for water electrolyzers and 10% for balance of plant equipment, there will be a 50% reduction in capital expenditures for both categories by 2030 due to a rapid growth of cumulative installed capacity in the coming years. For nitrogen synthesis equipment, a 10% total capital expenditure reduction by 2030 is expected. Novel small-scale ammonia synthesis systems cost will reduce 20% by 2030.

The importance of FTM systems accessing lower-cost electricity is evident in the projected decline in the LCOA for green ammonia. Access to cheaper electricity from diverse and large-scale power sources allows FTM systems to lower their operational costs over time, making DGA production increasingly competitive compared with blue and grey ammonia. As a result, the ability to tap into lower-cost grid electricity is crucial for driving down production costs and enhancing the economic viability of DGA.

Target Setting

The design of a coordinated plan for Minnesota to produce low-carbon fertilizers requires alignment between policymakers, investors, lenders, and developers to successfully deploy the first wave of DGA projects. Setting an ambitious target will help to anchor and measure the state's success in adopting green fertilizer, and new business models will help to scale successful frameworks.

Minnesota targets

To align DGA roadmap targets with existing statewide efforts, the overall 50% emissions reduction target from the **Minnesota Climate Action Framework** was used as an anchoring objective.[38] Drawing from 2020 production emissions, RMI established that total production emissions associated with annual Minnesota purchases of fertilizer is 2,267,991 tons CO_2e. Of those production emissions, 87% are attributable to nitrogen fertilizers. To meet annual Minnesota's nitrogen demand, approximately 900,000 tons of ammonia is needed. To reach a 50% reduction of emissions from ammonia production by 2030, the state would need to produce or import 450,000 tons of green ammonia per year. Achieving this target with production alone would necessitate a capacity of approximately 1 GW of electrolyzers and 2.5 GW of renewable energy. For context, no electrolyzer has been deployed in Minnesota, and the state will need to install new wind and solar that amounts to 40% of its current capacity of 6.3 GW to meet production requirements. To reach net-zero emissions by 2050, 2 GW of electrolyzer and 5 GW of renewable energy capacity dedicated to green ammonia production would be required, according to projections (see Exhibit 17).

Exhibit 17 Minnesota Ammonia Targets

Targets

Year	CO_2 Reduction	Ammonia Production Capacity	Required Electrolyzer Capacity	Required Renewable Energy Capacity
2030	50%	450 kt per year	1 GW	2.5 GW
2050	Net-Zero	900 kt per year	2 GW	5 GW

RMI Graphic. Source: RMI analysis



Business Models and Project Finance Risk Mitigation

Getting the first wave of projects off the ground will help de-risk DGA, spurring deployment of new systems in the future, which will ultimately help Minnesota reach its 2050 emissions reduction target. Effective business models play a crucial role in risk mitigation when structured appropriately. In the context of DGA projects, the initial focus is on minimizing risks associated with technology and offtake. Technology risks stem from DGA's novelty and its relatively low commercial maturation. Offtake risks center on securing a long-term offtake agreement from a creditworthy off-taker. It is paramount to address both.

Mitigating these risks commences with meticulously structuring project finance and contracts. This entails crafting offtake agreements tailored to the specifics of the project, considering factors such as the type and duration of the agreement. Establishing a suitable legal and business entity, often through a special purpose vehicle (SPV), offers insulation from liability. For smaller-scale ventures, joint ventures can be considered. Key tools for minimizing risk in project financing include assessing offtake contracts, prioritizing the creditworthiness of off-takers, and opting for SPV structures to shield parent companies from direct exposure. Evaluating the efficacy of these business models necessitates a comprehensive examination of their ability to address the unique risks inherent in DGA projects while also fostering profitability.

Beyond these tools, factors that determine the efficacy of a green ammonia business model include the type of offtake contract (i.e., length and price arrangements) and the ownership structure. The risk tolerance of investors, off-takers, and project developers informs both of these arrangements.

In considering pricing structures for ammonia offtake agreements, options include: (1) fully flexible price model; (2) floor-to-ceiling price model; and (3) fixed-price model. The fully flexible price model mirrors the current system in fertilizers, offering familiarity for off-takers but potentially making it more challenging for project developers to secure financing from lenders because the product price is unpredictable. The floor-to-ceiling price model offers the advantage of prearranged floor and ceiling prices, providing a semi-floating price for off-takers, yet it carries inherent risk because it relies on price estimations. Lastly, the fixed-price model offers a steady income stream and increases the likelihood of securing financing from lenders, although it may pose difficulties for agricultural co-ops seeking to enter into such offtake agreements.

In terms of length, short-term agreements are commonplace in the fertilizer market, whereas long-term agreements, though less common in this sector, can be instrumental in securing financing for ammonia projects. In general, conventional ammonia contracts are short term, with prices anchored to CFR Tampa spot prices — the benchmark for ammonia prices that fluctuate according to natural gas price variability. However, longer-term contracts, similar to power purchase agreements for clean electricity, might be generally preferred given the nascency of green ammonia projects.

As for ownership structures for these projects, a variety of actors within the ammonia ecosystem can be involved. During initial deployment of DGA projects, OEMs will likely play a role in demonstrating commercial proof of concept. However, traditionally, we would see initial ownership from project developers, often following a build-operate-transfer model. Co-ops, whether electric or agricultural, could also take ownership of DGA projects. Although co-ops might lack expertise in operating DGA systems, co-op ownership would directly reduce reliance on external suppliers for ammonia required for electricity or agricultural applications. Another ownership model could involve ethanol producers, where ethanol facilities would own a DGA facility to combine ammonia with captured biogenic CO_2 to produce low-carbon urea.

Standard Business Model

As an example, consider a standard business model where an agricultural co-op represents the primary revenue source (see Exhibit 18, next page). In such a scenario, risks related to technology and off-taker creditworthiness must be mitigated. The agricultural co-op's involvement introduces revenue stability but also necessitates careful management of technological risks associated with this novel ammonia production process. Technology risk can be mitigated through the involvement of credible project developers and technology providers. Additionally, ensuring the creditworthiness of the off-takers becomes crucial to guarantee consistent revenue streams and overall project viability. Both of these factors determine the willingness of investors and lenders to provide capital and the overall economic sustainability of the project, which can be addressed through long-term offtake agreements and credible players involved in the project development.

Co-op Owned Business Model

An alternative business model involves direct ownership from agricultural co-ops. Although this model presents similar challenges as the standard business model, it relies on farmers for the only revenue stream, so the project's feasibility hinges primarily on revenue stability. Without a direct offtake agreement in place, ensuring the economic viability of the project becomes uncertain. However, agricultural co-ops would gain full control over their supply chain, thereby avoiding additional costs incurred through intermediaries.

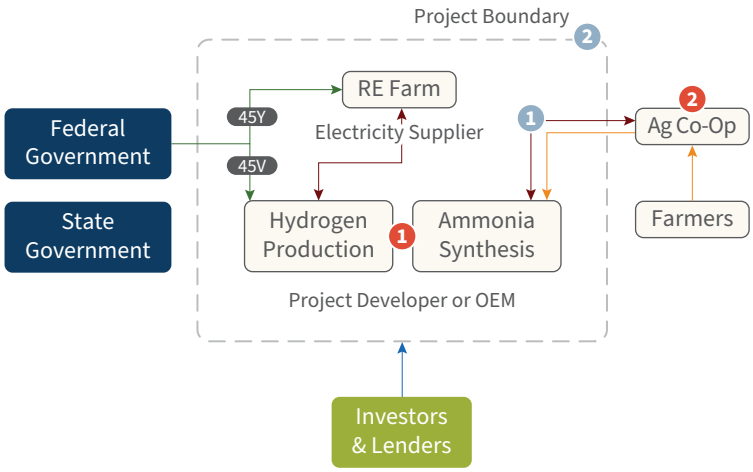
Moving Forward

These are just a few of the high-level risk considerations and mitigation tools project developers will encounter when assessing business models. Additional mitigation tools will vary depending on each project's specifics. Apart from economic tools, those developing a DGA project should also explore how policy can reduce overall investment risks.

Exhibit 18 Standard and Co-Op-Owned Business Models

Capital/Investments · Incentives · Revenue · Bilateral Offtake Agreement

STANDARD



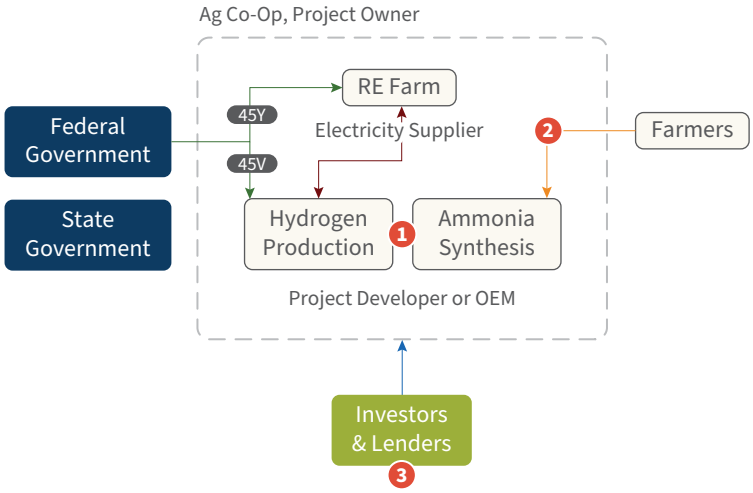
KEY RISKS

1. **New Technology** — DGA projects are still in their first commercial wave.
2. **Creditworthiness** — Suppliers should ensure ag co-ops are at least medium-sized and financially sound.

DYNAMICS

1. **Contract** — Length and type of contract will mainly determine the economic viability.
2. **Ownership**— Different types and players could be involved in the ownership, from ag co-ops to OEMS.

CO-OP-OWNED



KEY RISKS

1. **New Technology** — DGA projects are still in their first commercial wave.
2. **Revenue Stability** — Farmers, unless locked into an offtake agreement, do not represent a stable income source.
3. **Securing Financing** —Without having secured a large, credit-worthy offtaker, it might be more difficult to convince lenders.

RMI Graphics. Source: RMI analysis

Key Recommendations

Future Policy Considerations

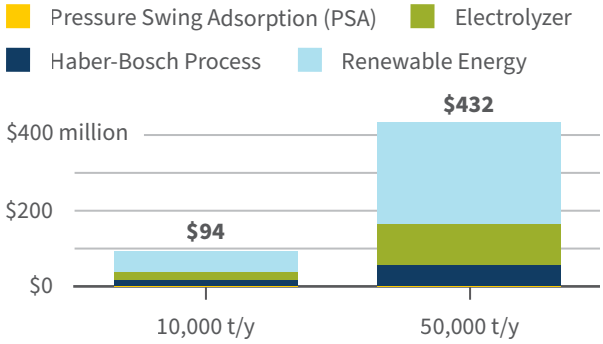
Policy Recommendation 1: Allocate Minnesota's green fertilizer grant for maximum impact

The Minnesota Department of Agriculture (MDA) is currently reviewing feedback received from stakeholders in its request for information on how to design the fertilizer grant program.[39] MDA can consider different alternatives to leverage the $7 million in current funding, along with potential additional funding, for maximum impact to help accelerate the first wave of DGA projects in the state.

Green ammonia plants, even relatively small-scale distributed ones, are capital intensive. Estimated capital expenditures for 10 ktpa and 50 ktpa systems range from $94 million to $432 million, including capital expenditures for RE generating capacity (see Exhibit 19). The broad goals of the grant are to support deployment of the first wave of projects and move the state toward reaching the proposed production targets. In addition, these initial projects can serve as case studies to help future projects raise capital and reach final investment decision.

Exhibit 19

Total Capital Expenditure of Main Equipment for Distributed Green Ammonia Production Systems



RMI Graphic. Source: RMI analysis

This list is not meant to be exhaustive, and some options might not be permitted under the current grant guidance, but it is presented here to encourage more radical thinking:

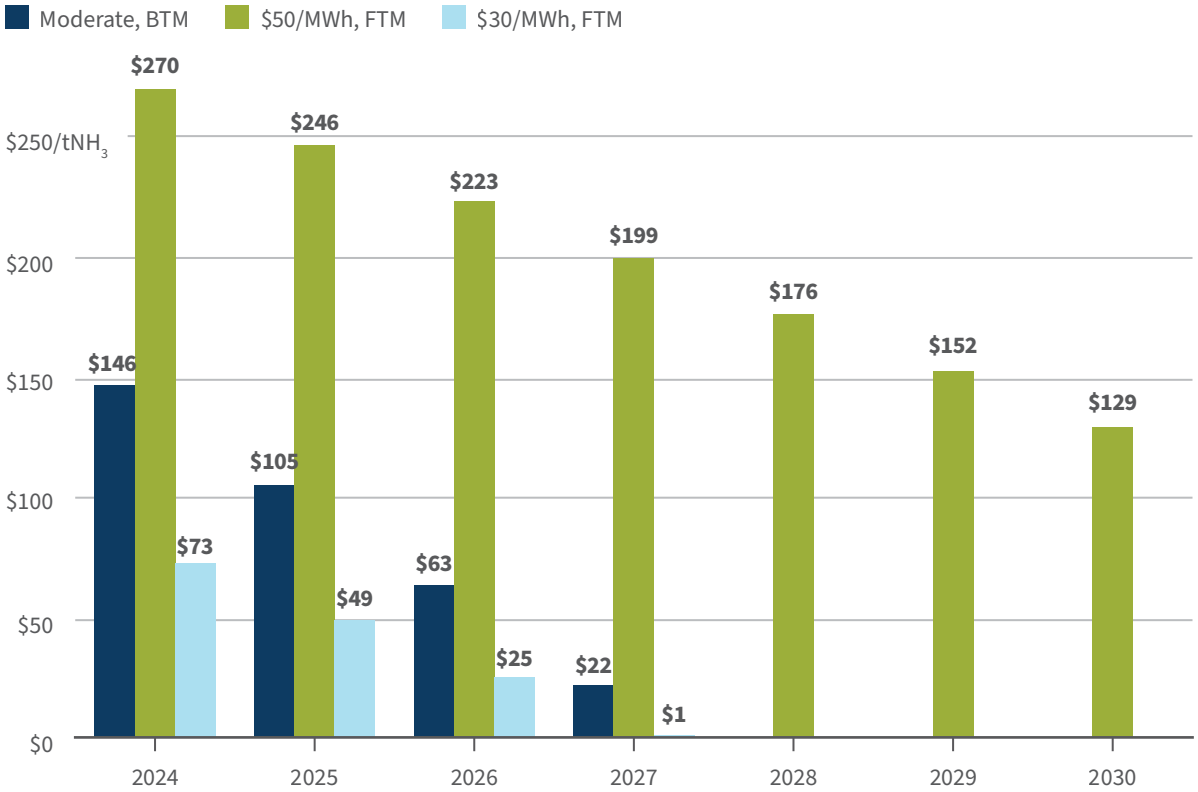
- Provide direct capital expenditure support for one project. For a single, 10 ktpa system this could offset more than 7%, whereas supporting a 50 ktpa system would offset only 2% of project costs.
- Fund pre-feasibility and feasibility studies for DGA systems to support developers and ensure that the grant facilitates practical, data-driven decisions for implementing decentralized ammonia production facilities in Minnesota.
- Provide funding as cost share if projects unlock federal funds such as LPO loans, up to a specified amount per project (or limited based on estimated production).
- Fund a supply-side competitive auction for green ammonia production. This would help close the gap with conventional ammonia by awarding contracts to producers that can offer the most competitive production volume with offtake agreements at the lowest subsidy required (see Policy Recommendation 2).

Policy Recommendation 2: Design a competitive mechanism to provide subsidies to make DGA projects bankable

DGA projects need offtake agreements to be bankable and reach final investment decision. Also, as shown in Exhibit 20, green ammonia projects are more expensive than conventional ammonia in the short term, making it difficult to close these offtake agreements. Based on the available budget and the deployment targets, Minnesota could fund a competitive auction to incentivize green ammonia for fertilizer production, in a structure similar to the one used by the European Hydrogen Bank.[iv]

Exhibit 20 provides a sense of the range of the premium needed to design an auction system. The cost gap between DCA and grey ammonia will vary based on the financial situation of each project and developer, and it does not have to be fully covered by state funding. However, Minnesota can play a crucial role in closing the gap by providing the needed funding to developers to close offtake agreements, ensure demand, and make these projects financially viable.

Exhibit 20 **Cost Gap Between DGA and Grey Ammonia**



Note: This exhibit illustrates three cost scenarios for a DGA facility of 50 ktpa: (1) Moderate, BTM; (2) $50/MWh, FTM; and (3) $30/MWh, FTM. The 2024 and 2030 LCOA values for each of these scenarios is drawn from Exhibit 13, and those values are then compared with the cost of grey ammonia production at $5/MMBtu ($499.69/tNH_3) to establish the cost gap.

RMI Graphic. Source: RMI analysis

iv The European Hydrogen Bank uses an auction system where companies bid to win a set amount of money (the premium) per kilogram of clean hydrogen they produce over a specific period.

The auction process could have the following criteria:

- **Eligibility:** Establish eligibility criteria for producers, including offtake agreements, carbon intensity thresholds, and a minimum production capacity.

- **Bidding:** Producers submit bids specifying:
  - The amount of green ammonia they can produce over a defined period (e.g., per year).
  - The minimum subsidy required per ton to sign the offtake agreement.

- **Evaluation and awarding contracts:** The auctioneer (a Minnesota government agency) would evaluate bids based on factors such as:
  - Cost competitiveness: producers that require the lowest amount of support to fulfill the supply contract.
  - Project viability: the technical and financial feasibility of the proposed production process.

- **Subsidy to close the gap:** Winners would be awarded contracts guaranteeing the requested subsidy per ton of ammonia produced for a set period. The government would essentially pay part of the difference between the production cost of incumbent grey ammonia and the producer's production cost for green ammonia. The subsidy can be a fixed premium on top of hydrogen offtake prices.

Additional considerations:

- **Reference production cost:** Minnesota can establish a reference cost for grey ammonia. This could be based on the average market cost of conventional grey ammonia. For example, Exhibit 20 presents the cost gap of $500 per ton of ammonia with a natural gas price of $5/MMBtu for different configurations of green ammonia versus grey ammonia.

- **Budget constraints:** The total program budget available would likely influence the final subsidy provided, where only viable projects that require a lower subsidy would be competitive in the auction.



Policy Recommendation 3: Provide access to lower capital cost with guaranteed loans

Co-ops can leverage LPO loans to access capital for the equipment needed for green ammonia production at a lower interest rate than conventional loans. LPO loans require projects to be innovative, implementing a technology that is not widely currently available on the market, such as DGA.

The recently created Minnesota Climate Innovation Finance Authority is seeking public comments through a request for information to act as a State Energy Financing Institution (SEFI) and leverage federal LPO funding.[40] Since SEFI-supported projects are exempt from the innovation requirement, Minnesota's green bank could co-lend loans with the LPO to produce green ammonia using commercial technologies, improving access to low-cost capital from federal funding.

Loans guaranteed with LPO funding can provide better interest rates than commercial banks, lowering the cost of capital and boosting the projects' financials. As of June 2024, the interest rate for the LPO's Title 17 projects was around 5%, notably lower than the 7% used in this report's analysis of BTM DGA systems (see Exhibit 21).[41]

The state can also develop its own loan program. North Dakota has adopted this model, where the legislature provides the Bank of North Dakota with $150 million for its Clean Sustainable Energy Loan Fund for green fertilizer projects in the state.[42]

Exhibit 21

Comparison of the Impact of a Lower Interest Rate on LCOA in 2024

Interest Rate	LCOA $/tNH$_3$
7%	$646
5%	$630

RMI Graphic. Source: RMI analysis; LPO's Title 17 financial program, **https://www.energy.gov/lpo/articles/pricing-lpo-financing-program**.

Policy Recommendation 4: Advocate to unlock existing USDA funding streams that aim to increase national production of fertilizer

The United States Department of Agriculture (USDA) has immediate opportunities to support green ammonia production for fertilizers. The USDA's Rural Energy for America Program received $145 million in funding from the IRA for 700 loans and grants to expand access to renewable energy.[43] In addition, the Fertilizer Production Expansion Program awarded $500 million in grants to increase US-made fertilizer production to spur competition and combat price hikes on US farmers.[44] Considering the importance of fertilizer in the state, Minnesota could advocate for the USDA to launch another round of the Fertilizer Production Expansion Program, focusing on DGA systems.

Policy Recommendation 5: Ensure an enabling environment for DGA deployment in the state

- **Workforce training:** Incentives to support workforce development through training and skills programs will be necessary for the establishment and longevity of this new industry. Minnesota can adapt existing grant programs, such as the training grant programs form the Minnesota Department of Employment and Economic Development (DEED), to develop the new workforce for green ammonia and hydrogen projects.[45]

- **One-stop shop permitting:** A one-stop shop permitting initiative would expedite the deployment

of green hydrogen and ammonia production infrastructure, enhancing efficiency and reducing costs while minimizing uncertainty and simplifying project management. It should involve implementing streamlined approaches to permitting and regulatory approval, along with developing clear guidance on hydrogen and ammonia permitting, with stakeholder engagement focusing on environmental, energy, and equity priorities. The initiative should also aim to facilitate project rollout by enabling quick commissioning through centralized permitting processes and environmental impact assessments. As an example, the EU, through the Net-Zero Industry Act, sets a 12-month permitting time limit for hydrogen projects with an annual capacity equal or less than 1 GW.[46]

- **Develop clear guidance for green ammonia certification:** Leveraging Minnesota's founding role in the Midwest Renewable Energy Tracking System (M-RETS), policymakers can establish clear criteria and definitions for what constitutes green ammonia within the M-RETS system. M-RETS will play a key role in providing the tracking infrastructure that developers can use to comply with 45V federal tax credits for hydrogen production because it anticipates issuing hourly renewable energy certificates during the next 12 to 18 months.[47] This can provide a foundation for a green ammonia certification scheme.

Moving Forward

The deployment of DGA systems to help decarbonize fertilizer emissions in Minnesota faces unique challenges. The evolution of ammonia to serve new markets will have a price-setting impact that could make it difficult for new players and projects to succeed in the fertilizer industry. In addition, the lack of product differentiation for fertilizers makes it challenging to increase buyers' willingness to pay for and thereby incentivize green fertilizer offtake without a green certification or other label that adds value in the market. Given the importance of fertilizers to the state's agriculture sector and the complex market dynamics, Minnesota should take a comprehensive and coordinated approach to design and implement policies to understand the impact of the different levers available

Future Work

There are multiple avenues to explore beyond the roadmap for DGA production presented here. Additional areas for research and analysis include:

- Evaluating applications of ammonia beyond fertilizers and how demand can smooth out the seasonal demand of ammonia for fertilizers
- Exploring additional policy and market mechanisms to accelerate green ammonia production and use across the Midwest
- Identifying the most effective low-carbon nitrogen fertilizer options and alternatives to decrease overall consumption emissions and assessing the most suitable solution to fully decarbonize the fertilizer sector
- Understanding the techno-economic feasibility and CO_2 sourcing for low-carbon urea as well as the infrastructure buildout needed to guarantee effective carbon management and utilization
- Engaging an array of stakeholders, including DGA ammonia suppliers, fertilizer distributors, farm groups, and state policymakers, to raise awareness of the DGA opportunity and accelerate project deployment

Conclusion

Minnesota is uniquely positioned to take advantage of DGA. The current centralized ammonia production system can provide farmers with low-cost fertilizer, but also exposes farmers to price volatility and supply chain disruptions. Localized, distributed ammonia production can complement the existing system to hedge against negative outcomes as well as reduce emissions from fertilizer production.

To enable the deployment of DGA projects in the state, credible consortia with effective business models and targeted policy support should be prioritized. Critically, easier access to capital tools, supplementary subsidies to offset the initially higher production cost of green ammonia, certification schemes to differentiate green ammonia from conventional production, faster permitting tracks, and in-state workforce training need to be introduced to fully realize the benefits and opportunities presented by DGA in the state. The cost of DGA is likely to fall rapidly as modular, containerized systems are able to take advantage of lessons learned by the first systems to be deployed and of rapid, iterative improvements in manufacturing.

The successful implementation of DGA projects in Minnesota and beyond hinges on collaborative efforts, innovative solutions, sound business models, and robust policy frameworks. By addressing these areas of further work and seizing opportunities, Minnesota can unlock the full potential of DGA and pave the way for a sustainable future in agriculture and beyond.

Appendices

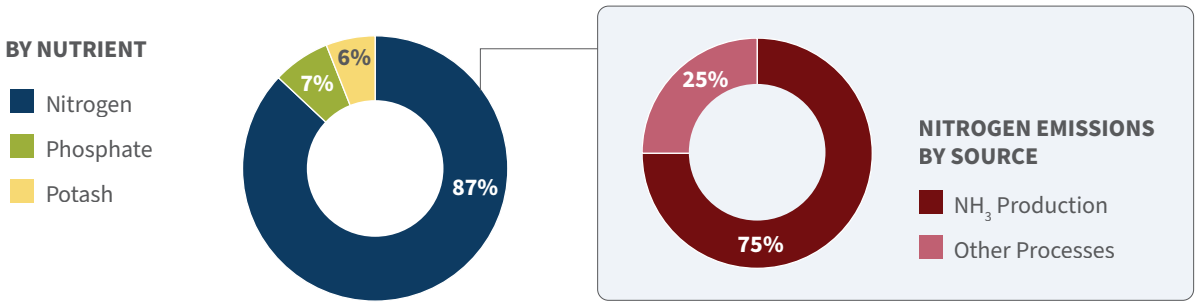
Appendix 1: Emissions from Fertilizer Production

Emissions stemming from fertilizer production are highly dependent on the nutrient produced. Three nutrients are needed for healthy plant growth: nitrogen, phosphorus, and potassium (potash). Phosphorus and potash are extracted from deposits and have comparatively low production emissions; in contrast, conventional nitrogen fertilizers are directly reliant on fossil fuels, incurring substantial emissions. This issue is exacerbated because nitrogen is the most critical — and subsequently the most used — fertilizer nutrient for plant growth.

All synthetic nitrogen fertilizers use ammonia as a precursor. Ammonia itself can be used as a fertilizer in the form of anhydrous ammonia. Conventional ammonia synthesis begins with hydrogen production via steam methane reformation (SMR), a carbon-intense process in which hydrogen is extracted from natural gas. Next, the hydrogen is combined with atmospheric nitrogen using the Haber-Bosch process, yielding ammonia. Accounting for the natural gas and energy consumption, producing 1 ton of ammonia emits around 2.34 tons of CO_2, equaling 2.85 tons CO_2 per ton of nitrogen. For comparison, the most common potash fertilizer, muriate of potash, has a per nutrient carbon intensity of 0.42 tons CO_2 per ton potash.[v] The stark difference in per nutrient carbon emissions illustrates why nitrogen is the primary nutrient contributing to fertilizer emissions. Further processing of ammonia into other nitrogen-based fertilizers will incur additional emissions based on fuel and electricity consumption needs and will further increase the per nutrient carbon intensity.

A look at fertilizers purchased in Minnesota confirms the dominance of nitrogen as the driver of production emissions. In 2020, nitrogen sales made up half of Minnesota's nutrient tonnage purchased but accounted for 87% of total associated production emissions. Exhibit A1 illustrates that nitrogen emissions significantly outpace emissions from other nutrients, with the main driver being the production of ammonia.

Exhibit A1 Production Emissions Breakdown of Fertilizer Nutrients Purchased in Minnesota



RMI Graphic. Source: RMI Analysis; MDA, **https://www.mda.state.mn.us/pesticide-fertilizer/fertilizer-use-sales-data**; International Fertiliser Society, **https://www.fertilizerseurope.com/publications/the-carbon-footprint-of-fertilizer-production-regional-reference-values/**; Brentrup et al., **https://www.researchgate.net/publication/329774170_Updated_carbon_footprint_values_for_mineral_fertilizer_from_different_world_regions**

v Based on RMI analysis.

The SMR process to separate hydrogen from natural gas produces over half of the production emissions associated with ammonia. Since hydrogen is used a chemical feedstock, the only way to decarbonize this component of the value chain is to produce hydrogen cleanly, with electrolysis powered by renewable energy. If renewable energy is also used to power the auxiliary stages of ammonia and fertilizer production, emissions are eliminated and what remains is a zero-carbon, green ammonia product.

A special case arises with the popular and versatile fertilizer urea. In 2020, urea and other urea-based fertilizers made up over 62% of Minnesota's total nitrogen sold, reflecting a broad preference for urea. Urea is currently produced in integrated facilities where conventional ammonia production routes the CO_2 stream from the SMR flue to the ammonia outlet where they are combined to form urea. Using this method, some of the CO_2 emissions from SMR hydrogen production are temporarily captured within the urea, though they will be released downstream during usage.

Due to urea's reliance on CO_2, decarbonizing urea production must involve a net-zero source of carbon. Biogenic CO_2 emerges as the most attractive candidate for early production, as alternatives such as direct air capture are far out from commercial viability. Minnesota has ample sources of biogenic CO_2 from its ethanol refineries, as well as a number of pulp and paper mills. This route is already being considered through the Heartland Hydrogen Hub, a DOE-funded project that spans Minnesota, North Dakota, and South Dakota. As part of the hub, Xcel Energy is planning a large-scale urea plant that use CO_2 offtake from ethanol refineries combined with green ammonia.[48]

It is important to note that Minnesota does not produce its own fertilizers but instead imports fertilizer from other states. In addition to production emissions, transportation of fertilizer incurs emissions at different rates depending on method. This dimension was analyzed to gauge its impact as part of the whole fertilizer value chain.



Emissions from Fertilizer Transportation

Since conventional ammonia production relies on natural gas as a feedstock, ammonia production is found primarily in regions with large oil and gas operations, such as the US Gulf Coast. Fertilizer produced in the Gulf Coast is distributed across the country by truck, rail, water, and pipeline, with trucking and rail carrying the vast majority of fertilizer tonnage. Rail is typically used for longer distances, carrying larger volumes, whereas trucks are used for distribution along shorter routes. Trucking is much more carbon intensive than rail: in 2017, national transportation of fertilizer using only trucking contributed over 10 times the emissions as fertilizer transported by only rail.[vi]

Emissions from fertilizer transportation to Minnesota were estimated to be around 130,000 tons CO_2. Compared with the total life cycle of said fertilizers, transportation amounts to only 1.7% of total emissions. While comparatively small, emissions savings can still be achieved through distributed ammonia production by producing fertilizers onsite, negating the need for transportation.

Urea, again, presents a unique scenario, this time within the discussion of transportation. A complicating factor in the integration of biogenic CO_2 for green urea production is the transportation of CO_2. Although CO_2 pipelines are an established technology, pipelines would be difficult to integrate into the decentralized model because an extensive network would be needed. An alternative would be trucked CO_2, with the trade-off being increased cost and potential associated transportation emissions. These constraints may signal green urea production is more suited for a centralized, dedicated plant position close to its CO_2 source.

Emissions from Fertilizer Usage

The usage of fertilizers releases emissions upon application to the soil. Nitrogen fertilizers are especially polluting and are responsible for nearly all use emissions. When applied, a proportion of nitrogen is lost through denitrification, in which organisms convert fertilizer to nitrous oxide (N_2O). N_2O is a greenhouse gas 298 times more potent than CO_2 that diffuses through the soil and is lost to the air. Though released in small quantities, the intensity of N_2O has significant ramifications for the climate. Assuming all fertilizer purchased in Minnesota in 2020 was used, Minnesota experienced approximately 5.6 million tons of CO_2e emitted due to fertilizer use alone, around 2.5 times the emissions associated with the production of said fertilizers.[vii]

Herein lies Minnesota's main fertilizer emissions problem. As discussed above, fertilizer production does not occur in Minnesota; it is instead imported from out-of-state. With transportation emissions low, emissions actually occurring in Minnesota are almost entirely due to fertilizer use. Unfortunately, this issue cannot be solved by green ammonia, since the end product is identical to its conventionally produce counterpart and will behave identically.

In addition to denitrification, the loss of nitrogen to the atmosphere as gaseous ammonia, or volatilization, can occur when nitrogen is reconverted to ammonia in the soil. This results in an indirect loss of nitrogen as N_2O. Gaseous losses are greatest with surface application due to proximity to the atmosphere. Another way nitrogen can be lost is with leaching, where nutrients move past the roots of plants where they cannot be absorbed. This is more likely to happen with fertilizers that are converted into nitrate in the soil, which is not held on to by soil particles. The likelihood of nitrogen loss is not only dependent on the fertilizer used. Soil conditions, such as acidity, temperature, and moisture, can affect how much nitrogen is lost.

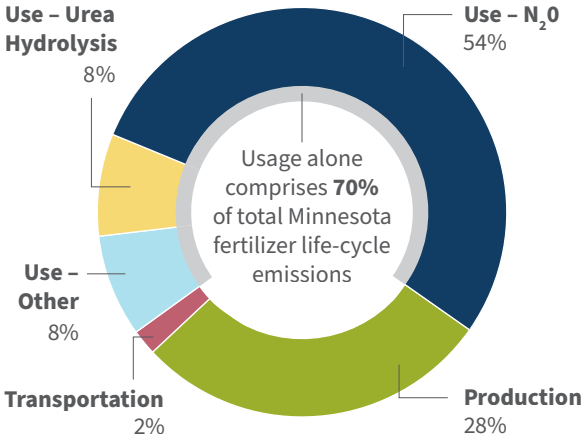
vi RMI analysis
vii RMI analysis

Urea is unique in the emissions attributed to it. As explained above, urea requires a source of CO_2 in its production — CO_2 that is initially captured within the fertilizer but released upon usage in a process called urea hydrolysis. To have a truly green product, the CO_2 for production must come from net-zero sources such as biomass. But urea does not only emit CO_2; it is one of the highest emitters of N_2O. Urea is not readily absorbed by crops, so it must be converted to ammonium and nitrate. This process begins with the hydrolysis process mentioned above: The naturally occurring soil enzyme urease converts urea into ammonia and carbamic acid (part of carbamic acid ultimately becomes CO_2 and is released to the atmosphere). A portion of the ammonia will be lost to the atmosphere as gas before it can be converted to ammonium and nitrate. These issues are exacerbated by urea's common surface application use as a top dressing.

Fertilizer usage emissions are also exacerbated by inefficient use (see Exhibit A2). Excess nitrogen applied is lost to the environment with no benefit. An important step to addressing fertilizer emissions is increasing nitrogen use efficiency, which has been found to be the single most effective method to reduce fertilizer emissions.[49]

Exhibit A2

Total Emissions Attributable to Minnesota Fertilizer Purchases by Value Chain Component



RMI Graphic. Source: RMI Analysis; MDA, **https://www.mda.state.mn.us/pesticide-fertilizer/fertilizer-use-sales-data**; International Fertiliser Society, **https://www.fertilizerseurope.com/publications/the-carbon-footprint-of-fertilizer-production-regional-reference-values/**; Brentrup et al., **https://www.researchgate.net/publication/329774170_Updated_carbon_footprint_values_for_mineral_fertilizer_from_different_world_regions**; US CBO, **https://www.cbo.gov/publication/58861**; US Census Bureau, **https://data.census.gov/table/CFSAREA2017.CF1700A13?q=cf1700a13&comm=22**; USGS, **https://www.usgs.gov/centers/national-minerals-information-center/commodity-statistics-and-information**

Inhibitors can be deployed with fertilizers to decrease nitrogen loss. Urease inhibitors, specific to urea use, apply a coating to urea that restricts the process of urea hydrolysis and subsequently the formation of ammonia, which prevents loss of that ammonia as gas. Regulation of urea has precedent; Germany requires the addition of a urease inhibitor when urea is used. Another form of inhibitor is a nitrification inhibitor, which delays the conversion of ammonium to nitrite. This gives crops more time to absorb ammonium while reducing nitrification, the process that releases N_2O to the atmosphere. Nitrification inhibitors can also prevent leaching since ammonium is held by soil, in contrast to nitrate (which nitrite converts to), which travels past the roots. Application can affect the output of emissions, too. Quickly incorporating urea into the soil or injecting urea, rather than simply applying it the topsoil, can limit the loss of nitrogen. However, this is not always possible due to various constraints such as no-till zones.

Ultimately, the most effective mitigation method for urea involves a transition away from urea and urea-based fertilizers to alternative nitrogen fertilizers. Urea and urea ammonium nitrate could be replaced by fertilizers that perform better on a use emissions base, such as ammonium nitrate.[50] Ammonium nitrate's nitrogen is readily available for crop uptake and does not suffer from use emissions to the same degree as urea.

The issue of fertilizer use requires more investigation because it represents more than twice the emissions of fertilizer production. Emissions mitigation is best used in tandem; Gao and Serrenho have found that combining a variety of use-based emissions mitigation approaches with green ammonia production can reduce 84% of worldwide synthetic nitrogen fertilizer emissions by 2050.49 For Minnesota, a holistic reduction of agriculture emissions requires a collection of mitigation efforts that include a deep look into use emissions. However, deployment of green ammonia is an important step to decarbonization of the industry.

Appendix 2: Model Methodology and Additional Information

We utilized an optimization model to assess the competitive position of DGA in Minnesota and evaluate its main cost factors and their dynamics. This model allows the analysis of levelized cost of green ammonia production for a given geographical location under various market scenarios.

Renewable Energy Generation Assumptions

Scenario	Unit	Value
CONSERVATIVE 2024		
Wind Lifetime	years	30
Onshore Wind Capex	$/kW	1333.32
Onshore Wind Turbine Height	Height in meters	100
Onshore Wind Turbine Type	Type of turbine (see ReNinja options)	Vestas V80 2000
Onshore Wind Operations & Maintenance (O&M)	$/kW-year	29.75
Solar Lifetime	years	30
Solar Single-Axis Tracking Capex	$/kW	1331.39
Solar Degradation	%/year	0.005
Solar O&M	$/kW-year	0.005
MODERATE 2024		
Wind Lifetime	years	30
Onshore Wind Capex	$/kW	1292
Onshore Wind Turbine Height	Height in meters	100
Onshore Wind Turbine Type	Type of turbine (see ReNinja options)	Vestas V80 2000
Onshore Wind O&M	$/kW-year	29.20
Solar Lifetime	years	30
Solar Single-Axis Tracking Capex	$/kW	1289.51
Solar Degradation	%/year	0.005
Solar O&M	$/kW-year	0.005

Scenario	Unit	Value
ADVANCED 2024		
Wind Lifetime	years	30
Onshore Wind Capex	$/kW	1273.96
Onshore Wind Turbine Height	Height in meters	100
Onshore Wind Turbine Type	Type of turbine (see ReNinja options)	Vestas V80 2000
Onshore Wind O&M	$/kW-year	28.10
Solar Lifetime	years	30
Solar Single-Axis Tracking Capex	$/kW	1259.24
Solar Degradation	%/year	0.005
Solar O&M	$/kW-year	0.005
CONSERVATIVE 2030		
Wind Lifetime	years	30
Onshore Wind Capex	$/kW	1273.96
Onshore Wind Turbine Height	Height in meters	100
Onshore Wind Turbine Type	Type of turbine (see ReNinja options)	Vestas V80 2000
Onshore Wind O&M	$/kW-year	28.65
Solar Lifetime	years	30
Solar Single-Axis Tracking Capex	$/kW	1205.96
Solar Degradation	%/year	0.005
Solar O&M	$/kW-year	0.005
MODERATE 2030		
Wind Lifetime	years	30
Onshore Wind Capex	$/kW	1150.00
Onshore Wind Turbine Height	Height in meters	100
Onshore Wind Turbine Type	Type of turbine (see ReNinja options)	Vestas V80 2000
Onshore Wind O&M	$/kW-year	27.00
Solar Lifetime	years	30
Solar Single-Axis Tracking Capex	$/kW	1038.44
Solar Degradation	%/year	0.005
Solar O&M	$/kW-year	0.005

Scenario	Unit	Value
MODERATE 2030		
Wind Lifetime	years	30
Onshore Wind Capex	$/kW	1095.87
Onshore Wind Turbine Height	Height in meters	100
Onshore Wind Turbine Type	Type of turbine (see ReNinja options)	Vestas V80 2000
Onshore Wind O&M	$/kW-year	23.70
Solar Lifetime	years	30
Solar Single-Axis Tracking Capex	$/kW	917.37
Solar Degradation	%/year	0.005
Solar O&M	$/kW-year	0.005

Ammonia and Nitrogen Production Assumptions

Production Scale	10 ktpa	50 ktpa	500 ktpa
Cost of a HB Reactor	$1,726/t$NH_3$	$1143/t$NH_3$	$630/t$NH_3$
Cost of Pressure Swing Adsorption (PSA)	$48/t$N_2$	$26/t$N_2$	–
Cost of Air Separation Unit (ASU)	–	–	$140/t$N_2$

Assumptions for Blue and Grey Ammonia Production Pathways

Parameter	Value
Capex Grey Steam Methane Reformer (SMR)	$713/kg$H_2$ per day
Opex Grey SMR	$22.11/kg$H_2$ per day
Capex Blue SMR	$1735/kg$H_2$ per day
Opex Blue SMR	$48.66/kg$H_2$ per day
Capture Rate Blue SMR	85%
Value of 45Q*	$0.51/kg$H_2$
HB Capex	$500/t$NH_3$
ASU Capex	$75/t$NH_2$
NH_3 Storage	$160/t$NH_3$
ASU & HB O&M	4% of Capex
Storage O&M	3% of Capex

* Section 45Q refers to the production tax credit based on the quantity of CO_2 captured and stored during the hydrogen synthesis process.

Appendix 3: Target Development

Targets for 2030 were developed using the Minnesota fertilizer sales data for 2020 as a baseline, with the assumption that sales remain flat over the decade. This approach was chosen since sales growth was slow decade over the previous decade, with only a 4% increase from 2010 to 2020. In addition, Minnesota has signaled its desire to reduce nitrogen fertilizer usage, which was assumed to offset any potential market growth.

Assuming all nitrogen fertilizer sold is synthetic with ammonia as a precursor, ammonia demand was determined by taking the total nitrogen sold (747,576 tons) and proportionally calculated based on the nitrogen content of ammonia by weight (82%), for a total of 911,678 tons of ammonia. The emissions-reduction targets of 50% for 2030 and net-zero for 2050 were chosen, in line with Minnesota's stated goals. Green ammonia was assumed to have zero production emissions associated with it, meaning half of ammonia demand by 2030 (approximately 450,000 tons) and all ammonia demand by 2050 (approximately 900,000 tons) would need to come from green ammonia.

Endnotes

1. *Making Net-Zero Ammonia Possible: An Industry-Backed, 1.5C-aligned Transition Strategy*, Mission Possible Partnership, 2022, **https://3stepsolutions.s3-accelerate.amazonaws.com/assets/custom/010856/downloads/Making-1.5-Aligned-Ammonia-possible.pdf**.

2. Eric Thorp, "EU Industrial Demand Uptick Could Be Short-Lived," *Energy Intelligence*, February 14, 2023, **https://www.energyintel.com/00000186-4f13-d910-af96-5f9b6d9f0000**, and "Iowa Production Cost," United States Department of Agriculture (USDA), accessed May 26, 2024, **https://mymarketnews.ams.usda.gov/viewReport/2863**.

3. *2023 Fact Book*, Nutrien, 2023, **https://nutrien-prod-asset.s3.us-east-2.amazonaws.com/s3fs-public/uploads/2024-01/Nutrien_2023Fact%20Book_Update_12624.pdf**.

4. "Kenya Nut and Talus Renewables to Manufacture Sustainable Fertilizer with Hydrogen," *Talus Ag*, November 2, 2023, **https://www.talusag.com/blog/kenya-nut-and-talus-renewables-to-manufacture-sustainable-fertilizer-with-hydrogen**.

5. "Trammo, ReMo Sign Green Ammonia MOU; Illinois Plant Expected Up in 2024," *Green Markets*, October 21, 2022, **https://fertilizerpricing.com/trammo-remo-sign-green-ammonia-mou-illinois-plant-expected-up-in-2024**.

6. "First Ammonia and Uniper announced cooperation on green ammonia project in Texas," *Uniper*, October 31, 2023, **https://www.uniper.energy/news/first-ammonia-and-uniper-announced-cooperation-on-green-ammonia-project-in-texas**.

7. Isabel Keltie, "Minbos and Stamicarbon sign MoU on green ammonia," *World Fertilizer Magazine*, June 30, 2022, **https://www.worldfertilizer.com/environment/30062022/minbos-and-stamicarbon-sign-mou-on-green-ammonia/**, and "Maire Tecnimont Group Starts Preliminary Work on Renewable Power-to-Fertilizer Plant in Kenya," Stamicarbon, May 17, 2021, **https://www.stamicarbon.com/press-release/maire-tecnimont-group-starts-preliminary-work-renewable-power-fertilizer-plant-kenya**.

8. "Pacific Green Fertilizer," Atlas Agro, accessed May 30, 2024, **https://www.atlasagro.ag/projects/pacific-green-fertilizer/**.

9. *Fertilizer Logistics and Transportation*, The Fertilizer Institute, March 2024, **https://www.tfi.org/wp-content/uploads/2024/03/TFI-fertilizer-logistics-and-transportation.pdf**.

10. *Fertilizer Logistics and Transportation*, 2024.

11. *Fertilizer Logistics and Transportation*, 2024.

12. Alexandra Diemer and Luca Zullo, *Securing a Better Future Through the Development of Green Ammonia Fertilizer Pathways*, 2023.

13. Michael Langemeier, Michael Gunderson, and Nathanael Thompson, "2023 Purdue Crop Cost and Return Guide," *Purdue Agricultural Economics Report*, Purdue University, 2023, **https://ag.purdue.edu/commercialag/home/paer-article/2023-purdue-crop-cost-and-return-guide/#:~=Variable%20cost%20per%20bushel%20in%202023%20is%20estimated,to%20%244.98%20per%20bushel%20from%202013%20to%202015**.

14. "Fertilizer Use and Sales Data," Minnesota Department of Agriculture, accessed May 30, 2024, **https://www.mda.state.mn.us/pesticide-fertilizer/fertilizer-use-sales-data**.

15. "Lead Green Ammonia," West Central Research and Outreach Center, University of Minnesota, accessed May 30, 2024, **https://wcroc.cfans.umn.edu/news/lead-green-ammonia**.

16. "Heartland Hydrogen Hub," University of North Dakota Energy & Environmental Research Center, accessed May 30, 2024, **https://undeerc.org/research/projects/heartland-h2-hub.html**.

17. "Scores are in on 2nd fertilizer plant proposals competing for $125M," Agweek, 2024, **https://www.agweek.com/agribusiness/scores-are-in-on-2-nd-fertilizer-plant-proposals-competing-for-125m**.

18. *2024 MN Energy Factsheet*, Clean Energy Economy Minnesota, 2024, **https://www.cleanenergyeconomymn.org/wp-content/uploads/2024/04/2024-Minnesota-Energy-Factsheet.pdf**.

19. "Profile Analysis: Minnesota," EIA, accessed May 20, 2024, **https://www.eia.gov/state/analysis.php?sid=MN**.

20. *2024 MN Energy Factsheet*, 2024.

21. "Profile Analysis: Minnesota," 2024.

22. "Biden-Harris Administration Invests in Clean Energy and Fertilizer Production to Strengthen American Farms and Businesses as Part of Investing in America Agenda," USDA, March 28, 2024, **https://www.usda.gov/media/press-releases/2024/03/28/biden-harris-administration-invests-clean-energy-and-fertilizer#:~:text=Through%20FPEP%2C%20USDA%20provides%20grants,fertilizer%20production%20plants%20and%20more**.

23. "US National Clean Hydrogen Strategy And Roadmap | Hydrogen Program," Energy.gov, n.d. **https://www.hydrogen.energy.gov/library/roadmaps-vision/clean-hydrogen-strategy-roadmap**.

24. "Fact Sheet: President Biden Sets 2030 Greenhouse Gas Pollution Reduction Target Aimed at Creating Good-Paying Union Jobs and Securing US Leadership on Clean Energy Technologies," The White House, April 22, 2021, **https://www.whitehouse.gov/briefing-room/statements-releases/2021/04/22/fact-sheet-president-biden-sets-2030-greenhouse-gas-pollution-reduction-target-aimed-at-creating-good-paying-union-jobs-and-securing-u-s-leadership-on-clean-energy-technologies/**.

25. *Industrial Decarbonization Roadmap*, US DOE, September 2022, **https://www.energy.gov/sites/default/files/2022-09/Industrial%20Decarbonization%20Roadmap.pdf**.

26. "Regional Clean Hydrogen Hubs," Energy.gov, n.d., **https://www.energy.gov/oced/regional-clean-hydrogen-hubs-0**.

27. "Regional Clean Hydrogen Hubs Selections for Award Negotiations," Energy.gov, n.d., **https://www.energy.gov/oced/regional-clean-hydrogen-hubs-selections-award-negotiations**.

28. "Biden-Harris Administration to Jumpstart Clean Hydrogen Economy with New Initiative to Provide Market Certainty and Unlock Private Investment," Energy.gov, n.d., **https://www.energy.gov/articles/biden-harris-administration-jumpstart-clean-hydrogen-economy-new-initiative-provide-market**.

29. "Title 17 Clean Energy Financing," Energy.gov, n.d., **https://www.energy.gov/lpo/title-17-clean-energy-financing**.

30. "Inflation Reduction Act of 2022," Energy.gov, n.d., **https://www.energy.gov/lpo/inflation-reduction-act-2022**.

31. "Title 17 Clean Energy Financing."

32. *Building a Clean Energy Economy Guidebook*, CleanEnergy.gov, January 2003, Version 2, **https://www.whitehouse.gov/wp-content/uploads/2022/12/Inflation-Reduction-Act-Guidebook.pdf**.

33. *Greenhouse gas emissions in Minnesota 2005-2020: Biennial report to the Legislature tracking the state's contribution to emissions contributing to climate change*, Minnesota Pollution Control Agency and Department of Commerce, January 2023, **https://www.pca.state.mn.us/sites/default/files/lraq-2sy23.pdf**.

34. "The Next Step in Our Clean Energy Transition," Our Minnesota Climate, n.d., **https://climate.state.mn.us/next-step-our-clean-energy-transition**.

35. Kelsey Misbrener, "Minnesota advances legislation to improve large-scale solar + storage permitting," Solar Power World, May 21, 2024, **https://www.solarpowerworldonline.com/2024/05/minnesota-advances-legislation-large-scale-solar-permitting**.

36. "Green Fertilizer Program, Minnesota Department of Agriculture, n.d., **https://www.mda.state.mn.us/green-fertilizer-program**.

37. "Minnesota Nitrogen Fertilizer Management Plan," Minnesota Department of Agriculture, n.d., **https://www.mda.state.mn.us/pesticide-fertilizer/minnesota-nitrogen-fertilizer-management-plan**.

38. *Greenhouse gas emissions in Minnesota 2005-2020: Biennial report to the Legislature tracking the state's contribution to emissions contributing to climate change*, Minnesota Pollution Control Agency and Department of Commerce, January 2023, **https://www.pca.state.mn.us/sites/default/files/lraq-2sy23.pdf**.

39. "Green Fertilizer Program," n.d.

40. "Minnesota Joins US Climate Alliance, Commits to Upholding Paris Climate Agreement," Minnesota Department of Commerce, February 13, 2024, **https://mn.gov/commerce/news/?id=17-606815**, and "State Energy Financing Institution (SEFI) Toolkit," Energy.gov, n.d., **https://www.energy.gov/LPO/SEFIToolkit**.

41. "Pricing for LPO Financing by Program," Energy.gov, n.d., **https://www.energy.gov/lpo/articles/pricing-lpo-financing-program**.

42. "CSEA Approves $7 Million Loan for Fertilizer Development," North Dakota Industrial Commission, March 4, 2024, **https://www.ndic.nd.gov/sites/www/files/documents/Press-Releases/2024/240304-CSEA-Fertilizer-Development-Loan.pdf**.

43. "Rural Energy for America Program (REAP)," USDA Rural Development, April 8, 2024, **https://www.rd.usda.gov/inflation-reduction-act/rural-energy-america-program-reap**.

44. "Fertilizer Production Expansion Program," USDA Rural Development, May 30, 2024, **https://www.rd.usda.gov/programs-services/business-programs/fertilizer-production-expansion-program**.

45. "Minnesota Job Skills Partnership," Minnesota Department of Employment and Economic Development, accessed May 30, 2024, **https://mn.gov/deed/business/financing-business/training-grant/**.

46. "Questions and Answers: The Net-Zero Industry Act and the European Hydrogen Bank*," European Commission, March 16, 2023, **https://ec.europa.eu/commission/presscorner/detail/en/qanda_23_1666**.

47. Rachel Terada, *Readiness for Hourly: US Renewable Energy Tracking Systems, Center for Resource Solutions*, June 15, 2023, **https://resource-solutions.org/wp-content/uploads/2023/06/Readiness-for-Hourly-US-Renewable-Energy-Tracking-Systems.pdf**.

48. "The Heartland Hydrogen Hub," Agricultural Utilization Research Institute, March 11, 2024, **https://www.youtube.com/watch?v=_wzOCTwZ8kc**.

49. Yunhu Gao and André Cabrera Serrenho, "Greenhouse Gas Emissions from Nitrogen Fertilizers Could Be Reduced by up to One-fifth of Current Levels by 2050 with Combined Interventions," *Nature Food*, February 9, 2023, **https://doi.org/10.1038/s43016-023-00698-w**.

50. *Decision 2013/20: Compliance by the European Union with its Obligations to Report on Strategies and Policies for Air Pollution Abatement (ECE/EB.AIR/129)*, United Nations Economic Commission for Europe, 2015, **https://unece.org/DAM/env/documents/2015/AIR/EB/ECE_EB.AIR_129_ENG.pdf**.

TJ Kirk, Anton Krimer, Sheran Munasinghe, Elina Rodriguez, Joaquin Rosas, and Quailan Homann, *Roadmap for Distributed Green Ammonia in Minnesota*, RMI, 2024, **https://rmi.org/roadmap-for-distributed-green-ammonia-in-minnesota/**.

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Local ammonia project could stabilize fertilizer supply for southern Minnesota farmers

Noah Fish

BLUE EARTH, Minn. — A southern Minnesota farm cooperative is working with energy and technology partners on a project that could create the first commercially available supply of locally produced ammonia fertilizer in Minnesota.

Central Farm Service announced a partnership with TalusAg and CleanCounts to build modular ammonia production systems in the city of Blue Earth in Faribault County, that would convert electricity, air and water into anhydrous ammonia, a key nitrogen fertilizer widely used in corn production.

The project depends on $8 million in funding from Minnesota's Renewable Development Account, which supporters hope lawmakers will approve during the current legislative session.

If completed, the system would produce more than 40 tons of ammonia per day and supply most of the annual fertilizer needs of Central Farm Service members, according to project leaders.

"Ammonia prices have swung by more than 300% in recent years," said KC Graner, president and CEO of Central Farm Service. "Local production gives our member-owners a level of control and predictability they've never had before."

Major input for corn production

Anhydrous ammonia is one of the most common nitrogen fertilizers used by corn growers across the upper Midwest. Graner said Central Farm Service, a farmer-owned cooperative serving members in southern Minnesota and northern Iowa, typically supplies between about 11,000 and 16,000 tons of ammonia annually depending on weather and the length of the fall fertilizer application window.

The proposed facility could produce roughly 12,000 tons annually, supplying between 80% and 100% of the cooperative's ammonia demand.

"That would pretty well service the majority of the acres that see anhydrous ammonia application in the fall in our geography," Graner said.

At typical application rates, the project could provide fertilizer for more than 200,000 acres of cropland, he said.

State funding request

Supporters are asking the Minnesota Legislature to approve funding through the Renewable Development Account, a program established to support innovative energy technologies.

Rob Davis of CleanCounts said the funding would help establish commercial-scale ammonia production in Minnesota.

“It’ll be the first time since we’ve been growing corn in the state of Minnesota that a co-op has been able to sign a 10-year fixed price for anhydrous ammonia,” Davis said.

The proposal is expected to be introduced later this legislative session by Rep. Paul Anderson, R-Starbuck, and Sen. Aric Putnam, D-St. Cloud, who chair agriculture committees in their respective chambers.

Reducing supply volatility

Nearly all ammonia fertilizer used in Minnesota agriculture is produced outside the state and transported long distances, often from facilities along the Gulf Coast. That reliance on distant production has exposed farmers to supply disruptions and large price swings tied to global energy markets.

Graner said fertilizer prices have occasionally climbed above $1,000 per ton in recent years, sometimes rising several hundred dollars during the fertilizer application season.

“The biggest thing would be shielding farmers from the supply crunches we’ve seen every fall,” he said. “We’ve seen massive price swings in season.”

Using excess wind power

Project leaders say the ammonia systems could use electricity generated by wind turbines during periods when energy production is curtailed because the electric grid cannot absorb additional power.

Davis said using that electricity to produce ammonia could help ensure wind generation is not wasted while supporting local industries.

“Ammonia is just one more tool in the tool belt to help make productive use of those wind turbines that are already existing on the landscape,” he said.

Part of broader industry effort

The Blue Earth project is also tied to the newly formed Minnesota Made Ammonia Coalition, which brings together organizations from agriculture, energy, manufacturing and environmental sectors to support development of a local ammonia industry.

“What's exciting about this is how many different parts of Minnesota's economy this touches, and it's not some distant future — it can happen here, now,” said Rachel Stuckey, executive director of the Minnesota Conservative Energy Forum. “We have the energy, the research, and demand, from agriculture to mining to manufacturing. This coalition is about connecting all of those pieces and turning them into a real statewide industry.”

Advocates say Minnesota is well-positioned to develop the industry because of its wind resources and research conducted at the University of Minnesota’s West Central Research and Outreach Center in Morris, which has studied renewable-powered ammonia production for more than a decade.

“Local production of nitrogen fertilizer makes sense for many reasons,” said Mike Reese, Green Ammonia Research Lead and Director of Operations at University of Minnesota’s West Central Research and Outreach Center. “Primarily, farmers are able to lock in the cost of a key crop input and, the dollars that typically go elsewhere to purchase this fertilizer remain in our communities helping support rural economies.”

Graner said cooperative investments like this are intended to help farmers manage major input costs and maintain profitability.

“Our job at the cooperative is to do the types of things for growers that they don’t have the capacity to do on their own,” he said. “We’re always trying to find innovative ways to help them compete and sustain their farms.”

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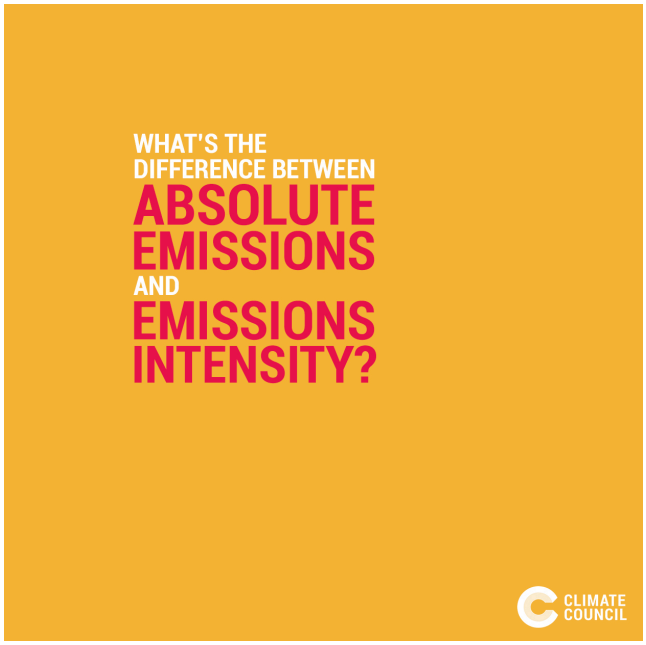
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Australia's capacity to reduce emissions is very high. For example, our emission intensity is roughly twice that of the USA (twice as many tonnes of CO2-e* per $million GDP) and about 2.5 times that of Europe. So really, we have the capacity to reduce our emissions more than either the USA or Europe. However, because we start from such a high emission intensity we have a lot of "low-hanging fruit" and even relatively easy reductions in emission intensity will look large in terms of percentage.

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Discover How U.S. Cows Are Shattering Milk Production Effficiency Records!

Friday, August 23rd, 2024

Prepare to be amazed by the U.S. dairy cows breaking and shattering milk production records. Curious about their secrets and what it means for global demand? Keep reading.

Summary: Have you ever been intrigued by the fierce competition among top-producing states in the U.S. dairy industry? This competition has led to a significant increase in milk production, with the average U.S. milk cow producing 63% more milk in 2023 than in 1990. Michigan, a key player in this competition, leads in efficiency. The U.S. dairy industry has become a global powerhouse, with increased per-cow output and butterfat levels. Over the past decade, U.S. dairy cows saw per cow output rise by 11%, from 21,722 lbs. in 2013 to 24,117 lbs. in 2023. Michigan tops the nation, producing 27,564 lbs. of milk per cow per year, an 81% increase since 1990. Advanced technology, genetic selection, and artificial insemination have led to healthier cows producing more milk, driving cash revenues to an expected $42 billion in 2022, up from $35 billion in 2013.

- Michigan leads the nation in milk production per cow, with an 81% increase since 1990.
- The average U.S. milk cow produced 63% more milk in 2023 compared to 1990.
- Butterfat levels in U.S. milk have significantly improved, contributing to increased dairy output.
- Top-producing states include Texas, New York, Wisconsin, and Idaho, with Texas leading in 2023.
- Advanced technology, genetic selection, and artificial insemination are critical drivers of increased efficiency.
- U.S. dairy cows saw an 11% rise in per-cow output over the past decade.
- The U.S. dairy industry's efficiency has made it a global powerhouse, with notable increases in cash revenues.



U.S. dairy cows, milk production, per-cow output, fat content of milk, butterfat level, milk cow, milk production efficiency, Michigan, Wyoming, Colorado, Texas, New York, Wisconsin, Idaho, milk yields, United Kingdom, Argentina, European Union, China, dairy farming innovations, advanced technology, milking machines, automated feeding systems, precision agricultural equipment, labor expenses, productivity, genetic selection, artificial insemination, healthier cows, cash revenues, dairy sector.

Over the past decade, the U.S. dairy industry has experienced a significant surge in milk production, marking a period of remarkable growth and transformation. Dairy cows have broken new milk production records, with the per-cow output increasing by an impressive 11%, from 21,722 lbs. in 2013 to 24,117 lbs. in 2023. This surge in production is not limited to the quantity of milk. Butterfat production in the United States has also seen a substantial increase of 23%, with the average butterfat content rising from 3.76% in 2013 to 4.11% in 2023. These consistent advances in efficiency have resulted in the typical U.S. milk cow producing 63% more milk in 2023 than in 1990. This unprecedented growth underscores the transformation of U.S. dairy farming, making our

cows some of the most productive in the world. But what is the key to these extraordinary accomplishments, and how have American dairy producers remained ahead of global competition? Let's delve into this record-breaking trend and explore the methods that produce these incredible outcomes.

Location	Average Milk Yield per Cow (lbs.)	% Increase Since 1990
Michigan	27,564	81%
Wyoming	26,000	100%
Colorado	24,000	51%
Texas	25,500	70%
Wisconsin	25,400	65%
Canada	23,900	Not Available
United Kingdom	19,000	Not Available
Argentina	17,000	Not Available
European Union	16,000	Not Available
China	11,000	Not Available
New Zealand	10,000	Not Available

The Golden Era of U.S. Dairy Farming: A Decade of Unparalleled Efficiency

The last decade has been nothing short of transformative, inspiring American dairy producers to reach new heights of efficiency. Have you ever wondered how much more efficient contemporary dairy farming has become? Let's look at some incredible data demonstrating the nationwide growth in milk production efficiency.

In only ten years, per-cow milk production increased by 11%, with the typical dairy cow producing 24,117 pounds of milk in 2023, up from 21,722 in 2013. Such significant increases do not end there. The fat content of milk—an important indication of quality—has also increased significantly. The average butterfat level in U.S. milk grew from 3.76% in 2013 to 4.11% in 2023, representing a 23% increase in total butterfat production.

Think about it. What exactly does this imply for the industry? This means that dairy producers may now produce more and higher-quality milk with fewer cows using innovative procedures and technologies created and perfected over time. These numbers highlight a remarkable trend of increased efficiency and production, establishing a new standard for dairy farming throughout the globe.

State-by-State Breakdown: The Top Performers in Milk Production

Let's look at the top milk producers in each state. Michigan has taken the top rank in terms of production. Michigan's dairy cows produce an astonishing 27,564 pounds of milk per cow per year, representing an 81% increase since 1990. This gigantic tower exemplifies the state's continuous pursuit of efficiency.

Wyoming is just a little behind, and it is also seeing remarkable development. Despite being a minor player, Wyoming's handful of dairy cattle have improved their game by more than tripling their milk supply since 1990, achieving second place. Colorado isn't slacking either; the state ranked third with a 51% increase in milk output over the same time.

The battle for fourth place is fierce among several central dairy states. Texas, for example, leads with yields surprisingly close to those of other heavyweights like New York, Wisconsin, and Idaho, averaging roughly 25,500 pounds per cow annually. However, the Lone Star State edged the competition to take the top spot in 2023.

Each state provides something unique, yet all are dedicated to pushing the limits of dairy efficiency. These states are boosting the dairy business in the United States to new heights by combining innovation, innovative technology, and a never-ending pursuit of progress.

How Do U.S. Dairy Farms Stack Up Against Their International Counterparts?

How do U.S. dairy farms compare to their overseas counterparts? Let's look at the data to discover why milk production in the United States is the industry gold standard.

Dairy cows in the United States are outperforming all other countries regarding milk production. In 2023, cows in the United States produced an average of 24,117 pounds of milk each year. In contrast, Canadian dairy cows generated 3% less milk while being the second most efficient globally. This implies that each cow in the United States produced around 724 pounds of extra milk yearly.

Looking farther out, the margin of advantage becomes much more enormous. The United Kingdom ranked third, behind by a considerable 24%, implying that its cows generated around 5,788 lbs. less milk per head. Argentina has significantly lower yields, behind the United States by 30%. Argentine cows generate around 7,235 kg. Less milk is produced per cow each year.

The European Union, a significant participant in the global dairy market, also lagged. With 34% lower yields than U.S. cows, this equates to an annual deficit of around 8,200 pounds per cow. Moving to Asia, China's dairy farming innovations have yet to overcome the gap; their outputs still fall short of what American cows generated in 1990. This reflects the United States' longtime leadership in efficient milk production.

Finally, consider New Zealand, which is known for its dairy exports. Despite worldwide renown, New Zealand's milk per cow fell 59% behind the United States. That's a stunning discrepancy, meaning that New Zealand cows generated roughly 14,235 pounds less milk each cow each year.

These figures show that American dairy farms are competing and improving milk production efficiency. This unprecedented productivity enables U.S. farmers to supply local and worldwide dairy demand successfully.

Ever Wondered What's Behind This Surge in Efficiency? Let's Dive into the Magic Formula Transforming U.S. Dairy Farming

Ever wonder what's behind this spike in efficiency? Look at the golden recipe revolutionizing dairy farming in the United States. Technology is playing an important role. Advanced milking machines, automated feeding systems, and precision agricultural equipment have transformed farm operations. These advancements are more than flashy gadgets; they are game changers that lower labor expenses and boost productivity.

However, technology alone does not tell the whole story. Breeding procedures have undergone a significant revision, and this is a crucial factor behind the surge in efficiency in U.S. dairy farming. Genetic selection and

artificial insemination enable producers to raise cows with better characteristics, leading to healthier cows that produce more milk. According to the USDA, selective breeding has considerably increased milk output per cow over the previous several decades. This, combined with advanced technology and cutting-edge agricultural management strategies, forms a multidimensional approach that keeps U.S. dairy farms at the forefront of global milk production, establishing new benchmarks for efficiency and productivity.

Let us remember cutting-edge agricultural management strategies. Farmers use data analytics to track cow health, milk quality, and overall farm performance. These data-driven solutions facilitate informed decision-making, improving resource use and cow wellbeing.

It is a multidimensional method that combines technology, research, and intelligent management. This comprehensive plan keeps U.S. dairy farms at the forefront of global milk production, establishing new benchmarks for efficiency and productivity. So, the next time you drink a glass of milk, know there's much thought and creativity behind that creamy pleasure.

The Ripple Effect: How Higher Milk Yields Are Transforming the Entire Dairy Industry

Higher milk yields aren't beneficial to individual dairy farms; they're practically rewriting the economic script for the dairy sector. Let us break it down. Dairy producers benefit immediately from improved milk output. Additional milk production produces additional products, including butter, cheese, and yogurt, resulting in a more diverse income stream. According to USDA research, the U.S. dairy sector's cash revenues would amount to $42 billion in 2022, up from $35 billion in 2013 [USDA research]. That's about a 20% increase in a little under a decade!

Furthermore, higher efficiency leads to decreased expenses per unit of milk produced. This is crucial because it increases farmers' competitiveness in the global market. Farmers in the United States have maintained operating expenses roughly unchanged while increasing output by optimizing feed, improving genetic selection programs, and introducing modern milking technology. This efficiency makes U.S. dairy goods appealing to overseas purchasers, increasing profitability. According to the National Milk Producers Federation, exports accounted for around 16% of total U.S. milk output in 2022, up from 9% a decade before [NMPF Statistics].

These advances impact the whole economy, not just the agriculture sector. Increased milk production benefits downstream businesses in transportation, retailing, and equipment manufacturing. Dairy farming has the potential to generate significant economic multiplier effects. In Michigan, for example, the dairy business provides more than $15 billion to the state's economy yearly, sustaining approximately 40,000 employees directly and indirectly. These figures demonstrate how increases in agricultural efficiency may benefit the whole area's economy.

The increase in milk output has far-reaching economic consequences. For dairy producers in the United States, this implies more profitability and a more decisive competitive advantage. For the larger economy, it represents strong growth and employment creation. These interconnected advantages demonstrate why efficiency in milk production is more than simply a source of pride; it is also a cornerstone of economic health.

The Bottom Line

In today's dairy sector, U.S. dairy cows' increasing efficiency and production are extraordinary. Over the past decade, milk yields and component levels have improved significantly, propelling American dairy farmers to the forefront of global dairy production. States such as Michigan, Wyoming, and Colorado have established remarkable standards, with milk production continually increasing due to agricultural discoveries and developments.

Globally, the United States outperforms other major dairy-exporting countries such as Canada, the United Kingdom, and New Zealand. This domination fulfills the increasing demand for dairy products and establishes new industry norms globally.

How can you use these insights and improvements to improve dairy operations? What actions can you take to make your dairy farm more efficient and join the ranks of these record-breaking producers?

Learn more:

- Unveiling the USDA Milk Report: Find Out Which States are Leading and Lagging!
- The Hidden Crisis: Why U.S. Dairy Farms Are Disappearing Faster Than Ever!
- USDA Reveals Sharp Decline in March 2024 Milk Production Across Top Dairy States

(T231, D1)

About Author



Andrew Hunt

Andrew grew up on a dairy farm in southern Ontario — which means he learned about herd management, hard work, and tight margins long before it became a career. He went on to build an animal genetics marketing company, running campaigns that actually moved the needle in a notoriously tough-to-reach industry. Today he channels that background into The Bullvine, where he writes about genetics, farm business, and the decisions that separate profitable operations from struggling ones. He doesn't pull punches, and dairy farmers seem to appreciate that.

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- The 52-Point Gap Hiding in Every Jersey Sire Catalog in Canada
- How Albert Cormier Rewrote the Rules of Global Holstein Business – and Made the Whole Industry Catch Up
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Fifty years of environmental progress for United States dairy farms

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ABSTRACT

Dairy farms in the United States have changed in many ways over the past 50 yr. Milk production efficiency has increased greatly, with ~30% fewer cows producing about twice the amount of milk today. Other improvements include increases in crop yields, fuel efficiency of farm equipment, and efficiency in producing most resources used on farms (e.g. electricity, fuel, fertilizer). These improvements have led to changes in the environmental impact of farms. Through simulation of representative dairy farms in 1971 and 2020, changes in nutrient losses and farmgate life cycle assessments of greenhouse gas (GHG) emissions, fossil energy use, and blue (ground and surface) water use were determined for 6 regions and the United States. For all environmental metrics studied, intensities expressed per unit of fat- and protein-corrected milk produced were reduced, but the total effects over all farms or milk produced increased for 5 of the 13 environmental metrics. Reductions in the impacts of dairy farms in the eastern United States were offset by large increases in western regions because of a major increase in cow numbers in the West. The national average intensity of GHG emissions decreased by 42%, which gave just a 14% increase in the total GHG emissions of all dairy farms over the 50-yr period. The intensity of fossil energy use decreased by 54%, with the total for all farms decreasing by 9%. Water use related to milk production decreased in intensity by 28%, but due to the large increase in dairy production in the dry western regions that have a greater dependence on irrigated feed crops, total blue water use increased by 42%. Major pathways of nitrogen loss included ammonia volatilization, leaching, and denitrification, where total ammonia emissions related to US dairy farms increased by 29%, while leaching losses decreased by 39%, with little change in nitrous oxide emissions. Simulated nitrogen and phosphorus runoff losses totaled for all dairy farms decreased by 27% to 51% through more efficient fertilizer use, reduced tillage, and greater use of cover crops. Emissions of methane and reactive non-methane volatile organic compounds increased by 32% and 53%, respectively, due to greater use of long-term manure storage and silage stored in bunkers and piles. Although much progress has been made in improving production efficiency, continued improvements with new strategies and technologies are needed to meet the demand for dairy products and mitigate total environmental impacts, particularly in view of projected climate variability.
Key words: dairy farm, life cycle assessment, gaseous emission, environmental impact, Integrated Farm System Model (IFSM)

INTRODUCTION

Changes have occurred in the technology, management, and resultant performance of US dairy farms over the past 50 yr. The most important change has been a major increase in milk production per cow and a subsequent improvement in feed efficiency (Capper et al., 2009; USDA NASS, 2023a). Crop yields have also increased, particularly for corn harvested as silage and grain (USDA NASS, 2023a). Tractors and other equipment have become more efficient in the use of fuel, and farm inputs such as fuel, electricity, and fertilizers have benefited through improved efficiency and reduced fossil energy use in production. A shift toward the use of fewer tillage operations and greater use of cover crops

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The list of standard abbreviations for JDS is available at adsa.org/jds-abbreviations-24. Nonstandard abbreviations are available in the Notes.

has provided environmental benefits primarily through reduced runoff loss of sediment and nutrients (Kleinman et al., 2019). Farm size and related manure handling strategies have also seen major changes (USDA NASS, 2023b), and their resulting effects on the environment are mixed.

Previous studies have looked at historical changes in the US dairy industry to document improvements in production efficiency and their resulting effects on environmental impacts (Naranjo et al., 2020; Capper et al., 2009; Capper and Cady, 2020). These studies were based upon general representations of dairy production in different time periods. They focused on greenhouse gas (**GHG**) emissions along with fossil energy, water, and land use. These studies emphasized environmental intensities, which provide the impact per unit of milk produced. The improvement made in feed efficiency has provided substantial reductions in these intensities. Although environmental intensities have improved, the amount of milk produced has also increased, which has increased the total impacts over all milk produced (Capper et al., 2009; Capper and Cady, 2020). A more comprehensive life cycle assessment is needed to explore a broader array of environmental metrics at the farm scale. Although intensity measures are important, a more in-depth study of the totals over all farms is needed.

A procedure has been developed and used to quantify the current national environmental impacts of US dairy farms using the Integrated Farm System Model (**IFSM**; Rotz et al., 2021). This procedure includes assessments of important resources used, gaseous emissions, and nutrient losses to the environment. Related issues such as biodiversity, soil quality, and animal welfare are also important, but they were beyond the scope of this work. By applying this modeling procedure to dairy farms around 1970, changes can be determined for various measures of farm performance and environmental impact. Farm data generated can also provide inventory for a more comprehensive life cycle assessment (**LCA**) covering more categories of environmental effects. This type of linkage of the farm model and LCA software has been demonstrated in the assessment of beef production in the United States (Rotz et al., 2019; Putman et al., 2023) and mitigation strategies applied to a dairy farm in the eastern United States (Kim et al., 2019).

Our objective was to model dairy farms throughout 6 regions of the United States and the full country for 1971 and 2020 to quantify improvements made in performance and environmental impacts, including both intensities and totals over of all farms or milk produced. Environmental metrics included differences in various forms of N, P, and C loss from farms and the farmgate LCA of GHG emissions, fossil energy use, and water use from ground and surface sources.

MATERIALS AND METHODS

Dairy farms were modeled in 2020 and 1971 using the procedure developed by Rotz et al. (2021). For each period, farms in each of 6 regions of the United States (Figure 1) were represented using 20 production systems. This gave a total of 120 systems representing US dairy production (Supplemental Tables S1 and S2; see Notes). Production systems, referred to as farms, were located in counties within each region where most of the milk was produced at that time (USDA NASS, 2023a). Farms were modeled to represent the range of sizes and associated management strategies found in those locations during each period. No human or animal subjects were used, so this analysis did not require approval by an Institutional Animal Care and Use Committee or Institutional Review Board.

As described by Holly et al. (2019), production systems consisted of 5 management types, defined as confined, semi-confined, management intensive grazing, organic, and Amish. All farm types were considered in 2020, but management intensive grazing and certified organic dairy farms were not common in 1971. To accommodate the diversity within each region, the number of farms of each size and associated management were set considering the portion that each contributed to the total milk produced in the region (USDA NASS, 2023b).

Modeling Procedure

Dairy production systems were simulated using the IFSM (USDA ARS, 2023). The IFSM used process-level simulation to predict the performance and environmental effects of each production system. The model simulated crop production, feed use, animal production, and the return of manure nutrients back to the land for 20 to 25 years of weather (Rotz et al., 2022). Daily growth and development of crops were a function of soil water and N availability and weather. Simulated tillage, planting, and harvest operations determined labor, fuel, and other resources used, the timeliness of operations, crop losses, and the nutritive quality of feeds produced. Animal feed intake, milk production, and nutrient excretion were a function of the type and nutrient contents of the feeds fed.

Nutrients (N, P, K) and C were tracked within the model to predict losses to the environment and whole-farm balances (Rotz et al., 2022). Paths of N loss included NH_3 volatilization, NO_3^- losses through leaching and runoff, and N_2O, N oxide, and dinitrogen emissions through nitrification and denitrification processes and engine emissions. Carbon emissions included CH_4 from enteric and manure sources, along with biogenic CO_2. Anthropogenic CO_2 emissions were released through fossil

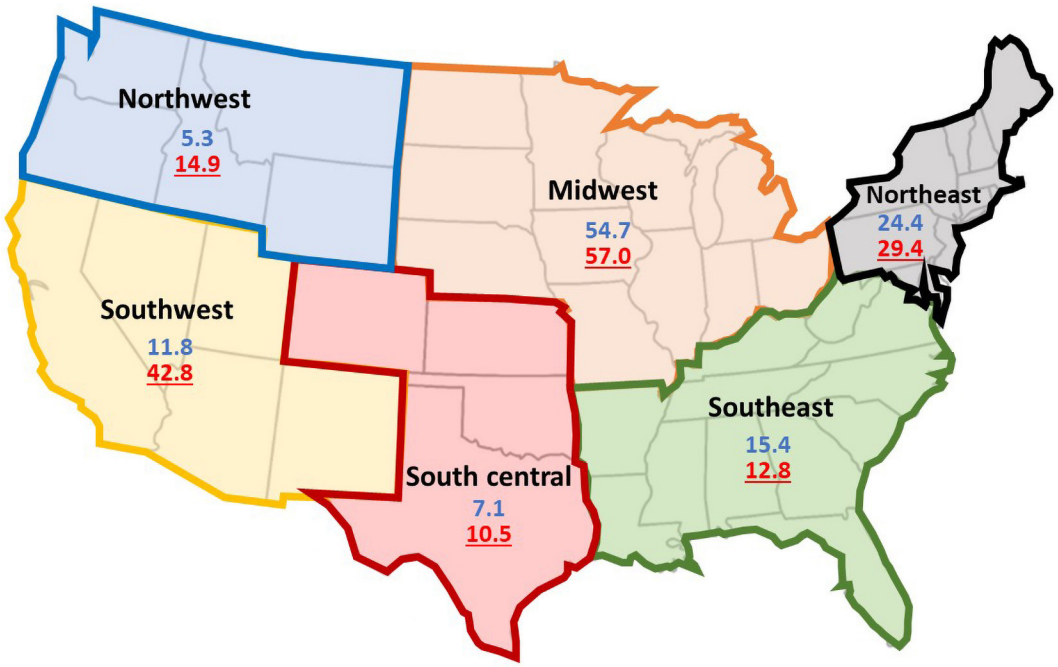


Figure 1. Regions of the United States as defined for our evaluation and comparison of the environmental impacts of dairy farms. Numbers are billion pounds of milk produced for each region in 1971 (blue) and 2020 (red; USDA NASS, 2023a).

fuel combustion and the decomposition of lime and urea fertilizer (IPCC, 2006). Other simulated losses included erosion of sediment and runoff across farm boundaries of sediment-bound and dissolved P (Rotz et al., 2022). Reactive volatile organic compound (**VOC**) emissions were predicted using a mass transfer model and estimated initial concentrations of important VOC when silage or manure were exposed to ambient air (Bonifacio et al., 2017). Emission processes were modeled using dynamic relationships influenced by temperature, wind speed, precipitation, soil conditions, and management practices (Rotz et al., 2014; Bonifacio et al., 2015; Rotz et al., 2022). Whole-farm mass balances of N, P, K, and C were the sum of nutrient imports in feed, fertilizer, deposition, and fixation, minus the exports in losses, manure leaving the farm, and feeds, milk, and animals sold.

The C balance did not include a change in long-term soil C concentration. Over this 50-yr period, some shifting occurred from the use of perennial forages to greater use of corn silage, which would indicate the potential for a loss of soil C (Gamble et al., 2021). The increased use of cover crops and no-till crop establishment may partially offset this loss (Blanco-Canqui, 2022). Considering the lack and uncertainty of available information, we chose to assume no change in soil C levels.

Following Livestock Environmental Assessment and Performance (LEAP, 2016) guidelines, a cradle-to-farmgate LCA was performed within IFSM (Rotz et al., 2022). The system boundary was that of the farm. Major components included the soil, feed crops, machinery operations for tillage, planting, harvest, feeding, and manure handling, cattle, animal facilities, and manure handling processes. Cattle included lactating and non-lactating cows, replacement heifers less than a year old, and older heifers. System inputs or resources used included fuel, electricity, fertilizer, purchased feeds and supplements, purchased animals, machinery, seed, and pesticides. Outputs or products were milk, animals sold, excess feeds sold, and various forms of C, N, and P losses. The resource inputs required and the various emissions were determined through the dynamic simulation.

The farmgate LCA determined the annual net GHG emissions, fossil energy use, and blue water use (Rotz et al., 2022). The annual GHG emission was the sum of the emissions of CH_4, N_2O, and anthropogenic CO_2 converted to CO_2 equivalents (**CO_2e**) using 100-yr global warming potentials of 28 for CH_4, 265 for N_2O, and 1 for CO_2 (Myhre et al., 2013). Emissions included direct emissions from the production system, as well as indirect N_2O emissions that occurred elsewhere in the environment resulting from transformation of NH_3 and NO_3^- lost from the production system (IPCC, 2006). Fossil energy use included fuel used in farm operations (machinery and truck use) along with that used to produce resources consumed on the operation. Blue water was defined as freshwater from ground and surface water sources, which was primarily water used for irrigated crop production,

along with that used for parlor cleaning, drinking, and cooling of cattle.

Environmental metrics associated with the production of resources used on dairy operations (upstream sources) were included in the LCA (Rotz et al., 2022). Upstream sources were those associated with production of the farm inputs (e.g. fuel, electricity, fertilizer). Annual quantities of each used were obtained through the farm simulations. Emission or consumption factors used for these upstream sources were set to reflect those of each period (Table 1).

Allocation was used to remove environmental effects associated with farm coproducts. A method recommended by the International Dairy Federation (IDF, 2015) was used to determine the portion of the farm impacts appropriated between milk and animals leaving farms for use in beef production. This was a physical allocation method reflecting feed energy used to produce the total annual body weight of culled calves, heifers, and cows exported relative to the weight of milk sold. Replacement heifers were produced on farms as part of the production system. The number produced was set to meet the replacement rate of the herd allowing for mortality and a few culled heifers. Calves not retained for replacements were sold soon after birth. When excess feeds produced on the farm were sold, all metrics associated with their production were removed from the dairy system.

Emissions and resource requirements for handling manure on the farm, including composting and anaerobic digestion on some operations, were included in our assessment of dairy production. Manure exported from

Table 1. Environmental intensities for the production of purchased resources and feeds, including transport and upstream sources, used in IFSM to assess cradle-to-farm gate environmental impacts of dairy production systems[1]

		GHG emission, kg CO_2e		Fossil energy use, MJ		Blue water use, L		Reactive N loss, g N	
Resource	Unit	1971	2020	1971	2020	1971	2020	1971	2020
Energy[2,3,4]									
Fuel	/L	0.70	0.55	5.2	4. 1	7.7	3.7	0.60	0.48
Gas	/m^3	0.50	0.40	3.2	2.5	0	0	0.93	0.74
Electricity	/kWh	0.52	0.42	7.6	5.7	33.1	21.6	0.34	0.27
Fertilizer[2,3]									
Nitrogen	/kg N	6.59	3.90	46.2	30.0	15	10	1.1	0.91
Phosphate	/kg P_2O_5	2.17	1.70	65.0	55.0	3.86	3.53	2.3	1.9
Potash	/kg K_2O	0.69	0.56	14.0	12.0	4.8	4.0	0.66	0.53
Lime[2,3]	/t	14	14	450	450	650	550	11	9
Machinery[3,4]	/kg mass	9.5	7.6	53.3	42.6	15	10	1.5	1.2
Seed[3,5]	/kg	0.62	0.50	106	85	11	50	7.0	7.0
Pesticide[3,4]	/kg active ingredient	28	22	344	275	34	34	14	11
Plastic wrap[3,4]	/kg	2.5	2.0	84	67	—	—	—	—
Purchased or sold heifers[5]	/kg BW	17	14	45	25	200	200	230	160
Purchased feed									
Corn[5]	/kg DM	0.54	0.41	4.3	2.8	56[6]	55[6]	9.9	6.6
Corn silage[5]	/kg DM	0.36	0.22	3.0	1.6	61	56	2.3	2.9
Alfalfa[5]	/kg DM	0.32	0.23	3.4	1.9	230	230	0.7	0.4
Alfalfa/grass hay[5]	/kg DM	0.46	0.36	4.1	3.0	160	180	3.5	2.6
Organic bedding[5]	/kg DM	0.23	0.16	2.9	2.0	22	17	2.6	1.3
Soybean/canola meal[7]	/kg DM	0.90	0.60	11.6	6.6	56	64	12.6	6.5
Corn gluten feed[7]	/kg DM	0.48	0.41	6.6	4.3	26	25	4.4	2.9
Protein mix[3,8]	/kg DM	1.10	0.90	11.0	9.0	30	20	1.8	1.0
General byproduct feed[3,8]	/kg DM	0.30	0.20	2.5	2.0	15	10	0.0	0.0
Distiller's grain[7]	/kg DM	0.58	0.50	5.5	4.6	37	36	6.3	4.2
Fat[3,8]	/kg DM	1.7	1.3	23	14	100	100	8.8	5.9
Mineral and vitamin mix[3,8]	/kg DM	1.9	1.6	20	16	60	60	—	—
Milk replacer[3]	/kg DM	15.1	12.1	74.0	58.1	1,450	1,450	55	45

[1]CO_2e = CO_2 equivalents.

[2]SimaPro 9.1 (PRé Sustainability; https://simapro.com/).

[3]Rotz et al. (2021) with 1971 values scaled using the change in energy intensities.

[4]Greenhouse Gases, Regulated Emissions, and Energy use in Transportation model (GREET, Argonne National Laboratory, U.S. Department of Energy, https://www.energy.gov/eere/greet, 2020).

[5]Obtained from simulated farms using the IFSM (USDA ARS, 2023).

[6]Water use is a weighted average of irrigated and non-irrigated crops in the United States (USDA NASS, 2023a). For irrigated crops in the western regions of the country, values are 300 and 700 L/kg DM for corn silage and alfalfa hay, respectively.

[7]Derived from simulations of crop farms using the IFSM (USDA ARS, 2023) and processing resource use with an economic allocation among the coproducts of the grains produced.

[8]Unpublished data (Greg Thoma, University of Arkansas, Fayetteville, AR).

farms was treated as a residual, i.e., no environmental effects associated with manure handling and storage were allocated to manure leaving the farm. When manure was applied to crops on the farm that were not used as dairy feed, that manure was also considered as exported because it was no longer part of the dairy system. Emissions from manure after removal from the farm were not included in the dairy system (LEAP, 2016).

Individual emissions of methane (CH_4), nitrous oxide (N_2O), and anthropogenic carbon dioxide (CO_2) were also studied. Nitrogen losses from farms included ammonia (NH_3) emissions to the atmosphere and nitrate (NO_3^-) losses through leaching to groundwater and runoff in surface water. Phosphorus runoff losses across farm boundaries in both soluble and sediment-bound forms were also compared. Emissions of reactive non-methane VOC were considered from silage and manure sources on the farms. The VOC included several compounds, but alcohols were the predominant forms (Bonifacio et al., 2017; Rotz et al., 2022).

Both the intensity expressed per unit of milk produced and the total of all farms or milk produced were compared between the 2 periods in time. Milk produced was converted to fat- and protein-corrected milk (**FPCM**) based upon 4.0% fat and 3.3% protein (IDF, 2015; Rotz et al., 2022). This correction accounted for differences in the solids content of milk among production systems.

Dairy Production Systems in 2020

For 2020, dairy production systems were modeled as documented by Rotz et al. (2021) (Supplemental Table S2). Minor adjustments were made to update this analysis from 2019 to 2020. The major change was to update the milk production data to that reported for 2020 (USDA NASS, 2023a). This increased the national production by 2.6%, with most of the increase coming in the western regions. Milk fat content also increased to 3.92% (USDA NASS, 2023a), which further increased the calculated value of FPCM (Rotz et al., 2021). This increase in milk production had minor effects throughout the system, as predicted by the model, including changes in feed consumption, manure production, and nutrient cycling.

Another important change was an update of the environmental intensities assumed for producing purchased resources and feeds used on farms (Table 1). This change was made to be more consistent with other recent life cycle assessments done with IFSM in conjunction with LCA software (Putman et al., 2023). We also wanted to be consistent in representing the changes that occurred in these upstream intensities from 1971 to 2020. The current upstream intensities did not change much, with some increasing and some decreasing. The greatest change was a decrease in GHG emissions in electricity production, which was partly due to recent improvements in production efficiency and greater use of renewable energy sources. Environmental intensities of purchased feeds were updated by simulating the production of feed crops with IFSM to determine their individual environmental intensities. Transportation effects were added, considering the weight transported and general transportation distances. Following processing, total production and transport intensities were allocated among feed components (e.g. hulls, meal, oil) based upon their relative economic values (Rotz et al., 2021).

Dairy Production Systems in 1971

Representative dairy production systems (farms) in 1971 were modeled using the same general procedure. However, with less data available for the earlier period, some differences were present in information sources. For the more important parameters, such as milk production, milk fat content, animal numbers, farm size, dairy locations, crops grown, and crop yields, data from the USDA National Agricultural Statistics Service (USDA NASS, 2023a,b) were used to guide the parameterization of farms (Table 2; Supplemental Table S1). Other survey information was also consulted (USDA APHIS, 2003; USDA ERS, 2007). For other parameters that were not as critical in our analysis, we relied on expert opinion obtained through interviews with producers and those working with dairy producers at that time.

As was done for the 2020 assessment, milk production per cow on individual farms was set so that the weighted average production per cow equaled that reported for each region in 1971 (USDA NASS, 2023a). Values for individual farms were set considering cattle breed and grazing use, with a trend toward greater production on larger farms (Supplemental Table S1). Milk production was converted to FPCM using reported values for fat content (USDA NASS, 2023a). Reported values were only available since 1981, but values before 2000 were relatively constant with an increase since 2010. Thus, the 1981 average fat content of 3.65% was used for 1971. The weighting among farms was based on farm size (number of cows). The distribution of farm sizes within each state was obtained from the Agricultural Census (USDA NASS, 2023b) for that period. The weight factor for each farm was the percentage of farms of that size in the region, which represented the portion of milk produced on farms of that size.

Farm locations were determined using county-level dairy cow records for that period (USDA NASS, 2023a). Counties containing a major portion of the cows were selected within each of the major dairy states of the region with different locations for each farm. Farms were

Table 2. Characteristics of representative dairy farms simulated across the United States for 1971 and 2020[1]

Characteristic	Unit	1971			2020		
		Minimum	Maximum	Mean	Minimum	Maximum	Mean
Animals and feeding							
Cows per farm	number	15	2,000	173	20	10,000	1,400
Heifers per farm	number	11	1,130	97	0	5,700	853
Milk yield[2]	kg/cow/yr	2,600	5,900	4,471	5,885	12,300	9,966
First-lactation cows	%	20	30	26	20	42	34
Diet protein content	%	16.9	19.3	18.0	16.0	19.0	17.0
Diet phosphorus content	%	0.45	0.52	0.48	0.33	0.45	0.39
Cropland							
Alfalfa	ha	0	300	30	0	1,000	91
Grass	ha	0	300	39	0	400	65
Corn	ha	0	400	30	0	1,800	218
Small grain	ha	0	50	12	0	160	4
Total cropland	ha	17	900	111	0	3,000	389
Pasture[3]	ha	0	150	15	0	250	21
Animal density	AU/ha	0.76	6.5	1.6	0.9	20	3.7
Crop yields[2]							
Alfalfa	t DM/ha	4.2	15.3	9.4	7.0	14.4	10.6
Grass	t DM/ha	1.5	10.1	5.8	1.1	11.1	5.9
Corn grain	t DM/ha	2.5	7.1	4.7	3.2	11.5	8.4
Corn silage	t DM/ha	7.4	16.5	11.8	11	24.3	18.0
Small grain	t DM/ha	0.7	2.8	2.1	3.8	5.5	4.6
Small grain silage	t DM/ha	5.2	7.6	6.3	3.2	11.0	6.5
Inorganic nitrogen fertilizer							
Alfalfa	kg N/ha	0	0	0	0	20	1.5
Grass	kg N/ha	0	300	90	0	200	50
Corn	kg N/ha	50	200	89	0	220	102
Small grain	kg N/ha	20	100	43	0	140	25
Inorganic phosphate fertilizer							
Alfalfa	kg P_2O_5/ha	10	50	31	0	55	6.1
Grass	kg P_2O_5/ha	0	35	17	0	30	0.3
Corn	kg P_2O_5/ha	15	40	31	0	30	4.7
Small grain	kg P_2O_5/ha	0	30	21	0	30	1.5
Lime, alfalfa	t/ha/yr	0	2.0	1.0	0	2.5	0.7
Lime, other crop	t/ha/yr	0	1.5	0.5	0	2.5	0.4
Manure export[4]	%	0	60	8.7	0	100	22

[1]Characteristics of individual farms can be found in Supplemental Tables S1 and S2 (see Notes).

[2]USDA NASS (2023a).

[3]Total land grazed primarily as pasture. Most pasture is used for heifers and dry cows, particularly in 1971. Some intensively managed grazing of lactating cows in 2020. Pasture is part of grassland.

[4]Includes manure applied to crops not producing feed.

simulated using 25 yr of historical daily weather for the selected location. Most weather data were obtained from the Integrated Surface Database of the National Climatic Data Center (NOAA, 2019). When measured weather data were not available, data were obtained from the University of Idaho (Moscow, ID) gridMET meteorological data system (Abatzoglou, 2013; Hardegree, 2023). Daily data included solar radiation; minimum, maximum, and mean temperature; precipitation; and wind speed. Available data did not always go back to 1971, but the oldest data available were used.

As was done for the 2020 simulated farms, soils were selected to represent those most common at the location. Predominant soils in the county were identified using the Web Soil Survey (NRCS, 2019) by defining an area of interest over agricultural land in the county. Characteristics of a predominant soil were used, which included clay, silt, and sand content, bulk density, available water-holding capacity, and pH. A different soil was used for each farm to get a broad representation of the region.

Feed crop production on each farm was guided by the predominant crops found in the selected county at that time (USDA NASS, 2023a). Crop options included corn silage, corn grain, alfalfa hay or silage, grass hay or silage, winter wheat or barley, spring oat grain, or spring oat silage planted with alfalfa. Wheat or barley grain were sold as cash crops, with straw harvested for bedding. Using soil and weather data for the farm location, model parameters for each simulated crop were adjusted to obtain an average yield within the range reported by USDA NASS (2023a) for that period at the location. Corn plant population was also reduced in 1971 (USDA NASS, 2023a; Table 3), which contributed to changes in grain and silage yields.

Table 3. Technical and management changes for dairy farms from 1971 to 2020

Characteristic	Unit	1971	2020
Diesel fuel use[1]	% of tractors and trucks	50	90
Diesel fuel efficiency[2]	% improvement	—	17
Corn plant population[3]	Plants/ha	60,000	84,000
Cover/double crop use	% of farms	8	30
Anaerobic digesters[4]	% of milk produced	0	7
Dry cow portion of herd	% of cows	15	15
Cow mortality	%/yr	4	5
Calf mortality	% of births	10	10
Heifer mortality	%/yr	2	2
Twin rate	%	4	4
Artificial insemination use[5]	% of farms	80	95

[1]Portion of engines using diesel fuel vs. gasoline.

[2]Improvement in fuel efficiency of diesel engines (Nebraska Tractor Test Laboratory, Lincoln, NE; https://tractortestlab.unl.edu/).

[3]From USDA NASS (2023a).

[4]Portion of total milk produced on farms using anaerobic digesters (US EPA, 2020).

[5]Bulls were included on farms where artificial insemination was not used.

To complete parameterization of the representative farms, additional information was needed on management procedures. This included tillage, cropping, grazing, feeding, housing, and manure management practices. These less critical parameters were set based upon the expert opinion of producers and those working with dairy producers at that time. This included most of the following management practices where quantifiable information did not exist.

Full tillage systems using multiple tillage tools were normally used in 1971. In the eastern regions, this often included a moldboard plow followed by disk and harrow operations. Complete inversion and disaggregation of the soil led to greater sediment and nutrient runoff. In western regions, multiple tillage operations were used, but chisel or disk plows were often the primary tillage operation.

Compared with current farms, inorganic fertilizers were used more heavily in 1971 with less consideration of nutrients available from manure. Application rates varied across regions as influenced by soil conditions and crops grown (Supplemental Table S1). Nitrogen fertilizer rates varied from 50 to 200 kg N/ha for corn and 0 to 300 kg N/ha for grass depending upon crop needs and expert opinion on common application rates (Table 2). Annual phosphate fertilization rates varied from 10 to 50 kg P_2O_5/ha, with average values of 31 kg P_2O_5/ha for alfalfa and corn and 17 kg P_2O_5/ha on grassland (Table 2). Lime (calcium carbonate) was applied on farms where a low soil pH was reported, with average annual rates varying from 0 to 2.0 t/ha, with a mean of 1.0 t/ha for alfalfa and 0.5 t/ha for all other crops (Table 2).

Planting and harvest dates of crops and the relative maturity index of corn were set to best represent agronomic practices at the farm location and to provide appropriate yields and suitable harvest moisture contents for corn silage. Corn was harvested as silage on all dairies that grew corn. When corn production exceeded silage needs, the remaining corn was harvested and fed as high-moisture or dry grain. Grain harvest primarily occurred on northeastern and midwestern farms. Alfalfa and grass were harvested as silage or dry hay for preservation. Tower silos were used on most farms in the midwestern and eastern regions, with bunkers and piles primarily used in the western regions. Dry hay was normally harvested in small rectangular bales and stored inside a barn or shed to reduce losses and preserve nutrients. On farms where excess feed or a cash-crop was produced and sold, the resource use and emissions associated with the feed sold were excluded from the LCA.

Pasture was used for lactating cows on grazing, Amish, and semi-confinement farms (Supplemental Table S1). On smaller confinement farms in the eastern regions, grazing was also used for heifers. Grazing occurred for 5 to 12 mo of the year depending upon the location. Pasture was not a large portion of land on most farms, averaging about 13% of total dairy farmland in 1971 (Table 2). The pastureland available was set to reflect the continuous grazing and often overstocking practices at that time. For lactating cows, a portion of their forage need was met through grazing during summer months, but the major portion of their diet most often came through conserved feeds. When grazing was used for heifers and nonlactating cows, pasture met most of their feed needs during summer months.

Most dairies produced enough forage to meet herd requirements. Corn grain was commonly grown for feed in eastern regions, but additional grain and other concentrates were often required to meet energy requirements of the herd. Purchased supplemental feeds were also used to

meet or exceed protein and mineral requirements of all animal groups (Rotz et al., 2022). Byproduct feeds, including distiller's grain, were used to supplement energy and protein needs (Table 1). Diet protein and P contents were assigned to each farm to average 6% greater protein and 23% greater P compared with 2020 (Table 2). Values were assigned to individual farms considering the forage used (greater values when alfalfa or grazing were used) with a trend toward more efficient use on larger farms.

Cattle genetics were primarily Holstein, with 12% of farms using Jersey or cross-bred cattle (Supplemental Table S1). Lactating cow replacement rates varied from a low of 20% for some grazing farms to a high of 30% in high-producing confined herds. This rate averaged 24% less than that used in 2020 (Table 2). A random calving cycle was used on all dairies except for a few grazing farms where spring calving was used to better align pasture availability with animal needs.

Animal housing and manure handling systems varied among farms and over time (Supplemental Tables S1 and S2). In 1971, smaller farms (<100 cows) in the East normally used tiestall barns with daily manure hauling and short-term manure storage. Heifers were often housed in bedded pack barns where accumulated manure was removed and applied to fields in the spring and fall. Thus, manure from these farms was handled in semisolid and solid forms. On larger farms (≥100 cows) in the East and sometimes in the West, cattle were housed in freestall barns where manure was removed daily, stored in a slurry or liquid form for 4 to 12 mo in a tank or earthen basin, and then applied to cropland. In the western regions, cows on larger farms were often housed in open lots where solid manure was collected and stored before spreading on cropland. Manure was normally broadcast on cropland where it remained on the surface for an extended time, but it was incorporated by tillage soon after spreading on a few farms (Supplemental Table S1).

Fuel efficiency improved over time through increased use of diesel engines on tractors and other farm equipment, improvements in engine design, and the use of larger and more efficient machinery. Fuels used varied, with more gasoline use in 1971, primarily for older tractors and trucks commonly found on farms at that time. Along with this, diesel fuel efficiency was 17% less in 1971 (Table 3).

Regional and National Analyses

Milk production was a critical factor in the comparison of dairy farms of 1971 and 2020. A check was made to ensure that the average milk production per cow simulated for each region agreed with that reported by USDA NASS (2023a) for 1971 or 2020. Average per cow production of each region was determined as the total of the reported milk production of all states of the region divided by the total number of dairy cows reported in those states. This value was compared with the weighted average milk production per cow of the simulated dairies in the region to ensure that they were equal. Average production per cow for the United States was also determined as the total milk produced in the country divided by the reported total number of dairy cows. The weighted average of the 6 regions equaled this value.

All effects were compared using weighted average intensities and regional and national totals. Weighted intensities were determined for each region, where the weight factor was the portion of the regional milk coming from the state where the farm was located multiplied by the portion of farms in the state of similar size. In 2020, anaerobic digesters were used, which required a special weighting factor. For regions where digesters were found, one of the farms was simulated using a digester, where the weight factor was the portion of cows in the region on farms using digesters (Rotz et al., 2021).

Life cycle feed consumption was determined for each period as the feed consumed by heifers and cows on each farm, as simulated by IFSM (Rotz et al., 2022). This included forages, grain, and other concentrates. The total feed consumed on dairy farms was allocated between dairy and beef production using the allocation method described previously (IDF, 2015). Although variation existed among farms, on average, 73% of the feed consumed in 1971 was allocated to dairy production, with 86% allocated in 2020. This difference was due to the much greater amount of milk produced per animal sold in 2020. The intensity of feed consumption was calculated as the feed allocated to dairy divided by the FPCM produced.

Life cycle environmental metrics (GHG emissions, fossil energy use, and blue water use) and other emissions and losses were summarized for each region and the nation. The intensity of each metric or loss on each farm was determined by dividing the total emission or use by the amount of FPCM produced. Individual emissions of C, N, and P were also compared on both an intensity and total basis. These included the emission from the dairy farm along with that from farms producing feed purchased by the dairy. Those associated with purchased feed were determined by simulating crop farms to obtain typical losses per unit of feed produced (Rotz et al., 2021). This was primarily grain crops and byproduct feeds derived from grain crops, particularly in 1971, when most of the forage was produced on the dairy farm.

National totals for the various environmental metrics were determined as the weighted total of all regions. This was the amount of FPCM produced multiplied by the weighted average intensity of the region summed across the 6 regions. A national average intensity was then de-

termined as the national total divided by the total FPCM produced in the United States. Changes over the 50 yr were determined by comparing the regional and national totals and intensities of the 2 periods.

Sensitivity Analysis

An analysis was conducted to examine the sensitivity of the resulting environmental intensity to changes in some of the farm parameters or assumptions. Because some farm characteristics were based upon the expert opinion of those working with the dairy industry in the early 1970s, the sensitivity analysis determined how much of an effect the characteristics used had on the results. A low sensitivity indicated that changes in those assumptions would have little effect on the results; thus, error in the expert assumption would not affect the results.

For this analysis, simulating all farms with each change was infeasible and unnecessary. A farm was chosen from each region that best represented that region. The sensitivity analysis was done by making changes to each of these 6 farms and determining the impact on each of the environmental metrics studied. The regional values were totaled and weighted by the amount of milk produced in each region to determine a national result.

A sensitivity index was calculated as the ratio of the percent change in the assessed output over a change in the tested parameter or assumption. A sensitivity index near 0 indicated low sensitivity, and indexes close to or greater than 1 indicated high sensitivity. As sensitivity increases, higher quality data are needed for an accurate evaluation. The tested change was 10% of the difference between the values used for 1971 and 2020. For example, the difference in annual milk yield over this period was 5,495 kg/cow (Table 2). Therefore, each farm was simulated in 1971 with annual milk production increased by 550 kg/cow to reduce the difference by 10%. After making this change, the percent change in the difference determined for each environmental metric was divided by 10 to obtain the sensitivity index.

Parameters or assumptions tested included milk yield per cow, farm size, cow replacement rate, diet CP content, diet P content, portion of manure exported, N fertilizer use, P fertilizer use, manure handling, irrigation water use, and water runoff across farm boundaries. To test the effect of farm size, the crop areas and animal numbers were increased by 10% on the farms in 1971, along with a few minor changes (such as silo size) to ensure feed production and use remained the same. To test the effect of manure handling, the dairy farm in the Southwest was changed from an open lot dairy with stacked manure storage to a freestall operation with liquid manure collection and storage. This was used to generally represent a 10% change in manure handling over all farms. Sensitivity to irrigation water use was determined by reducing the simulated efficiency of irrigation water use in 1971 by 10%, which decreased the difference in the amount of irrigation water used to produce on-farm and purchased feeds between 1971 and 2020. The difference in other tested parameters were determined from Table 2.

RESULTS AND DISCUSSION

Changes in management and performance of dairy farms over the past 50 yr have provided substantial improvements in production. Feed efficiency has improved as more energy intake is used to produce milk compared with that required for maintenance of the animal (VandeHaar and St-Pierre, 2006). The maintenance energy requirement has increased due to an increase in cow size, but that used to produce milk has increased at a greater rate. This dilution of maintenance effect has increased production efficiency, which has reduced the intensity of environmental impacts (Capper et al., 2009).

Milk production per cow increased 2.4-fold over these years (USDA NASS, 2023a; Table 4), which has decreased intensities expressed per unit of FPCM for nearly all metrics studied. Changes in the total impacts over all milk produced varied greatly among regions of the United States due to a large increase in cow numbers in the western (south central, northwest, and southwest) regions, with declining numbers in the eastern regions (USDA NASS, 2023a; Table 4).

Changes in animal management and feeding have affected the amount and type of feeds consumed over the life cycle of milk production (Table 5). Our simulations indicate that nationally, 14% more feed was used in 2020 than 1971. Although the number of cows has decreased and feed efficiency has improved, more feed energy and other nutrients were required to produce the additional milk. Considering the large increase in milk produced, this increase in feed consumed to produce that milk was relatively small due to the maintenance requirement dilution.

Changes also occurred in the feeds being fed. Purchased concentrate feeds composed of many different byproduct feeds, as well as grain, increased by 82% (Table 4). Forage consumption did not change much over this time, but less forage was consumed by grazing in 2020. In the eastern regions, life cycle feed consumption decreased by 25%, with a slightly higher reduction in forage consumption than concentrate use. Due to the large growth in animal numbers in the western regions, feed consumption increased by 187% in the West, with a greater increase in concentrate feed use than forage.

Table 4. Changes in cow numbers and milk production from 1971 to 2020 (USDA NASS, 2023a)

Item	Unit	1971	2020	% Increase
Eastern regions				
Cows	1,000 cows	9,662	4,919	−49
Milk yield	kg/cow	4,435	10,606	139
FPCM[1] yield	kg/cow	4,196	10,498	150
FPCM production	Gg	40,539	51,639	27
Western regions				
Cows	1,000 cows	2,177	4,424	103
Milk yield	kg/cow	5,022	11,103	121
FPCM yield	kg/cow	4,751	11,041	132
FPCM production	Gg	10,343	48,845	372
National				
Cows	1,000 cows	11,839	9,342	−31
Milk yield	kg/cow	4,543	10,843	138
Milk fat	%	3.65	3.92	7
FPCM yield	kg/cow	4,298	10,756	150
FPCM production	Gg	50,882	100,483	97

[1]Fat- and protein-corrected milk (FPCM) is milk corrected to 4% fat and 3.3% protein.

GHG Emissions

Across regions, changes in GHG emission intensities were relatively consistent with decreases of 37% to 44% (Table 6). The weighted national average intensity of 1.0 kg CO_2e/kg FPCM in 2020 was 42% less than the 1.7 kg CO_2e/kg FPCM found in 1971 (Table 6). Intensities calculated for individual farms in 1971 varied from 1.3 to 2.3 kg CO_2e/kg FPCM, with similar ranges in all regions. No farm type, size, or management approach was found to consistently provide the lowest or highest values within this range. Many factors affect the environmental intensity of milk production including climate, soil properties, and management interactions. These factors contribute to the variation among farms along, with trends related to farm size and management (Rotz et al., 2020).

Our change in GHG emission intensity of dairy farms compares well with similar studies. In an assessment of California dairy farms, a 45% reduction was found over a similar time interval (Naranjo et al., 2020). Over 64 yr from 1944 to 2007, Capper et al. (2009) reported a 63% reduction. An assessment of raw milk production in the Netherlands has shown a 35% reduction over the past 30 yr (Hospers et al., 2022). These studies all indicate that

Table 5. Life cycle feed consumption allocated to milk production on US dairy farms in 1971 to 2020; intensities are expressed per kilogram of FPCM produced

	Weighted[1] mean intensity[2]				Weighted[1] total[3]			
Item	Unit	1971	2020	% Decrease	Unit	1971	2020	% Decrease
Eastern regions								
Grazed forage	g/kg FPCM	264	54	80	Gg	10,702	2,767	74
Conserved forage	g/kg FPCM	864	544	37	Gg	35,034	28,115	20
Harvested grain	g/kg FPCM	204	151	26	Gg	8,276	7,809	6
Purchased concentrates	g/kg FPCM	303	214	29	Gg	12,266	11,041	10
Total feed	g/kg FPCM	1,635	963	41	Gg	66,278	49,732	25
Western regions								
Grazed forage	g/kg FPCM	144	14	90	Gg	1,488	707	52
Conserved forage	g/kg FPCM	833	466	44	Gg	8,616	22,781	−164
Harvested grain	g/kg FPCM	73	12	84	Gg	756	563	26
Purchased concentrates	g/kg FPCM	384	380	1	Gg	3,969	18,548	−367
Total feed	g/kg FPCM	1,434	872	39	Gg	14,828	42,598	−187
National								
Grazed forage	g/kg FPCM	240	35	86	Gg	12,190	3,474	71
Conserved forage	g/kg FPCM	858	507	41	Gg	43,650	50,896	−17
Harvested grain	g/kg FPCM	178	83	53	Gg	9,032	8,372	7
Purchased concentrates	g/kg FPCM	319	294	8	Gg	16,234	29,588	−82
Total feed	g/kg FPCM	1,594	919	42	Gg	81,106	92,330	−14

[1]Weighted across farm sizes and types by the portion of the milk produced by each.

[2]Total based upon total FPCM produced in 1971 and 2020, respectively.

[3]Total life cycle feed consumption allocated to milk production.

Table 6. Progress made in reducing selected life cycle environmental metrics of United States dairy farms from 1971 to 2020; intensities are expressed per kilogram of FPCM produced

		Intensity 1971			Intensity 2020				Weighted[1] total[2]			
		Range			Range							
Item[3]	Unit	Minimum	Maximum	Weighted[1] mean	Minimum	Maximum	Weighted[1] mean	Decrease, %	Unit	1971	2020	Decrease, %
Northeast												
GHG emissions, CO2e	kg/kg FPCM	1.47	1.97	1.69	0.65	1.16	0.97	42	Tg	17.6	13.4	24
Fossil energy use	MJ/kg FPCM	4.94	6.68	5.93	1.80	3.64	2.82	53	PJ	62.0	38.9	37
Water use	kg/kg FPCM	27.3	46.3	33.5	17.5	69.4	24.1	28	Tg	350	332	5
Southeast												
GHG emissions, CO_2e	kg/kg FPCM	1.56	2.32	1.95	0.79	1.52	1.23	37	Tg	12.9	4.66	64
Fossil energy use	MJ/kg FPCM	3.44	8.81	5.64	2.11	3.90	2.97	47	PJ	37.2	11.2	70
Water use	kg/kg FPCM	27.3	65.0	37.4	18.7	141	57.4	−54	Tg	246	217	12
Midwest												
GHG emissions, CO_2e	kg/kg FPCM	1.41	2.05	1.66	0.75	1.16	0.92	44	Tg	39.0	31.4	19
Fossil energy use	MJ/kg FPCM	4.95	7.57	6.02	2.14	3.06	2.46	59	PJ	141.4	83.7	41
Water use	kg/kg FPCM	28.9	46.4	35.2	17.4	100	29.1	17	Tg	828	991	−20
Northwest												
GHG emissions, CO_2e	kg/kg FPCM	1.30	2.05	1.64	0.81	1.13	0.98	40	Tg	3.70	11.7	−216
Fossil energy use	MJ/kg FPCM	3.71	8.15	5.26	2.01	3.19	2.59	51	PJ	11.9	30.9	−160
Water use	kg/kg FPCM	33.5	747	325	29	371	171	48	Tg	736	2,039	−177
South central												
GHG emissions, CO_2e	kg/kg FPCM	1.49	2.01	1.77	0.86	1.67	1.05	41	Tg	5.37	12.0	−123
Fossil energy use	MJ/kg FPCM	3.97	7.34	5.56	2.00	3.94	2.70	51	PJ	16.9	30.7	−82
Water use	kg/kg FPCM	34.0	600	176	25	278	103	42	Tg	533	1,168	−119
Southwest												
GHG emissions, CO_2e	kg/kg FPCM	1.48	2.13	1.77	0.76	1.16	1.04	41	Tg	8.95	26.6	−197
Fossil energy use	MJ/kg FPCM	3.84	6.46	4.78	2.19	3.75	2.85	41	PJ	24.1	72.6	−201
Water use	kg/kg FPCM	354	800	576	81	235	126	78	Tg	2,908	3,219	−11
National												
GHG emissions, CO_2e	kg/kg FPCM	1.30	2.32	1.72	0.65	1.67	0.99	42	Tg	87.5	99.7	−14
Fossil energy use	MJ/kg FPCM	3.44	8.81	5.77	1.80	3.94	2.67	54	PJ	294	268	9
Water use	kg/kg FPCM	27.3	800	110	17.4	371	79	28	Tg	5,602	7,967	−42

[1]Weighted across farm sizes and types by the portion of the milk produced by each. National means are weighted by the portion of milk produced in each region.

[2]Total farmgate emission or use allocated to milk production in 1971 and 2020, respectively.

[3]CO_2e = CO_2 equivalents.

GHG emission intensity of dairy production has been improving at a rate near 1% per year in the United States and other developed countries.

The change in total GHG emissions associated with all dairy farms varied greatly across regions, from a decrease of 64% in the Southeast to 3-fold increases in the northwest and southwest regions (Table 6). This was due to the decreasing cow numbers in the eastern regions with large increases in the western regions (Table 4). The total emissions related to US dairy farms increased by 14% from about 88 Tg CO_2e in 1971 to 100 Tg CO_2e in 2020. This indicates that US dairy farms are now producing about twice the FPCM with just 14% more GHG emissions compared with those in 1971.

Fossil Energy Use

The farmgate life cycle fossil energy use includes that used on the farm as well as that used to produce electricity, fertilizer, purchased feeds, equipment, and other resources used on dairy farms. As previously reported (Rotz et al., 2021), most of the energy was used off-farm to produce these resources.

The intensity of fossil energy use related to dairy farm production varied from 4.8 to 6.0 MJ/kg FPCM across regions in 1971, with the lowest values in the Southwest and the highest in the Northeast and Midwest. This regional variation was influenced by farm size and climate. The smaller farms in these cooler regions were less energy efficient in producing feed, handling manure, and housing animals. The national average was 5.8 MJ/kg FPCM, which was more than double that found for 2020. As with GHG emissions, much of this reduction in intensity over the 50 yr was due to improvements in milk production efficiency. In addition, improvements in fuel efficiency of machinery operations (including greater use of diesel engines) and the efficiency in producing fuel, electricity, fertilizer, and other farm inputs have reduced the energy input into dairy farms (Table 1). Use of anaerobic digesters to generate electricity for on-farm use also contributed to lower fossil energy use in 2020 (Rotz et al., 2021).

Little has been done previously to compare life cycle energy use in dairy production over time. For a similar 50-yr period, Naranjo et al. (2020) reported a reduction in the intensity of electricity and fuel use on California farms of about 58%. This compares well to the 54% reduction we found for the United States but is greater than the 41% we found for the southwest region (Table 6).

The total upstream and on-farm use of fossil energy on dairy farms was found to decrease 9% from 294 PJ to 268 PJ (Table 6). This implies that the larger and more efficiently operated dairy farms today are using similar and perhaps a little less fossil energy than that used to produce milk in 1971. This is partly due to greater efficiency in on-farm use, but also the improved efficiency in producing electricity, increased use of renewable energy, and more efficient off-farm production of resource inputs. As found with GHG, this change varied greatly across regions, from a 70% decrease in the Southeast to a 3-fold increase in the Southwest. This was heavily influenced by a relatively small increase in the milk produced in the eastern regions with a nearly 5-fold increase in the western regions (Table 4; USDA NASS, 2023a).

Blue Water Use

Water obtained from surface and groundwater sources varied greatly across regions, with a large majority of this water used to irrigate feed crops (Rotz et al., 2021). In eastern regions where irrigation was rarely used on dairy farms in the 1970s, the intensity of water use was about 35 kg/kg FPCM (Table 6). This included drinking water and milking equipment cleaning with some production of purchased feeds that were irrigated. This intensity of water use did not change much over the 50-yr period in the eastern regions, but the use of irrigated feed crops in the Southeast did increase somewhat. In the western regions, where feed was heavily dependent upon irrigated crops, the intensity of water use in 1971 varied from 176 kg/kg FPCM in the south central region to 576 kg/kg FPCM in the Southwest. The national intensity decreased by about 50% over the 50-yr period due to conversion from furrow irrigation to more efficient center pivot irrigation systems, along with the improvement in cattle feed efficiency.

A couple of other studies have quantified changes in dairy farm water use intensity in the United States. In California, Naranjo et al. (2020) found about an 89% reduction in the intensity of water use over the past 50 yrs. For our southwest region, which is primarily California dairy farms, we found a little lower reduction of 60% (Table 6). Capper et al. (2009) reported a reduction of 55% over their 64-yr period, which is similar to our result, but a little less on a per-year basis.

Total water use by US dairy farms was found to increase 42% over the 50-yr period (Table 6). This increase was due to the shift in milk production from the humid eastern climate to the dry climate of the western regions (Table 4). Although the intensity of water use improved, total water use increased dramatically, with much more milk produced in the West using irrigated production of feed crops.

Water requirements are a concern for the sustainability of dairy farms in western regions. Water shortages have increased in recent years, creating limits on availability for crop irrigation (US EPA, 2023). Increasing ambient temperatures and reductions in precipitation have exac-

Table 7. Progress made in reducing selected emissions and nutrient losses from dairy farms in the United States from 1971 to 2020; all intensities are expressed per kilogram of FPCM produced

	Weighted[1] mean intensity[2]				Weighted[1] total[3]			
Item[4]	Unit	1971	2020	% Decrease	Unit	1971	2020	% Decrease
Eastern regions								
Methane	g/kg FPCM	31.5	21.5	32	Gg	1,279	1,112	13
Nitrous oxide	g/kg FPCM	0.73	0.33	55	Gg	29	17	42
Anthropogenic CO_2	g/kg FPCM	123	59	52	Gg	4,973	3,035	39
Ammonia	g/kg FPCM	10.6	6.29	41	Gg	429	325	24
Leached N	g/kg FPCM	5.40	2.24	58	Gg	219	116	47
Runoff N	mg/kg FPCM	222	91.6	59	Mg	8,997	4,729	47
Non-methane VOC	g/kg FPCM	1.51	1.50	1	Gg	61	78	−26
Soluble P runoff	mg/kg FPCM	36.1	15.0	58	Mg	1,464	776	47
Sediment P runoff	mg/kg FPCM	161	47.9	70	Mg	6,535	2,473	62
Surplus P	g/kg FPCM	2.84	0.47	84	Gg	115	24	79
Western regions								
Methane	g/kg FPCM	29.5	20.0	32	Gg	305	976	−220
Nitrous oxide	g/kg FPCM	1.41	0.53	62	Gg	15	26	−78
Anthropogenic CO_2	g/kg FPCM	91.5	45.7	50	Gg	946	2,233	−136
Ammonia	g/kg FPCM	15.6	8.97	43	Gg	162	438	−171
Leached N	g/kg FPCM	4.56	0.94	79	Gg	47	46	2
Runoff N	mg/kg FPCM	180	65.9	63	Mg	1,864	3,217	−73
Non-methane VOC	g/kg FPCM	2.20	1.05	52	Gg	23	51	−125
Soluble P runoff	mg/kg FPCM	21.7	8.95	59	Mg	224	437	−95
Sediment P runoff	mg/kg FPCM	70.1	22.8	68	Mg	725	1,111	−53
Surplus P	g/kg FPCM	2.44	0.30	88	Gg	25	15	42
National								
Methane	g/kg FPCM	31.1	20.8	33	Gg	1,583	2,088	−32
Nitrous oxide	g/kg FPCM	0.86	0.43	51	Gg	44	43	3
Anthropogenic CO_2	g/kg FPCM	116	52.4	55	Gg	5,919	5,268	11
Ammonia	g/kg FPCM	11.6	7.59	35	Gg	591	763	−29
Leached N	g/kg FPCM	5.23	1.61	69	Gg	266	162	39
Runoff N	mg/kg FPCM	213	79.1	63	Mg	10,861	7,947	27
Non-methane VOC	g/kg FPCM	1.65	1.28	22	Gg	84	129	−53
Soluble P runoff	mg/kg FPCM	33.2	12.1	64	Mg	1,688	1,213	28
Sediment P runoff	mg/kg FPCM	143	35.7	75	Mg	7,260	3,584	51
Surplus P	g/kg FPCM	2.76	0.39	86	Gg	140	39	72

[1]Weighted across farm sizes and types by the amount of milk produced.

[2]Expressed per unit of FPCM produced in 1971 and 2020, respectively.

[3]Based upon total FPCM produced in 1971 and 2020, respectively.

[4]Surplus P = the difference between P imported to the farm and that leaving in milk, animals, excess feed sold, and losses to the environment.

erbated issues of water availability (Melillo et al., 2014). Warmer temperatures and sometimes reduced snowfall are reducing snowpack in the mountains, which is a major source of irrigation water for some areas (US EPA, 2023). Climate projections for these regions also predict further increases in temperature and longer periods of drought, worsening the problem of water availability (Melillo et al., 2014). The demand for water and projections for reduced water availability suggest a need for strategies to further improve water use efficiency and otherwise reduce the use of water in dairy production (Mpanga and Idowu, 2021).

Nitrogen Losses

Important forms of N loss across farm boundaries include NH_3 volatilization, NO_3^- leaching to groundwater, N runoff in surface water, and denitrification loss as N_2O. The intensity of NH_3 emissions decreased by 35% over the 50-yr period, with a somewhat greater decrease in the western regions than the eastern regions (Table 7). This decrease in intensity was again due to the large increase in milk production per cow which reduced the loss per unit of milk produced. Total NH_3 emissions from all dairy farms increased by 29%, primarily due to the increased use of long-term manure storage and more cows on open lots in the western regions. Ammonia emissions are relatively high from these sources (Rotz et al., 2014).

Percentage changes in N leaching and N runoff were similar. Nitrogen leaching loss was modeled as N that moves through the soil profile to below the root zone (Rotz et al., 2022). Runoff was modeled as N moving across the farm boundaries. These values were not necessarily the N lost to the environment, but the change in loss across the 50-yr span should reflect the change in loss to the environment. National intensities showed

decreases of 69% and 63% for leaching and runoff, respectively (Table 7). Considering the large increase in milk production, predicted total losses on a national scale decreased by 39% and 27%, respectively. The implementation of nutrient management plans has made better use of manure N with reduced use of inorganic fertilizer, contributing to these reductions. Increased N loss in the form of NH_3 also meant less manure N was incorporated into the soil, where leaching and runoff losses occur. Greater use of cover crops and reduced tillage practices also contributed to reduced losses (Castaño-Sánchez et al., 2022).

The emission of nitrous oxide is a concern due to its warming potential as a GHG. As with the other N emissions, the intensity decreased considerably over the 50 yr (Table 7). The total emissions from all farms showed little change, so the reduction in intensity offset the large increase in milk production. Similar to leaching and runoff losses, this offset can be attributed to greater NH_3 emissions (less manure N incorporated into soil), more efficient use of inorganic N fertilizer, and the use of cover crops to carry more of the soil N through the winter months (Castaño-Sánchez et al., 2022).

Among the various forms of N loss from dairy farms, NH_3 emissions may be the greatest threat to future sustainability. Ammonia is recognized as an important air pollutant that has harmful effects on human health and sensitive ecosystems (NRC, 2003). Through the Clean Air Act, ammonia emissions can be regulated, but regulation of farm sources has been challenging due to difficulty in measurement and control. Dairy farms are a major source, contributing as much as 24% of the national inventory of NH_3 emissions (Rotz et al., 2021). Projected future increases in ambient temperatures across the country will tend to further increase NH_3 emissions (Hristov et al., 2018). Strategies for mitigating NH_3 emissions are available, but finding economical solutions is challenging (Veltman et al., 2021).

Phosphorus Runoff

Simulated P runoff losses also decreased substantially over the 50-yr span. Total soluble and sediment-bound P runoff losses decreased by 28% and 51%, respectively (Table 7). Several factors contributed to this substantial decrease. Greater use of cover crops and fewer tillage operations reduced nutrient and sediment runoff (Veltman et al., 2021). More rapid incorporation of manure into the soil, including some use of subsurface injection, has also reduced the potential for runoff. These management changes have provided greater reductions in sediment-bound P, with less reduction in soluble P runoff. With less tillage being used, more manure nutrients remain on the surface, contributing to more runoff of soluble P compared with sediment-bound P. The shift of dairy production from the eastern regions to the dry western climate also contributed to less runoff in the production of milk.

Reduced feeding of supplemental P in cattle diets and reduced use of inorganic P fertilizer have led to substantial reductions in the overall farm balance (P in minus P out). This has provided a reduction in the accumulation rate of surplus P in farm soils (Table 7). Reduced feeding of P in recent years (Table 2) also reduced the P excreted in manure and thus the potential for soluble runoff. Most of the benefit from reduced accumulation of soil P comes through the long-term future reduction in potential runoff losses.

Another influence on P runoff losses is the way they are being predicted by the model. Simulated losses are those moving across the farm boundaries. With much larger farms in 2020, there was less boundary per unit of cropland, and this reduced predicted runoff losses. Although this latter influence is a real consideration, this modeled effect may tend to overestimate the environmental benefit. Nutrients crossing the farm boundaries do not directly represent those leaving the watershed or entering sensitive water bodies such as the Chesapeake Bay or Gulf of Mexico. However, the relative change over time should reflect the change in that leaving the watershed.

Although major improvements have been made in reducing P runoff, eutrophication from P in surface waters continues to be a challenge, particularly in the eastern regions (Kleinman et al., 2019). Predicted increases in precipitation in eastern regions through more intense storms will exacerbate P runoff losses (Hristov et al., 2018; Veltman et al., 2021). Practices and technologies such as greater use of perennial crops and cover crops, reduced tillage, and subsurface manure injection help mitigate this pollutant source from dairy farms (Sharpley et al., 2006).

Volatile Organic Compounds

The emission of CH_4 decreased in intensity by ~33% across all regions and nationally, but total national emissions increased by 32% (Table 7). Dairy farms in the eastern regions produced 13% less total CH_4 in 2020 due primarily to fewer cows with greater milk yield and improved feed efficiency, with some offset through greater use of long-term slurry and liquid forms of manure storage. In western regions, total CH_4 emissions increased by 220% due to the large increase in cow numbers and greater use of long-term manure storage, particularly that stored in lagoons.

Emissions of non-CH_4 VOC have also benefited through improvements in milk production efficiency. Nationally, the intensity of this pollutant decreased by 22%,

Table 8. Sensitivity[1] of the difference in environmental metrics between 1971 and 2020 to a change in various farm parameters

Item	GHG emission	Energy use	Water use	Ammonia emission	VOC emission	Soluble P loss	Sediment P loss	Soil P buildup	Runoff N loss
Milk yield	0.66	0.34	0.85	0.86	1.63	0.42	0.31	0.20	0.45
Farm size[2]	0.15	0.28	0.04	0.03	0.05	0.00	0.07	0.01	0.03
Replacement rate	0.03	0.04	0.08	0.03	0.00	0.00	0.00	0.00	0.00
Diet CP content	0.04	0.03	0.00	0.08	0.01	0.00	0.00	0.00	0.01
Diet P content	0.01	0.01	0.00	0.00	0.00	0.03	0.00	0.04	0.00
Manure export	0.00	0.00	0.00	0.01	0.01	0.02	0.00	0.03	0.02
N fertilizer use	0.01	0.01	0.00	0.01	0.00	0.00	0.00	0.00	0.02
P fertilizer use	0.00	0.03	0.00	0.00	0.00	0.00	0.00	0.11	0.00
Manure handling[3]	0.00	0.00	0.03	0.79	0.07	0.00	0.00	0.00	0.03
Irrigation water use	0.02	0.03	0.79	0.00	0.00	0.00	0.00	0.00	0.00
Precipitation runoff	0.00	0.00	0.00	0.00	0.02	0.31	0.16	0.01	0.29

[1]Sensitivity index defined as the ratio of the percent change in the difference in an environmental output parameter caused by a 10% change in the difference of the input parameter between 1971 and 2020. An index of 1 means that a 10% change in the input difference causes a 10% change in the environmental output difference. An index greater than 1 is very sensitive, between 0.6 and 1 is sensitive, 0.3 to 0.6 is moderately sensitive, and below 0.3 is not sensitive.

[2]Animal numbers and crop areas were each increased 10% along with other minor changes to ensure the correct portions of feed were produced and fed.

[3]Open lot housing with stack storage was replaced with a freestall barn and liquid storage on the Southwest dairy farm to generally represent a 10% change in manure handling practice.

with most of this improvement coming in the western regions. This improvement has been offset by greater use of long-term manure storage and large bunker or pile silos. These relatively large open surfaces and the biological processes in the material generate greater emissions (Bonifacio et al., 2017). With all factors considered, our analysis shows a 53% increase in reactive non-CH_4 VOC emissions from all US dairy farms, with most of this increase coming from farms in the western regions (Table 7). This increase is due to the large increase in cow numbers and the associated increases in feed and manure storage.

Like other gaseous emissions, VOC emissions (primarily alcohols from dairy farms) are sensitive to temperature (Bonifacio et al., 2017). With projected increases in ambient temperature, increases in CH_4 and other VOC from manure and silage are anticipated (Bonifacio et al., 2017; Hristov et al., 2018). Strategies such as covered manure storage, subsurface injection of manure, and reduced exposure of silage surfaces can help mitigate these emission sources (Bonifacio et al., 2017).

Sensitivity to Model Inputs

The sensitivity analysis was done to evaluate the robustness of the results as influenced by assumptions made, particularly those determined through expert opinion. Predicted differences in most environmental metrics between 1971 and 2020 were sensitive to the increased difference in milk yield per cow used across the 50 yr (Table 8). Water use and NH_3 and VOC emissions were highly sensitive, where a 10% decrease in the assumed increase in milk yield gave a similar decrease in their differences. This shows that the difference in milk yield had little effect on the simulated difference in farm-level effects of these emissions. Because the farm impact did not change much, the 10% reduction in milk per cow created about a 10% reduction in their total impact. Greenhouse gas emissions, fossil energy use, and P and N runoff losses were moderately sensitive to the difference in milk yield where the 10% reduction in increased milk yield created a 3 to 7% reduction in their total farm impacts (sensitivity indexes of 0.31–0.66; Table 8). Historical milk production data for US dairy farms were accurately documented (USDA NASS, 2023a). Although our results were sensitive to milk production data, the data used have a high accuracy and thus were not improperly biasing the results.

Greenhouse gas emissions and fossil energy use were slightly sensitive to a change in the difference in farm size, but this change had little effect on the other environmental metrics studied (Table 8). With all other factors held as constant as possible, the increase in the difference in farm size between 1971 and 2020 decreased the difference in total energy use. Changes in assumed differences through time in cow replacement rate, diet protein content, diet P content, manure export, N fertilizer use, and P fertilizer use had little or no effect on the difference in total environmental impacts (Table 8). The increase in ammonia emissions was slightly influenced by the change in the difference in protein content of cow diets, and the accumulated soil P on the farm was slightly sensitive to a decrease in the difference in P fertilizer use.

Our assumed change in handling some manure from an open lot with stacked storage to a freestall barn with liquid storage created a substantial change in the difference in NH_3 emissions over the 50 yr, with little effect on all other changes in environmental impacts (Table 8).

Although this type of change in manure handling would affect CH_4 and N_2O emissions, in this case, these changes did not have much effect on the difference in total GHG emissions between 1971 and 2020. Other changes in animal housing and manure handling may affect various environmental concerns, but the largest effects would likely be on NH_3 and VOC emissions. As illustrated by this example, differences in all other environmental metrics between 1971 and 2020 were not sensitive to changes in manure handling practices.

Irrigation water use had a major effect on the increase in water use over the 50-yr period. A 10% change in the efficiency of irrigation water use caused a similar change in total water use (sensitivity index of 0.79; Table 8). Energy use and GHG emissions were just slightly sensitive to irrigation water use due to the energy used to pump irrigation water. The changes in other environmental metrics were not affected by this change (Table 8).

Our assumed change in tillage practices over the 50 yr had some effect on runoff of N and P (Table 7). A 10% reduction in the difference in modeled surface water runoff created a moderate 2% to 3% change in the runoff of soluble and sediment-bound P and N (sensitivity indexes of 0.16–0.31; Table 8). Although the assumed changes in tillage practices created large changes in runoff, major changes in tillage practices would be required to make much of a change in the predicted decreases in nutrient runoff losses found in our assessment.

The sensitivity analysis shows that the results compared across the 50-yr span were not highly sensitive to our assumptions coming through expert opinion or other limited information. Where sensitivities were found, major changes in our assumptions would be required to create substantial changes in our comparisons across time. This supports the robustness of our analysis. If more accurate data or information were available on dairy farm management in 1970, improved assumptions would not likely have much effect on the results and overall conclusions of this analysis.

CONCLUSIONS

Through substantial improvements made in the efficiency of producing milk, feed, and resources used in dairy production, much progress has been made in reducing farmgate environmental intensities of milk production in the United States. Across all environmental metrics studied, intensities expressed per unit of FPCM produced decreased from 25% to 75%. Totals from all dairy farms in the United States show increases in NH_3, CH_4, and reactive non-CH_4 VOC emissions. Total GHG emissions related to dairy farms have increased by just 14%, while total fossil energy use has shown little change, and nutrient losses to ground and surface waters have shown substantial improvements. The movement of dairy production from the humid eastern climate to the dry climate of the West has contributed to a 42% increase in water use, which is an important concern for future sustainability. Although much progress has been made in improving production efficiency and reducing or controlling environmental impacts, further mitigation strategies and technologies are needed to continue improving the sustainability of the dairy industry.

NOTES

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Abbreviations used: CO_2e = CO_2 equivalents; FPCM = fat- and protein-corrected milk, GHG = greenhouse gas, IFSM = Integrated Farm System Model, LCA = life cycle assessment, VOC = volatile organic compound.

REFERENCES

Abatzoglou, J. T. 2013. Development of gridded surface meteorological data for ecological applications and modelling. Int. J. Climatol. 33:121–131. https://doi.org/10.1002/joc.3413.

Blanco-Canqui, H. 2022. Cover crops and carbon sequestration: Lessons from U.S. studies. Soil Sci. Soc. Am. J. 86:501–519. https://doi.org/10.1002/saj2.20378.

Bonifacio, H. F., C. A. Rotz, S. D. Hafner, F. Montes, M. Cohen, and F. M. Mitloehner. 2017. A process-based emission model of volatile organic compounds from silage sources on farms. Atmos. Environ. 152:85–97. https://doi.org/10.1016/j.atmosenv.2016.12.024.

Bonifacio, H. F., C. A. Rotz, A. B. Leytem, H. M. Waldrip, and R. W. Todd. 2015. Process-based modeling of ammonia and nitrous oxide emissions from open lot beef and dairy facilities. Trans. ASABE 58:827–846. https://doi.org/10.13031/trans.58.11112.

Capper, J. L., and R. A. Cady. 2020. The effects of improved performance in the U.S. dairy cattle industry on environmental impacts between 2007 and 2017. J. Anim. Sci. 98:skz291. https://doi.org/10.1093/jas/skz291.

Capper, J. L., R. A. Cady, and D. E. Bauman. 2009. The environmental impact of dairy production: 1944 compared with 2007. J. Anim. Sci. 87:2160–2167. https://doi.org/10.2527/jas.2009-1781.

Castaño-Sánchez, J. P., H. D. Karsten, and C. A. Rotz. 2022. Double cropping and manure management mitigate the environmental im-

pact of a dairy farm under present and future climate. Agric. Syst. 196:103326. https://doi.org/10.1016/j.agsy.2021.103326.
Gamble, J. D., G. W. Feyereisen, T. J. Griffis, C. D. Wente, and J. M. Baker. 2021. Long-term ecosystem carbon losses from silage maize-based forage cropping systems. Agric. For. Meteorol. 306:108438. https://doi.org/10.1016/j.agrformet.2021.108438.
Hardegree, S. P. 2023. LTAR Weather Beta. Accessed Mar. 15, 2024. https://webapps.jornada.nmsu.edu/weather/.
Holly, M. A., K. M. Gunn, C. A. Rotz, and P. J. A. Kleinman. 2019. Management characteristics of Pennsylvania dairy farms. Appl. Anim. Sci. 35:325–338. https://doi.org/10.15232/aas.2018-01833.
Hospers, J., L. Kuling, P. Modernel, J. P. Lesschen, H. Blonk, L. Batlle-Bayer, W. van Straalen, and S. Dekker. 2022. The evolution of the carbon footprint of Dutch raw milk production between 1990 and 2019. J. Clean. Prod. 380:134863 https://doi.org/10.1016/j.jclepro.2022.134863.
Hristov, A. N., A. T. Degaetano, C. A. Rotz, E. Hoberg, R. H. Skinner, T. Felix, H. Li, P. H. Patterson, G. Roth, M. Hall, T. L. Ott, L. Baumgard, W. Staniar, R. M. Hulet, C. Dell, A. F. Brito, and D. Y. Hollinger. 2018. Climate change effects on livestock in the Northeast U.S. and strategies for adaptation. Clim. Change 146:33–45. https://doi.org/10.1007/s10584-017-2023-z.
International Dairy Federation (IDF). 2015. A common carbon footprint approach for dairy. Bulletin 479/2015. International Dairy Federation. Brussels, Belgium. Accessed Jul. 19, 2019. https://www.fil-idf.org/wp-content/uploads/2016/09/Bulletin479-2015_A-common-carbon-footprint-approach-for-the-dairy-sector.CAT.pdf.
International Panel on Climate Change (IPCC). 2006. Guidelines for national greenhouse inventories. Vol. 4: Agriculture, forestry and other land use. International Panel on Climate Change. Accessed Jul. 19, 2019. http://www.ipcc-nggip.iges.or.jp/public/2006gl/vol4.html.
Kim, D. N., N. Stoddart, C. A. Rotz, K. Veltman, L. Chase, J. Cooper, P. Ingraham, R. C. Izaurralde, C. D. Jones, R. Gaillard, H. A. Aguirre-Villegas, R. A. Larson, M. Ruark, W. Salas, O. Jolliet, and G. J. Thoma. 2019. Analysis of beneficial management practices to mitigate environmental impacts in dairy production systems around the Great Lakes. Agric. Syst. 176:102660. https://doi.org/10.1016/j.agsy.2019.102660.
Kleinman, P. J. A., R. M. Fanelli, R. M. Hirsch, A. R. Buda, Z. M. Easton, L. A. Wainger, C. Brosch, M. Lowenfish, A. S. Collick, A. Shirmohammadi, K. Boomer, J. A. Hubbart, R. B. Bryant, and G. W. Shenk. 2019. Phosphorus and the Chesapeake Bay: Lingering issues and emerging concerns for agriculture. J. Environ. Qual. 48:1191–1203. https://doi.org/10.2134/jeq2019.03.0112.
Livestock Environmental Assessment and Performance Partnership (LEAP). 2016. Environmental performance of large ruminant supply chains: Guidelines for assessment. Food and Agriculture Organization of the United Nations. Accessed Apr. 23, 2018. http://www.fao.org/3/a-i6494e.pdf.
Melillo, J. M., T. C. Richmond, and G. W. Yohe, eds. 2014. Climate Change Impacts in the United States: The Third National Climate Assessment. US Global Change Research Program. US Government Printing Office, Washington, DC. https://doi.org/10.7930/J0Z31WJ2.
Mpanga, I. K., and O. J. Idowu. 2021. A decade of irrigation water use trends in southwestern USA: The role of irrigation technology, best management practices, and outreach education programs. Agric. Water Manage. 243:106438. https://doi.org/10.1016/j.agwat.2020.106438.
Myhre, G., D. Shindell, F.-M. Bréon, W. Collins, J. S. Fuglestvedt, J. Huang, D. Koch, J. F. Lamarque, D. Lee, B. Mendoza, T. Takemura, and H. Zhang. 2013. 8, Anthropogenic and natural radiative forcing. Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. T. F. Stocker, D. Qin, G. K. Plattner, M. Tignor, S. K, Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, and P. M. Midgley, ed. Cambridge University Press, Cambridge, UK.
Naranjo, A., A. Johnson, H. Rossow, and E. Kebreab. 2020. Greenhouse gas, water, and land footprint per unit of production of the California dairy industry over 50 years. J. Dairy Sci. 103:3760–3773. https://doi.org/10.3168/jds.2019-16576.
National Oceanic and Atmospheric Administration (NOAA). 2019. Land-Based Station Data. National Climatic Data Center. National Oceanic and Atmospheric Administration. Accessed May 8, 2019. https://www.ncdc.noaa.gov/cdo-web/.
National Research Council (NRC). 2003. Air Emissions from Animal Feeding Operations: Current Knowledge, Future Needs. National Research Council, The National Academies Press, Washington, DC.
Natural Resource and Conservation Service (NRCS). 2019. Web Soil Survey. Natural Resource and Conservation Service, USDA. Accessed Mar. 16, 2018. http://websoilsurvey.sc.egov.usda.gov/App/WebSoilSurvey.aspx.
Putman, B., C. A. Rotz, and G. Thoma. 2023. A comprehensive environmental assessment of beef production and consumption in the United States. J. Clean. Prod. 402:136766. https://doi.org/10.1016/j.jclepro.2023.136766.
Rotz, C. A., S. Asem-Hiablie, S. Place, and G. Thoma. 2019. Environmental footprints of beef cattle production in the United States. Agric. Syst. 169:1–13. https://doi.org/10.1016/j.agsy.2018.11.005.
Rotz, C. A., M. S. Corson, D. S. Chianese, F. Montes, S. D. Hafner, H. Bonifacio, and C. U. Coiner. 2022. Integrated Farm System Model: Reference Manual, version 4.7. USDA Agricultural Research Service, University Park, PA.
Rotz, C. A., F. Montes, S. D. Hafner, A. J. Heber, and R. H. Grant. 2014. Ammonia emission model for whole farm evaluation of dairy production systems. J. Environ. Qual. 43:1143–1158. https://doi.org/10.2134/jeq2013.04.0121.
Rotz, C. A., R. Stout, A. Leytem, G. Feyereisen, H. Waldrip, G. Thoma, M. Holly, D. Bjorneberg, J. Baker, P. Vadas, and P. Kleinman. 2021. Environmental assessment of United States dairy farms. J. Clean. Prod. 315:128153. https://doi.org/10.1016/j.jclepro.2021.128153.
Rotz, C. A., R. C. Stout, M. A. Holly, and P. J. A. Kleinman. 2020. Regional environmental assessment of dairy farms. J. Dairy Sci. 103:3275–3288. https://doi.org/10.3168/jds.2019-17388.
Sharpley, A. N., T. Daniel, G. Gibson, L. Bundy, M. Cabrera, T. Sims, R. Stevens, J. Lemunyon, P. Kleinman, and R. Parry. 2006. Best management practices to minimize agricultural phosphorus impacts on water quality. USDA, Agricultural Research Service, ARS-163.
USDA Animal and Plant Health Inspection Service (USDA APHIS). 2003. Dairy 2002 Part II: Changes in the United States Dairy Industry, 1991–2002. USDA Animal and Plant Health Inspection Service. Accessed Mar. 9, 2022. https://www.aphis.usda.gov/animal_health/nahms/dairy/downloads/dairy02/Dairy02_dr_PartII_1.pdf.
USDA Agricultural Research Service (USDA ARS). 2023. The integrated farm system model, version 4.8. USDA Agricultural Research Service. University Park, PA. Accessed Jul. 5, 2023. https://www.ars.usda.gov/northeast-area/up-pa/pswmru/docs/integrated-farm-system-model.
USDA Economic Research Service (USDA ERS). 2007. Profits, costs, and the changing structure of dairy farming. Economic research report no. 47. USDA Economic Research Service. Accessed Mar. 9, 2022. https://www.ers.usda.gov/webdocs/publications/45868/11138_err47_1_.pdf?v=1292.9.
USDA National Agricultural Statics Service (USDA NASS). 2023a. Quick Stats 2.0. USDA National Agricultural Statics Service. Accessed Jul. 5, 2023. http://quickstats.nass.usda.gov.
USDA National Agricultural Statics Service (USDA NASS). 2023b. Historical census of agricultural production. USDA National Agricultural Statics Service. Accessed Jul. 5, 2023. https://www.nass.usda.gov/AgCensus/index.php.
US Environmental Protection Agency (US EPA). 2020. AgSTAR livestock anaerobic digester database. US Environmental Protection Agency. Accessed Nov. 6, 2020. https://www.epa.gov/agstar/livestock-anaerobic-digester-database.
US Environmental Protection Agency (US EPA). 2023. Climate change indicators in the United States. US Environmental Protection Agency. Accessed Jul. 7, 2023. https://www.epa.gov/climate-indicators.
VandeHaar, M. J., and N. St-Pierre. 2006. Major advances in nutrition: Relevance to the sustainability of the dairy industry. J. Dairy Sci. 89:1280–1291. https://doi.org/10.3168/jds.S0022-0302(06)72196-8.

Veltman, K., C. A. Rotz, L. Chase, J. Cooper, C. E. Forest, P. Ingraham, R. C. Izaurralde, C. D. Jones, R. E. Nicholas, M. Ruark, W. Salas, G. Thoma, and O. Jolliet. 2021. Assessing and reducing the environmental impact of dairy production systems in the northern US in a changing climate. Agric. Syst. 192:103170–14. https://doi.org/10.1016/j.agsy.2021.103170.

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Symposium review: Greenhouse gas emissions from liquid dairy manure: Prediction and mitigation[1]

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ABSTRACT

The handling and use of manure on livestock farms contributes to emissions of the greenhouse gases (GHG) CH_4 and N_2O, especially with liquid manure management. Dairy farms are diverse with respect to manure management, with practices ranging from daily spreading to long-term storage for more efficient recycling of manure nutrients for crop production. Opportunities for GHG mitigation will depend on the baseline situation with respect to handling and storage, and therefore prediction and mitigation at the farm level requires a dynamic description of housing systems and storage conditions, and use of treatment technologies. Also, effects of treatment and handling on the properties of field-applied manure must be taken into account. Storage conditions and manure composition importantly define carbon and nitrogen transformations, and the resulting emissions of CH_4 and N_2O, as well as CO_2 and NH_3, which are all important for the GHG balance. Currently, inventories for CH_4 and N_2O emissions from manure are based on emission factors for a limited number of production systems, together with average annual temperature, but the inherent uncertainty of this approach is a barrier toward prediction and mitigation. Although more representative emission factors may be determined at country level, this is both challenging and costly, and effects of management changes for GHG mitigation are not easily quantified. An empirical model of CH_4 emissions during storage is discussed that is based on daily time steps, and a parameterization based on measurements. A distinction between emissions from manure in barns and outside storage facilities is important for assessing effects of treatment technologies, such as anaerobic digestion, where only posttreatment emissions are affected. Upon field application, manure and soil together define the equilibrium distribution of labile carbon and nitrogen between bulk soil and manure hotspots. This introduces heterogeneity with respect to potential for N_2O emissions, which is not represented in existing prediction models. Manure treatment and management options for GHG mitigation are discussed with emphasis on effects on manure volatile solids and N availability. Anaerobic digestion and acidification represent treatment technologies that are relevant for GHG mitigation on dairy farms.

Key words: manure management, methane, nitrous oxide, volatile solids

INTRODUCTION

According to a recent life cycle analysis (Thoma et al., 2013a), the United States dairy sector is responsible for 1.9% of total national greenhouse gas (**GHG**) emissions, whereas globally this contribution is 3 to 5% (FAO, 2010). Main sources are CH_4 emissions associated with enteric fermentation and manure management, and N_2O emissions from feed and food production, which are therefore also key targets of efforts to quantify emissions and mitigation potentials (Henriksson et al., 2011; Thoma et al., 2013a).

Dairy production systems are extremely diverse with respect to manure management practices and environmental conditions (Sommer et al., 2009; Thoma et al., 2013b), and this will influence the effectiveness of GHG mitigation measures. For example, Sommer et al. (2009) showed that CH_4 emissions from manure in 5 European countries were affected differently by several treatment technologies due to differences in management and storage temperature. Similarly, the 2 states in the United States with the largest dairy herds, California (**CA**) and Wisconsin (**WI**), are different with respect to both climate and manure management practices; a survey found that 50 to 67% of WI dairy farms spread manure year-round without storage, representing on average 45% of the manure volume (Turnquist et al., 2006), whereas this was the case on only 26 to 27% of CA dairy farms in a survey of 2 counties (Meyer et

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al., 2011). As a consequence, the potential for mitigating CH_4 emissions during storage would be greater for CA dairy farms, whereas the potential for improved N use efficiency and, in turn, N_2O mitigation would be greater for WI dairy farms. Effective mitigation strategies thus depend on an accurate description of on-farm conditions.

Contributions from CH_4 and N_2O

Greenhouse gas emissions on dairy farms are dominated by CH_4 and N_2O (Chianese et al., 2009; Kristensen et al., 2011). Even in regions where the number of cows have declined, such as North America and Western Europe, a change toward liquid manure management and extended storage have increased emissions of both gases (Wightman and Woodbury, 2016). The global warming potential (**GWP**) of CH_4 and N_2O are normally considered for a time horizon of 100 yr, and current estimates of GWP_{100} for CH_4 and N_2O are, respectively, 34 and 298 times the GWP_{100} of CO_2 (Myhre et al., 2013). However, CH_4 has a half-life in the atmosphere of only 12 to 13 yr, and thus for a 20-yr time horizon, GWP_{20}, the contribution of CH_4 is 2.5-fold higher at 86, which increases the relevance of CH_4 mitigation efforts to curb global warming in the short term.

Emissions of N_2O are associated with N transformations via nitrification and denitrification under oxygen-limited conditions (Maharjan and Venterea, 2013). Sustained emissions require that aerobic and anaerobic environments exist in close proximity, which may be the case in organic crusts formed during liquid manure storage (Wood et al., 2012), and in solid manure (Webb et al., 2011). Upon field application, factors such as manure composition, application method and soil conditions together determine the potential for N_2O emissions, but given the unpredictable effects of climate, effects of treatment and management can vary dramatically. A recent meta-analysis (Charles et al., 2017) found that liquid and solid organic residues (including manure) are characterized by N_2O emissions that are, respectively, above and below the emission factor currently used by most countries. However, the analysis also found strong positive interactions with soil N status, clay content, and precipitation, indicating that defining local conditions, as for CH_4, is critical for more accurate estimation of emissions.

Gaseous N losses through NH_3, nitrogen oxides (NO_x), and N_2, and leaching losses mainly as NO_3^-, are quantitatively much more important than direct emissions of N_2O (Venterea et al., 2012). Because both NH_3 volatilization and NO_3^- leaching are indirect sources of N_2O, the prevention of these losses through better N use efficiency is an effective strategy for N_2O mitigation.

Objectives

Predicting CH_4 and N_2O emissions from livestock farms is a significant challenge, and currently the uncertainty associated with emission estimates effectively prevents accountability, regulation, and mitigation. Several recent papers and meta analyses have reviewed GHG emissions from manure management and mitigation options (e.g., Hristov et al., 2011; Petersen et al., 2013a; Hou et al., 2015; Jayasundara et al., 2016). In this review, I will instead highlight selected aspects of manure treatment and management that research, from laboratory to practical scale, has shown to be of particular importance for gaseous emissions of carbon (CH_4, CO_2) and nitrogen (N_2O, NH_3). The main emphasis will be on dairy production systems. In view of the many potential interactions between different management stages, the discussion will address both manure management on the farm and subsequent field application.

DRIVERS OF GHG EMISSIONS FROM MANURE

Gerber et al. (2011) reported that the shares of solid and liquid manure management on dairy farms in North America were, respectively, 31 and 36%, whereas the corresponding numbers for Western Europe were 36 and 38%. In many parts of the world, the share of liquid manure management is increasing due to intensification of livestock production (Bouwman et al., 2013) and due to recommendations to store manure to recycle manure nutrients for crop production (Oenema et al., 2011). Because the potential for CH_4 production is estimated to be 4- to 20-fold higher with liquid compared with solid manure management depending on storage temperature (IPCC, 2006), it can be estimated that, for example, in Western Europe liquid manure accounts for >90% of total CH_4 emissions from solid and liquid storage. As stated above, the potential for N_2O emissions after field application is also higher from liquid manure (Charles et al., 2017), and the focus of this review is therefore on liquid manure management. It should be noted, however, that recently introduced deep litter systems also may have a high potential for CH_4 as well as N_2O emissions (Barberg et al., 2007; Galama, 2011).

Storage Environment

An overview of livestock manure handling systems was presented by Sørensen et al. (2013). Collection

inside barns may occur in deep or shallow pits, and excreta may be scraped or flushed, or exported by gravity flow, for outside storage. Outside storage can take place in a concrete tank or pond, or lagoon(s). Dairy farms rely on an in-house pit or outside storage, or both. In pits beneath slatted floors, a significant volume of manure may be maintained to enable mobilization of settling solids during export; a recent survey found that in Denmark the resulting hydraulic retention time (**HRT**) for cattle slurry was 30 to 40 d (Kai et al., 2015). Anaerobic lagoons are widely used in North America as a cost-effective method to stabilize effluents through biodegradation of organic matter and settling of solids, but due to the prolonged retention time and large surface area, the potential for CH_4 and NH_3 emissions is high compared with storage tanks (IPCC, 2006; McGinn et al., 2008). Depending on in-barn and outside storage temperatures, the retention time in barns and outside storage, and any treatment in between, can significantly influence the fate of manure organic matter and nutrients before land application.

A storage design parameter of potential importance for the GHG balance of manure management is surface-to-volume ratio. It is well established that the loss of N via NH_3 emission is high in the absence of a cover such as a natural crust, floating membrane, or roof structure on storages to restrict gas exchange (Sommer et al., 1993). However, C metabolism is also influenced by gas exchange across the manure-air interface because manure represents a sink for atmospheric O_2. The flux of O_2 is proportional to the concentration gradient across the diffusive boundary layer (Jørgensen and Revsbech, 1985; Hafner et al., 2017). Thus, with uncovered liquid manure the mass transfer of dissolved organic C to the surface through the effect of wind or convective heat transfer (Hafner et al., 2017) will result in steep dissolved organic C concentration gradients that enhance O_2 consumption compared with storages with a synthetic membrane or natural crust cover, because here the diffusive boundary layer is much greater and mixing less. Because the end product of aerobic heterotrophic activity is CO_2, processes at manure surfaces will influence the proportions of volatile solids (**VS**) lost as CH_4 and CO_2 (Møller et al., 2004). Furthermore, both $CO_2/HCO_3^-/CO_3^{2-}$ and NH_3/NH_4^+ are important components of the buffer system of manure (Sommer and Husted, 1995), and CO_2 emissions from manure can enhance NH_3 emissions by raising pH at the manure-air interface (Hafner et al., 2017). The relative importance of processes at this interface will also depend on the degree of filling; the surface-to-volume ratio thus increases after manure removal for field application.

The presence of active methanogens is a precondition for CH_4 emissions during storage, but methanogens in fresh excreta may not thrive in harsh liquid manure environments (Chen et al., 2008a), and this can delay the appearance of CH_4 emissions for weeks or even months (Sommer et al., 2007). Adaptation is therefore required, or inoculation with methanogens from residual manure in the pit, which is already adapted to this environment. Flushing and emptying of manure pits or storage tanks have been shown to delay the onset of methanogenesis (e.g., Haeussermann et al., 2006), but under practical storage conditions this can be difficult to achieve. Recently, Baldé et al. (2016) reported that removal of sludge from concrete tanks on a dairy farm in autumn had no detectable effect on CH_4 emissions during storage the following summer.

Manure Volatile Solids

Volatile solids in liquid cattle manure typically constitute 75 to 85% of TS, the rest being sand and minerals (Møller et al., 2002; Petersen et al., 2003). According to Møller et al. (2004), labile fractions (VFA, protein, lipids, degradable carbohydrate) constitute around 69% of VS in cattle manure, and 79% in finishing pig manure. Any bedding will add to the concentration of DM, whereas effects on VS concentration will depend on the material used, such as straw, sawdust, sand, or recycled manure solids, which differ with respect to CH_4 production potential, but also animal welfare, cost, and labor (Møller et al., 2004; Zdanowicz et al., 2004). Møller et al. (2002) found that 50% of TS in cattle manure were degraded during 7 mo of storage at 20°C. Assuming that labile pools of manure OM were lost to a greater extent than more recalcitrant components, the potential is significant for loss of labile VS, and thus CH_4 emissions, even within a few weeks of storage, which has implications for manure treatment and management.

During storage, organic particles may remain suspended, settle, or float to the surface to form a natural crust. Up-drift may be created by gas bubbles (consisting mainly of CH_4 and CO_2) derived from methanogenic activity, and crust formation on dairy cattle manure has been observed to coincide with the onset of CH_4 emissions (Misselbrook et al., 2005c; Wood et al., 2012). Also, Misselbrook et al. (2005c) reported that a glucose-starch additive promoted crust formation. Buoyancy of a crust is further supported by pockets of gas beneath the crust, which are intermittently deflated through cracks, as observed by Duan et al. (2017) using an oxygen microsensor. Thus, crust formation is a product of both recalcitrant and labile manure OM.

Depending on weather conditions (rainfall, temperature), a variety of microbial populations may develop in surface crusts. The microbial community will include populations of CH_4 oxidizing bacteria, or methano-

trophs (e.g., Petersen et al., 2005; Duan et al., 2017). Their activity depends on both availability of substrates (CH_4, O_2) and inhibitory effects of mineral N, but recent evidence suggests that mainly the activity of so-called type 1 methanotrophs responds to elevated CH_4 availability in aerated parts of the crust (Duan et al., 2017). However, at this time limited information is available about the importance of methanotrophic activity in surface crusts for CH_4 emissions. Natural crusts on manure storages are also a potential source of N_2O; this will be discussed later.

Manure Nitrogen

Manure recycling for crop production can significantly reduce the need for imported fertilizers, although ensuring a balanced nutrient supply with respect to N, P, K, and S can be difficult with manure alone. For dairy cattle manure a direct relationship exists between N intake and excretion (Kebreab et al., 2001). The N excreted is partly unavoidable losses associated with, for example, microbial cell walls and residual protein, and partly a variable fraction of excess N excreted mainly as urea in the urine (Petersen et al., 1998). Urea is rapidly hydrolyzed to form NH_4^+ and NH_3 (total ammoniacal N, **TAN**), whereas mineralization of organic N is slower and temperature dependent. Sommer et al. (2007) found that mineralization of organic N in liquid pig and cattle manure varied between 5 and 85% when stored at 10, 15, or 20°C for up to 200 d. Mineralization of organic N will increase manure N availability and pH (Eriksen et al., 2012), and therefore also the potential for environmental loss of TAN through NH_3 emission. Depending on length of storage and ambient temperature, effective recycling of N for crop production will require NH_3 mitigation measures.

Upon field application, both particle size distribution and soil properties influence redistribution of manure constituents. Vadas (2006) found that around 80% of the DM in liquid dairy and swine manure applied on top of a fine-loamy soil was retained at the surface, whereas the 20% of manure solids entering the soil was predominantly recovered within 10 mm distance from the surface. This is in accordance with the distribution of dissolved organic C and NH_4^+ observed in soil around cattle manure layers, that is, 2-dimensional manure hotspots, in laboratory setups (e.g., Petersen et al., 1996), suggesting that C and N transformations and N_2O emissions are concentrated within a limited soil volume in close contact with manure after field application. The VS in manure has a high water retention capacity compared with mineral soil; exponential relationships between manure VS concentration and water retention were described by Petersen et al. (2003).

PREDICTING GHG EMISSIONS FROM MANURE

The need to use a transparent and consistent methodology for national GHG inventories is widely accepted, and the United Nations' Framework Convention on Climate Change has recommended the use of guidelines developed by the Intergovernmental Panel on Climate Change (**IPCC**). This methodology is based on annual emission factors defined for a limited number of production systems, but several studies have pointed out that quantifying farm-level emissions is problematic with a methodology that is insensitive to local management (Weiske et al., 2006; Schils et al., 2007; Crosson et al., 2011; VanderZaag et al., 2013). Hence, more dynamic, yet transparent and consistent, methods to estimate GHG sources and sinks are needed, as well as mitigation potentials of treatment and management. This section discusses challenges and opportunities in relation to prediction of CH_4 and N_2O emissions from manure.

Controls of CH_4 Emissions

The IPCC methodology for estimating CH_4 emissions from manure management recommends use of a so-called methane conversion factor (**MCF**) to represent local manure storage conditions (IPCC, 2006). Default MCF values are proposed for a range of production systems based on average annual temperature, although countries are recommended to develop national or regional MCF through measurements, if possible. An MCF value must account for timing and length of storage, manure composition, presence of inoculum with adapted methanogens from older manure, daily and seasonal temperature variations, and retention time in the barn (IPCC, 2006). With such a wide range of storage conditions to be represented by a single value, the uncertainty associated with MCF is necessarily high, and it is relevant to consider the scope for a more dynamic description of key drivers.

Time is a key variable because management decisions influence storage conditions on a daily basis, and storage time before/after manure treatment if applicable. Manure volume and retention time in barns and outside storage facilities are readily calculated by day knowing the number of animals and grazing periods, excretion rate, and timing of transfer from barn to outside storage. This information can then be used to define storage temperature with daily time steps, which is critical to account for regional and seasonal differences in temperature that may be significant. For example, the average annual temperature in Milwaukee, WI, varied moderately between 4.4 and 13.1°C in the period from 1981 to 2010, but average monthly temperature

varied between −9.1 and 26.7°C (Prism Climate Group, 2017). Detailed information about local temperature is generally accessible and hence may support a better spatio-temporal resolution of CH_4 emission estimates.

The greatest challenge in predicting CH_4 emissions may be the documentation of CH_4 production rates. Four contrasting manure materials (pig manure, cattle manure, fresh digestate, and aged digestate) were found to have very similar activation energies, E_a (i.e., temperature sensitivity), of methanogenesis in the range of 5 to 37°C (Elsgaard et al., 2016), whereas actual CH_4 production rates were very different (Figure 1). The latter was partly explained by the differences in origin and treatment, but in practice CH_4 production potential also varies with feeding (Jayasundara et al., 2016), as well as age and storage temperature (Sommer et al., 2007), and storage environment (Barret et al., 2013). Across 90 individual manure samples from 4 storage tanks with either pig or dairy cattle manure, Barret et al. (2013) observed a negative effect of VFA (and positive effect of pH), presumably because methanogens were inhibited by the acidification associated with VFA accumulation (Chen et al., 2008a). There was also inter-storage and temporal variability in methangenic community composition, and a lower potential for CH_4 production near the surface in pig manure, but not dairy manure. Although a multiple linear regression equation was able to describe the observed CH_4 emissions based on 16 microbiological and chemical manure characteristics, it was acknowledged that additional complexity is introduced under practical storage conditions (Barret et al., 2013). Notably, the average age of the manure in a storage, and hence the extent of VS degradation at the time of observation, is typically unknown. In accordance with this, a sensitivity analysis found that estimates of CH_4 production rate in individual manure materials were much more sensitive to CH_4 production potential, as represented by lnA (see next section), than to temperature or VS composition (Petersen et al., 2016).

Aerobic degradation near the manure-air interface (Patni and Jui, 1987; Møller et al., 2004; Barret et al., 2013) further complicates the prediction of CH_4 emissions, since the removal of labile VS in the manure via aerobic degradation to CO_2 will change the balance between CH_4 and CO_2 associated with loss of VS during storage. Implications of aerobic degradation for CH_4 emissions will be greater for a pond with a surface area of up to several hectares (Leytem et al., 2011) compared with slurry tanks of 20 m diameter (Baldé et al., 2016). Observations from practical and pilot-scale storage confirm that proportions of CH_4 and CO_2 emitted are highly variable. In a study of emissions from a slurry tank, Laguë et al. (2005) observed CH_4-C/(CH_4-C + CO_2-C) ratios in 3 seasons that ranged from 0.36 to 0.45, whereas these ratios for 2 earthen basins averaged 0.24 (no cover) and 0.06 (straw cover). Viguria et al. (2015) found proportions of CH_4 in emissions from 2 lagoons during spring corresponding to 0.15 to 0.2 (range: 0.1 to 0.4). Sommer et al. (2007) compared CH_4-C/(CH_4-C + CO_2-C) ratios of slurry during simulated pit storage at 10, 15, and 20°C; whereas at 10°C the ratios were 0.1 to 0.3, at 20°C the ratios for cattle slurry shifted during storage from 0.2 to 0.5, and to 0.65 in pig slurry. For the data presented by Leytem et al. (2011), CH_4-C/(CH_4-C + CO_2-C) ratios of emissions from a dairy wastewater pond in early May, late May, August, and October were, respectively, 0.08, 0.25, 0.38, and 0.45 at temperatures of 5.0, 15.4, 20.8, and 15.3. The importance of methanogenesis may increase over time as a result of microbial adaptation or changes in the storage environment (Sommer et al., 2007; Barret et al., 2013), but will then, as mentioned above, be constrained by the remaining substrate.

Estimating On-Farm CH_4 Emissions from Manure

A dynamic method is needed to accurately estimate CH_4 emissions from manure management; some main drivers (retention time, storage temperature, and methanogenic potential) were discussed above. Production systems may be classified on the basis of housing and

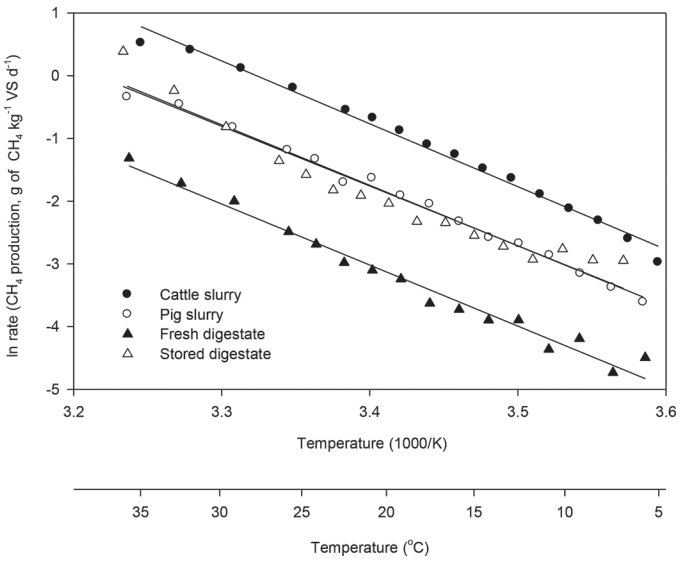


Figure 1. Arrhenius plots (ln rate versus inverse temperature, K) of the temperature response of CH_4 production in 4 contrasting liquid manure materials for the temperature range of 5 to 37°C. The manure materials were cattle slurry, pig slurry, fresh digestate from a thermophilic digester, and digestate from the same digester after several weeks of storage. The slopes of regression lines were not significantly different and averaged 81 kJ/mol. VS = volatile solids. Reproduced with permission from Elsgaard et al. (2016).

storage design, whereas treatment and management practices define manure retention times and storage temperatures in barn and outside storage. Estimation of daily emissions is needed to analyze effects of storage conditions and management in detail. Models using daily time steps for manure management include the Integrated Farm Systems Model (Chianese et al., 2009) and Manure-DNDC (Li et al., 2012). Both models depend on external parameters; that is, the temperature relationship of Integrated Farm Systems Model was adopted from Sommer et al. (2004) who in turn based values on a compilation of data from storage experiments, whereas Manure-DNDC relies on a submodel developed for soil environments, and a constant redox potential of −300 mV is used (Li et al., 2012). As an alternative approach, Petersen et al. (2016) proposed a method where estimation of CH_4 emissions is based on an in vitro anaerobic assay of CH_4 production rates in freshly collected samples when incubated at near-ambient temperature. Assuming this represents CH_4 emissions from the bulk liquid phase, rate measurements were used to parameterize a simple algorithm relating CH_4 emissions to temperature:

$$F_t = \left(\mathrm{VS_d} + 0.01\mathrm{VS_{nd}}\right) e^{\left(\mathrm{lnA} - \frac{E_a}{RT}\right)}. \quad [1]$$

In this equation, originally proposed by Sommer et al. (2004), F_t is CH_4 production rate (mg of CH_4/kg of VS/h); VS_d and VS_{nd} (kg/kg of VS) are degradable and recalcitrant ("nondegradable") manure organic matter; E_a is activation energy [81,000 J/mol (Elsgaard et al., 2016)] and lnA represents the pre-exponential factor (g of CH_4/kg of VS per hour) of an Arrhenius equation describing temperature sensitivity. Finally, R is the universal gas constant R (8.314 J/K/mol), and T is the ambient temperature at sampling (K). Sommer et al. (2004) calculated the VS_d from the biochemical composition of fresh excreta, but this approach is not feasible with partly degraded manure collected from a storage facility or pit, and Petersen et al. (2016) instead used an aerobic incubation assay to estimate VS degradability. This parameter, as well as the scaling factor of 0.01 between VS_d and VS_{nd} degradability, require further documentation, but a sensitivity analysis showed that model results mainly depended on the term lnA which represents the CH_4 production potential. The value of lnA can be estimated for the individual manure samples by rearrangement of Equation [1] once F_t has been determined. Although the individual estimate of lnA has little predictive power, a database of measurements for a given production system can provide an estimate and uncertainty range, the representativeness of which would improve as the database of system-specific CH_4 production rates expands.

Prediction of CH_4 emissions, however, also requires information about VS degradation during manure storage (Petersen et al., 2016). Existing models assume a constant ratio between CH_4 and CO_2 for estimation of VS loss (IPCC, 2006; Mangino et al., 2001; Sommer et al., 2004; Li et al., 2012), but as shown above this ratio is highly variable and may change with manure treatment and storage time. A separate assay would be needed to estimate C loss as CH_4 and CO_2 at the manure-air interface, and such an incubation system has yet to be developed. The method described thus requires further development, but has a potential for dynamic modeling of CH_4 emissions and VS loss during manure storage with direct reference to experimental data, where information about total C loss can help constrain estimates of VS_d.

Daily emission estimates can be recalculated to an MCF value for reporting, or separate MCF values can be calculated for in-barn and outside storage (Mikkelsen et al., 2016). This is important if manure treatment takes place following export from the barn because then only posttreatment emissions are affected. By reducing uncertainties for individual sources, it would allow for more effective GHG mitigation.

Controls of N_2O Emissions

Ammonia losses during manure management are a significant indirect source of N_2O (Hristov et al., 2011). McGinn et al. (2008) found that 13% of TAN was lost from a lagoon with cattle manure during summer storage in Western Canada. They further reported that wind speed and surface temperature together explained 59% of the variability in NH_3 emissions, and in accordance with this up to 35% of TAN may be lost in warmer climates (McGinn et al., 2008). Ammonia losses during manure storage can be reduced by around 80% with a cover in the form of a natural crust or synthetic membrane (Sommer et al., 1993; Miner et al., 2003). With a natural crust, however, the reduction of NH_3 emissions may be accompanied by direct emissions of N_2O produced around aerobic-anaerobic interfaces (Duan et al., 2017).

For liquid manure developing a natural crust, the IPCC (2006) guidelines recommend an N_2O emission factor of 0.005 kg of N_2O-N/kg of N stored, with an uncertainty range of 0.0025 to 0.01 kg of N_2O-N/kg of N. Available results from pilot-scale data are mostly within this range (Jayasundara et al., 2016), but there is a need for documenting emissions at a practical scale, and to better understand what constrains this source.

Typically crust formation is followed by a lag phase of several weeks before N_2O is observed (Sommer et al., 2000; Wood et al., 2012; Petersen et al., 2013b), which indicates that conditions in the crust do not support nitrification and denitrification activity during this period. Sommer et al. (2000) found that temporal dynamics were related to the water balance of the crust (precipitation minus evapotranspiration), suggesting that initially crust wetness is the limiting factor, but interactions between microbial activities and the physical and chemical environment of the crust are not well characterized at present.

For field-applied manure, as for mineral N fertilizers, an emission factor of 0.01 kg of N_2O-N/kg of N is recommended (IPCC, 2006). An increasing number of both experimental and model studies report that the relationship between N input and N_2O emissions is exponential rather than linear (e.g., McSwiney and Robertson, 2005; Philibert et al., 2012), and it has been proposed that high emissions are mainly associated with conditions where N input exceeds crop demand (i.e., where mineral N accumulates in the soil). However, meta-analyses also indicate that the uncertainty of N_2O emission estimates can be reduced by including aspects of management or soil characteristics (Shcherbak et al., 2014; Charles et al., 2017).

One source of variability, which has so far not been addressed in prediction models, is the spatial heterogeneity of manure in soil. The liquid phase of manure will partly infiltrate the soil in response to water potential gradients (Petersen et al., 2003), a process that is largely complete within 24 h (Misselbrook et al., 2005b). Temporally stable gradients in volumetric water content are established (Petersen et al., 2003), which therefore represent also the distribution of dissolved (and mostly labile) C and N shortly after manure application. The potential for partial reallocation of both C and N constituents is important for N_2O emissions because turnover of components infiltrating the bulk soil takes place in an environment with a higher O_2 availability than manure "hotspots" where both water content and O_2 demand is much higher than in the surrounding soil (Petersen et al., 1996; Baral et al., 2016). It is probably important to acknowledge that N_2O emissions associated with organic hotspots that are dominated by manure (or crop residues) follow different dynamics compared with N_2O emissions from bulk soil where the potential for emissions depends mainly on bulk soil properties such as gas diffusivity (Balaine et al., 2013).

Manure application method will evidently influence the size distribution of manure hotspots, with direct injection, band-spreading, and broadcasting representing methods with increasing contact between manure and soil. Manure distribution in soil following application has, however, mainly been described for injection methods (Petersen et al., 2003; Rahman et al., 2004) and surface application (Misselbrook et al., 2005b).

Estimating N_2O Emissions After Field Application

The IPCC methodology for estimating N_2O emissions from field-applied manure is based on annual emission factors, where the default (Tier 1) emission factor is 0.01 kg of N_2O-N/kg of N. The associated uncertainty range of 0.003 to 0.3 kg of N_2O-N/kg of N of the Tier 1 emission factor probably reflects inherent diversity of soil conditions that the emission factor is expected to represent because little improvement in precision was achieved by expanding the database (Stehfest and Bouwman, 2006). There is thus a pressing need for more informed estimates of N_2O emissions from N applied to soil. Experimental determination of N_2O emissions can provide Tier 2 emission factors at country level, although this requires a significant effort (e.g., Bell et al., 2015) and is not realistically done for all relevant combinations of N input and soil conditions. Dynamic models, referred to as Tier 3 in the IPCC terminology, have also been investigated for prediction of N_2O emissions from soil, but data requirement for parameterization is high, and deviations in the reproduction of temporal dynamics (e.g., Li et al., 2012) suggest that underlying processes are not fully understood.

Chen et al. (2008b) reviewed several process-based models for estimating N_2O emissions from soil, including NGAS-DAYCENT, DNDC, *ecosys*, NLOSS, Expert-N, WNMM, FASSET, and CERES-NOE. A common feature of these models is that they define soil layers assumed to be uniform with respect to physical, chemical, and microbiological characteristics. The application of liquid manure and other residues presents a challenge for such models insofar as individual constituents (water, C pools, N pools), and therefore labile C and N are in fact not evenly distributed within a given layer, but will be partly concentrated in manure-affected volumes that may be viewed as hotspots of intense C and N cycling. Size and distribution of manure hotspots will depend on application method and any subsequent tillage. Many studies have demonstrated how interactions between aerobic heterotrophic activity, nitrification, and denitrification in the gradient environment around such hotspots interact with soil conditions in determining the extent of denitrification and N_2O emissions (Nielsen and Revsbech, 1994; Petersen et al., 1996; Markfoged et al., 2011; Baral et al., 2016). Presumably the surface-to-volume ratio of manure hotspots is critical for predicting N_2O emissions, by determining the balance between aerobic and anaerobic degradation of labile C and N (Baral et al., 2016), and this could be

the reason why models that distribute manure constituents uniformly throughout a 2-dimensional soil layer fail to reproduce the dynamics of observed emissions (Chen et al., 2008b).

The distribution of manure C and N will approach a new equilibrium distribution within 24 h after field application of liquid manure (Misselbrook et al., 2005b). One way to account for this heterogeneity could be to use this new distribution as boundary conditions for transformations of labile manure C and N (including mineral N) after field application. Bulk soil conditions in the relevant soil layer could then be assumed for manure C and N transformations of the fraction infiltrating the soil. In contrast, separate conditions would need to be defined for an environment representing manure hotspots, to account for the co-occurrence of elevated water content and O_2 demand, and the coupling of nitrification and denitrification around aerobic-anaerobic interfaces (see Nielsen and Revsbech, 1994, and references therein). One requirement for this hypothetical model for manure distribution in soil is an estimate of the allocation of labile C and N between bulk soil and manure hotspots. An approach was proposed by Sommer et al. (2004) based on previously observed exponential relationships between water potential and VS in 22 manure materials including cattle manure, pig manure, and digestates:

$$f_R = 1 - 1/(1 + aVS), \quad [2]$$

and

$$a = 0.063 + 1.33e^{77.8\psi}, \quad [3]$$

where f_R is the proportion of manure water retained by VS, ψ (MPa) is soil water potential at the time of application, and a is a parameter defined by Ψ. Assuming that water retention in manure hotspots is a function of particulate VS (VS_{nd}, g/100 g) and a variable fraction (f_R) of labile VS (VS_d, g/100 g), that is, $VS_{hotspots} = VS_{nd} + f_R VS_d$, then f_R also defines the fraction of VS_d (and labile N) retained in hotspots, which can be determined by iteration. This empirical approach requires further validation, but could be a starting point for attempts to integrate heterogeneity in simulations of manure C and N turnover in soil.

MITIGATING GHG EMISSIONS FROM MANURE

The previous sections have indicated that both particulate (recalcitrant) and dissolved (labile) VS are important determinants of both CH_4 and N_2O emissions from manure management and after field application. During storage, labile C and N are sources of CH_4 and N_2O (in part via NH_3 emissions), whereas particulate VS may restrict atmospheric emissions if a natural crust forms. Surface crusts are themselves a potential site of CH_4 and N_2O metabolism. Upon field application, the amount and composition of VS in manure are important controls of the redistribution of labile C and N which, together with soil properties, determine the potential for N_2O emissions. In view of these and other mechanisms, by which manure VS can affect emissions, it may be useful to also discuss potential mitigation strategies in terms of their effect on manure VS composition or turnover.

Feeding

Jayasundara et al. (2016) presented a thorough review of relationships between cattle dietary changes and additives, and CH_4 emissions. The most consistent effects have been seen for lipid supplements, where a regression analysis indicated that a 9 to 12% reduction is achievable, but it was stressed that such effects may be reciprocated by higher CH_4 emissions from the manure, as exemplified by Hellwing et al. (2014). This negative interaction is compounded in warmer climates and stresses the need to consider GHG mitigation at farm level. Among additives, the most promising results have been with nitrate and 3-nitrooxypropanol, in some cases with CH_4 mitigation effects of 30 to 60% (Jayasundara et al., 2016). For these additives, however, more research is needed to fully document implications for environment and animal health. Reducing the protein in DMI of dairy cows will also influence the N content and composition of excretal returns, by selectively reducing the amount of N excreted as urea in the urine. A reduction of urinary N can reduce NH_3 losses (Petersen et al., 1998; Misselbrook et al., 2005a) and hence indirect N_2O emissions.

In-House Acidification

Ammonia emissions from liquid manure can be reduced by commercially available technologies for acidification. The manure in pits below slatted floors is acidified by pumping manure to an external treatment tank for daily adjustment to pH 5.5 with sulfuric acid (H_2SO_4) in a strictly contained and automated process, or acidification can take place directly in storage tanks or during field application (Fangueiro et al., 2015). Acidification effectively reduces NH_3 emissions from the liquid manure, but not from slats and soiled surfaces, and thus for cattle barns a reduction of 50% is acknowledged for regulatory purposes (http://www.vera-verification.eu/).

Table 1. Reduction in CH_4 emissions by anaerobic digestion (AD), and interaction with shorter hydraulic retention time (HRT) in the pit before digestion (Mikkelsen et al., 2016); model parameters are from Petersen et al. (2016)

Item	kg of CO_2 eq[1]/Mg of slurry, cattle	kg of CO_2 eq/Mg of slurry, pig	Gg of CO_2 eq/PJ of energy
Untreated	19.25	62.25	NA[2]
AD,[3] HRT of 20 d	−7.88	−15.32	−8.72
AD,[3] HRT of 7 d[4]	−13.75	−42.33	−20.75

[1]eq = equivalent.

[2]NA = not applicable.

[3]Digestate assumed to contain 58% cattle slurry and 42% pig slurry by volume, in accordance with national statistics for Denmark.

[4]Where possible.

Interestingly, storage experiments have also shown that H_2SO_4 addition inhibits CH_4 emissions from manure during storage. For example, reductions of 67 to 87% (Petersen et al., 2012) and 61 to 75% (Misselbrook et al., 2016) were observed in experiments with cattle manure stored for up to 3 mo, indicating that a 60% reduction of CH_4 emissions from manure management is realistic by in-house acidification. Petersen et al. (2012) also found significant CH_4 mitigation by SO_4^{2-} or methionine addition without pH change, and by acidification with an alternative acid, and it was speculated that different mechanisms contribute to inhibition of methanogenesis. Environmental issues to be considered with this technology are changes in the odor profile, and field application of S in excess of crop needs, because 5 to 6 kg/t of H_2SO_4 is needed for acidification of cattle slurry (Danish Centre for Verification of Climate and Environmental Technologies, 2012).

Anaerobic Digestion

Anaerobic digestion of livestock manure has several environmental benefits, including CH_4 and odor mitigation, and improved plant N availability (Massé et al., 2011). Anaerobic digestion (**AD**) technologies range from on-farm covers of pits or lagoons, with or without heating, to centralized reactors with heating and active mixing, and often organic co-digestates are included to boost gas production. According to Key and Sneeringer (2011), 60% of US dairy production takes place on farms where manure management systems allow AD treatment. Due to the moderate methanogenic potential of manure, profitability of AD is low, but it has been argued that environmental and societal benefits should also be taken into account (Yiridoe et al., 2009).

Manure can only be treated by AD following export from the barn, and therefore only posttreatment emissions are affected. Because VS degradation takes place also during the collection period, the in-barn HRT becomes critical for GHG mitigation (i.e., a shorter retention time in the pit before treatment can reduce CH_4 emissions and VS loss during collection while also boosting biogas yields). Annual MCF are evidently not useful for evaluating scenarios with different retention times. Instead the method represented by Equation [1] could be applied, as exemplified in Table 1 (Mikkelsen et al., 2016). Here, CH_4 mitigation by AD treatment of pig and cattle manure in Denmark was estimated for HRT in the barn of either 20 or 7 d before digestion. Increasing the frequency of export was in this example projected to increase the CH_4 mitigation potential of AD 2- to 3-fold. The most recent Danish national inventory for agricultural GHG emissions estimated a 41% reduction of CH_4 emissions by AD treatment of cattle manure using this approach (Nielsen et al., 2016).

Cover on Storage Facilities

It is well established that methanotrophs inhabit surface crusts on manure, and the 2006 IPCC guidelines assumed a 40% reduction of CH_4 emissions due to this activity (IPCC, 2006). However, no strong support has been found for an effect of this magnitude, and if in fact CH_4 escapes mainly via cracks, as discussed above, then CH_4 availability in the crust could be limiting. It has been proposed that an additional cover on manure storages combined with a crust, and with passive or active ventilation to maintain elevated CH_4 concentrations in the headspace, could enhance methanotrophic activity by increasing CH_4 availability in the air above the crust (Petersen and Miller, 2006). The most recent evidence regarding methanotrophs in surface crusts, their requirements for CH_4 and O_2, and sensitivity toward mineral N, indicates that there is indeed a potential for stimulating CH_4 oxidation in well-established natural crusts through controlled ventilation which should be explored (Duan et al., 2017). Covers for slurry tanks of concrete or tarpaulin are already available for protec-

tion against NH_3 losses, and could be adopted together with surveillance or even active control of O_2 and CH_4 availability.

Reducing Nitrogen Surplus

Several opportunities for management and treatment have already been discussed that can increase the manure N use efficiency (dietary changes, shorter HRT, cover on storages, acidification, and AD), although in some cases mitigation measures must be combined to avoid negative interactions between stages of management with respect to NH_3 emissions (Hutchings et al., 1996). Powell and Rotz (2015) discussed several strategies for mitigating N surplus in dairy production systems and concluded that in many cases both dietary CP intake and mineral fertilizer N can be reduced with little effect on productivity. Schils et al. (2006) reported a reduction of N surplus on Dutch dairy farms of 20%, from 300 to 240 kg of N/ha, between 1990 and 1999 as a result of less mineral fertilizer N applied and fewer grazing days, but because more manure was collected and stored on the farm, emissions of CH_4 increased. An overall reduction of GHG emissions of 6% was calculated, though with a potential for improvement by adopting mitigation measures against CH_4 emissions during manure storage.

Nitrification inhibitors have a potential to reduce N_2O emissions, as well as N leaching from manure and fertilizers, and the reduction may be as high as 40 to 50% according to some meta-analyses (e.g., Qiao et al., 2015). This is accompanied by positive trends in crop N uptake and N recovery, although for individual experiments these effects are often not statistically significant. This mitigation strategy certainly deserves attention, but to achieve GHG mitigation the N surplus should also be reduced to prevent that direct N_2O emissions are replaced by indirect emissions. In documenting effects of nitrification inhibitors, it is important to acknowledge the great diversity of active compounds in terms of water solubility, volatility, and persistence in the soil environment (Subbarao et al., 2007), and to investigate potential side effects (Kong et al., 2016).

Enteric Emissions vs. Manure Management

The relative importance of enteric fermentation and manure as sources of CH_4 emissions on dairy farms will depend on housing system, management, and storage conditions, including climate. In temperate regions the proportion of CH_4 emissions from liquid manure management on dairy farms is typically 15 to 20% (Chianese et al., 2009; Kristensen et al., 2011). However, in warmer climates the relative importance of CH_4 emissions from manure may be much greater. Thus, Owen and Silver (2015) reported that for US dairy farms the average proportion of CH_4 from manure management in 2011 was 43%, and in California as high as 54%.

Referring to the numbers given in previous subsections for effects of mitigation strategies, the CH_4 mitigation potential of dietary changes on dairy farms in temperate climates would be in the range of 7 to 10% (i.e., a 9–12% reduction of enteric emissions constituting 80 to 85% of total CH_4 emissions on dairy farms), and this assumes any increase in CH_4 emissions from manure is avoided. By comparison, the potential for mitigation of CH_4 emissions from manure through in-barn acidification may be 9 to 12% in temperate climates, and by AD treatment the potential may be 6 to 8%. Here, indirect effects on NH_3 emissions and N use efficiency should also be estimated. In warmer climates the CH_4 mitigation potential and relative importance of manure treatment technologies would be greater. Although uncertainties are present and further documentation is required for both dietary changes and manure treatment technologies, these estimated mitigation potentials do highlight the relevance of considering GHG mitigation for manure management.

CONCLUSIONS

The diversity of manure management practices on dairy farms is high, with intensification favoring liquid manure management. This trend increases the potential for both CH_4 and N_2O emissions, and the need for mitigation. The existing IPCC methodology for estimating emissions from manure is not well suited to describe management at the farm level, and effects of management changes or manure treatment are not easily quantified, which is also a barrier toward future regulation of emissions. Both recalcitrant and labile fractions of VS in liquid manure were shown to be important for CH_4 and N_2O emissions during storage and after field application. For accurate estimation of CH_4 emissions from manure, and CH_4 mitigation potentials, it is important to estimate VS loss during storage in barns and outside storages separately. Accounting for manure N availability in fertilizer plans is a precondition for effective N_2O mitigation. Adoption of GHG estimation methods with a better representation of temporal and spatial variability may offer the flexibility needed to quantify effects of manure treatment and management, and mitigation potentials.

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REFERENCES

Balaine, N., T. J. Clough, M. H. Beare, S. M. Thomas, E. D. Meenken, and J. G. Ross. 2013. Changes in relative gas diffusivity explain soil nitrous oxide flux dynamics. Soil Sci. Soc. Am. J. 77:1496–1505.

Baldé, H., A. C. VanderZaag, S. D. Burtt, R. J. Gordon, and R. L. Desjardins. 2016. Does fall removal of the dairy manure sludge in a storage tank reduce subsequent methane emissions? J. Environ. Qual. 45:2038–2043.

Baral, K. R., E. Arthur, J. E. Olesen, and S. O. Petersen. 2016. Predicting N_2O emissions from manure properties and soil moisture: An incubation experiment. Soil Biol. Biochem. 97:112–120.

Barberg, A. E., M. I. Endres, J. A. Salfer, and J. K. Reneau. 2007. Performance and welfare of dairy cows in an alternative housing system in Minnesota. J. Dairy Sci. 90:1575–1583.

Barret, M., N. Gagnon, E. Topp, L. Masse, D. I. Massé, and G. Talbot. 2013. Physico-chemical characteristics and methanogen communities in swine and dairy manure storage tanks: Spatio-temporal variations and impact on methanogenic activity. Water Res. 47:737–746.

Bell, M. J., N. Winning, R. M. Rees, J. M. Cloy, K. Topp, L. Cardenas, N. Donovan, T. Scott, C. Webster, A. Whitmore, J. Williams, H. Balshaw, F. Paine, and D. Chadwick. 2015. Nitrous oxide emissions from fertilised UK arable soils: Quantification and mitigation. Agric. Ecosyst. Environ. 212:134–147.

Bouwman, L., K. K. Goldewijk, K. W. Van Der Hoek, A. H. W. Beusen, D. P. Van Vuuren, J. Willems, M. C. Rufino, and E. Stehfest. 2013. Exploring global changes in nitrogen and phosphorus cycles in agriculture induced by livestock production over the 1900–2050 period. Proc. Natl. Acad. Sci. USA 110:20882–20887.

Charles, A., P. Rochette, J. K. Whalen, D. A. Angers, M. H. Chantigny, and N. Bertrand. 2017. Global nitrous oxide emission factors from agricultural soils after addition of organic amendments: A meta-analysis. Agric. Ecosyst. Environ. 236:88–98.

Chen, D., Y. Li, P. Grace, and A. Mosier. 2008b. N_2O emissions from agricultural lands: A synthesis of simulation approaches. Plant Soil 309:169–189.

Chen, Y., J. J. Cheng, and K. S. Creamer. 2008a. Inhibition of anaerobic digestion process: A review. Bioresour. Technol. 99:4044–4064.

Chianese, D. S., C. A. Rotz, and T. L. Richard. 2009. Whole-farm greenhouse gas emissions: A review with application to a Pennsylvania dairy farm. Appl. Eng. Agric. 25:431–442.

Crosson, P., L. Shalloo, D. O'Brien, G. J. Lanigan, P. A. Foley, T. M. Boland, and D. A. Kenny. 2011. A review of whole farm systems models of greenhouse gas emissions from beef and dairy cattle production systems. Anim. Feed Sci. Technol. 166–167:29–45.

Danish Centre for Verification of Climate and Environmental Technologies. 2012. Statement of Verification. Acidification of cattle slurry for reduced ammonia emission. Accessed Sep. 2, 2017. http://www.etv-denmark.com/files/agriculture/JH-Forsuring_Verification_Statement_Ver%201-6.pdf.

Duan, Y. F., S. Reinsch, P. Ambus, L. Elsgaard, and S. O. Petersen. 2017. Methanotrophic activity in slurry surface crusts as influenced by CH_4, O_2, and inorganic N. J. Environ. Qual. In press.

Elsgaard, L., A. B. Olsen, and S. O. Petersen. 2016. Temperature response of methane production in liquid manure and co-digestates. Sci. Total Environ. 539:78–84.

Eriksen, J., A. J. Andersen, H. V. Poulsen, A. P. S. Adamsen, and S. O. Petersen. 2012. Sulfur turnover and emissions during storage of cattle slurry: Effects of acidification and sulfur addition. J. Environ. Qual. 41:1633–1641.

Fangueiro, D., M. Hjorth, and F. Gioelli. 2015. Acidification of animal slurry–A review. J. Environ. Manage. 149:46–56.

FAO (Food and Agriculture Organization of the United Nations). 2010. Greenhouse gas emissions from the dairy sector. A life cycle assessment. Rome, Italy, 94 pp. Accessed Sep. 4, 2017. http://www.fao.org/docrep/012/k7930e/k7930e00.pdf.

Galama, P. 2011. Prospects for bedded pack barns for dairy cattle. Wageningen UR Livestock Research, Publ. No. 16, 74 pp. Accessed Sep. 4, 2017. http://www.vrijloopstallen.nl/documenten/Prospects_for_bedded_pack_barns_for_dairy_cattle.pdf.

Gerber, P., T. Vellinga, C. Opio, and H. Steinfeld. 2011. Productivity gains and greenhouse gas emissions intensity in dairy systems. Livest. Sci. 139:100–108.

Haeussermann, A., E. Hartung, E. Gallmann, and T. Jungbluth. 2006. Influence of season, ventilation strategy, and slurry removal on methane emissions from pig houses. Agric. Ecosyst. Environ. 112:115–121.

Hafner, S. D., S. G. Sommer, V. Petersen, and R. Markfoged. 2017. Effects of carbon dioxide hydration kinetics and evaporative convection on pH profile development during interfacial mass transfer of ammonia and carbon dioxide. Heat Mass Transf. 53:1335–1342.

Hellwing, A. L. F., M. R. Weisbjerg, and H. B. Møller. 2014. Enteric and manure-derived methane emissions and biogas yield of slurry from dairy cows fed grass silage or maize silage with and without supplementation of rapeseed. Livest. Sci. 165:189–199.

Henriksson, M., A. Flysjö, C. Cederberg, and C. Swensson. 2011. Variation in carbon footprint of milk due to management differences between Swedish dairy farms. Animal 5:1474–1484.

Hou, Y., G. L. Velthof, and O. Oenema. 2015. Mitigation of ammonia, nitrous oxide and methane emissions from manure management chains: A meta-analysis and integrated assessment. Glob. Change Biol. 21:1293–1312.

Hristov, A. N., M. Hanigan, A. Cole, R. Todd, T. A. McAllister, P. M. Ndegwa, and A. Rotz. 2011. Ammonia emissions from dairy farms and beef feedlots. Can. J. Anim. Sci. 91:1–35.

Hutchings, N. J., S. G. Sommer, and S. C. Jarvis. 1996. A model of ammonia volatilization from a grazing livestock farm. Atmos. Environ. 30:589–599.

IPCC. 2006. 2006 IPCC Guidelines for National Greenhouse Gas Inventories, Prepared by the National Greenhouse Gas Inventories Programme. H. S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe, ed. Published: IGES, Japan. Accessed Sep. 4, 2017. http://www.ipcc-nggip.iges.or.jp/public/2006gl/.

Jayasundara, S., J. A. D. Ranga Niroshan Appuhamy, E. Kebreab, and C. Wagner-Riddle. 2016. Methane and nitrous oxide emissions from Canadian dairy farms and mitigation options: An updated review. Can. J. Anim. Sci. 96:306–331.

Jørgensen, B. B., and N. P. Revsbech. 1985. Diffusive boundary layers and the oxygen uptake of sediments and detritus. Limnol. Oceanogr. 30:111–122.

Kai, P., T. Birkmose, and S. Petersen. 2015. Slurry volumes and estimated storage time of slurry in Danish livestock buildings. AgroTech Report Dec 2015, 32 pp. (in Danish). Accessed Sep. 4, 2017. https://ens.dk/ansvarsomraader/bioenergi/biogas-taskforce.

Kebreab, E., J. France, D. E. Beever, and A. R. Castillo. 2001. Nitrogen pollution by dairy cows and its mitigation by dietary manipulation. Nutr. Cycl. Agroecosyst. 60:275–285.

Key, N., and S. Sneeringer. 2011. Climate Change Policy and the Adoption of Methane Digesters on Livestock Operations. USDA Economic Research Report No. 111, 47 pp.

Kong, X., Y.-F. Duan, A. Schramm, J. Eriksen, and S. O. Petersen. 2016. 3,4-Dimethylpyrazole phosphate (DMPP) reduces activity of ammonia oxidizers without adverse effects on non-target soil microorganisms and functions. Appl. Soil Ecol. 105:67–75.

Kristensen, T., L. Mogensen, M. T. Knudsen, and J. E. Hermansen. 2011. Effect of production system and farming strategy on greenhouse gas emissions from commercial dairy farms in a life cycle approach. Livest. Sci. 140:136–148.

Laguë, C., É. Gaudet, J. Agnew, and T. A. Fonstad. 2005. Greenhouse gas emissions from liquid swine manure storage facilities in Saskatchewan. Trans. ASAE 48:2289–2296.

Leytem, A. B., R. S. Dungan, D. L. Bjorneberg, and A. C. Koehn. 2011. Emissions of ammonia, methane, carbon dioxide, and nitrous oxide from dairy cattle housing and manure management systems. J. Environ. Qual. 40:1383–1394.

Li, C., W. Salas, R. Zhang, C. Krauter, A. Rotz, and F. Mitloehner. 2012. Manure-DNDC: A biogeochemical process model for quantifying greenhouse gas and ammonia emissions from livestock manure systems. Nutr. Cycl. Agroecosyst. 93:163–200.

Maharjan, B., and R. T. Venterea. 2013. Nitrite intensity explains N management effects on N_2O emissions in maize. Soil Biol. Biochem. 66:229–238.

Mangino, J., D. Bartram, and A. Brazy. 2001. Development of a methane conversion factor to estimate emissions from animal waste lagoons. US EPA 17th Annual Emission Inventory Conference, USEPA, Research Triangle Park, NC. 16–18 April 2002, Atlanta, GA. Accessed Sep. 4, 2017. https://www3.epa.gov/ttnchie1/conference/ei11/ammonia/mangino.pdf.

Markfoged, R., L. P. Nielsen, T. Nyord, L. D. M. Ottosen, and N. P. Revsbech. 2011. Transient N_2O accumulation and emission caused by O_2 depletion in soil after liquid manure injection. Eur. J. Soil Sci. 62:541–550.

Massé, D. I., G. Talbot, and Y. Gilbert. 2011. On farm biogas production: A method to reduce GHG emissions and develop more sustainable livestock operations. Anim. Feed Sci. Technol. 166–167:436–445.

McGinn, S. M., T. Coates, T. K. Flesch, and B. Crenna. 2008. Ammonia emission from dairy cow manure stored in a lagoon over summer. Can. J. Soil Sci. 88:611–615.

McSwiney, C. P., and G. P. Robertson. 2005. Nonlinear response of N_2O flux to incremental fertilizer addition in a continuous maize (Zea mays L.) cropping system. Glob. Change Biol. 11:1712–1719.

Meyer, D., P. L. Price, H. A. Rossow, N. Silva-del-Rio, B. L. Karle, P. H. Robinson, E. J. DePeters, and J. G. Fadel. 2011. Survey of dairy housing and manure management practices in California. J. Dairy Sci. 94:4744–4750.

Mikkelsen, M. H., R. Albrektsen, and S. Gyldenkærne. 2016. Consequences of biogas production for greehouse gas emissions within agriculture (Biogasproduktions konsekvenser for drivhusgasudledning i landbruget). Aarhus University, DCE–National Centre for Environment and Energy, 41 pp. Report No. 197 (in Danish). http://dce2.au.dk/pub/SR197.pdf

Miner, J. R., F. J. Humenik, J. M. Rice, D. M. C. Rashash, C. Williams, and W. Robarge. 2003. Evaluation of a permeable, 5 cm thick, polyethylene foam lagoon cover. Trans. ASAE 46:1421–1426.

Misselbrook, T., J. Hunt, F. Perazzolo, and G. Provolo. 2016. Greenhouse gas and ammonia emissions from slurry storage: Impacts of temperature and potential mitigation through covering (pig slurry) or acidification (cattle slurry). J. Environ. Qual. 45:1520–1530.

Misselbrook, T. H., S. K. E. Brookman, K. A. Smith, T. Cumby, A. G. Williams, and D. F. McCrory. 2005c. Crusting of stored dairy slurry to abate ammonia emissions: Pilot-scale studies. J. Environ. Qual. 34:411–419.

Misselbrook, T. H., J. M. Powell, G. A. Broderick, and J. H. Grabber. 2005a. Dietary manipulation in dairy cattle: Laboratory experiments to assess the influence on ammonia emissions. J. Dairy Sci. 88:1765–1777.

Misselbrook, T. H., D. Scholefield, and R. Parkinson. 2005b. Using time domain reflectometry to characterize cattle and pig slurry infiltration into soil. Soil Use Manage. 21:167–172.

Møller, H. B., S. G. Sommer, and B. K. Ahring. 2002. Separation efficiency and particle size distribution in relation to manure type and storage conditions. Bioresour. Technol. 85:189–196.

Møller, H. B., S. G. Sommer, and B. K. Ahring. 2004. Biological degradation and greenhouse gas emissions during pre-storage of liquid animal manure. J. Environ. Qual. 33:27–36.

Myhre, G., D. Shindell, F.-M. Bréon, W. Collins, J. Fuglestvedt, J. Huang, D. Koch, J.-F. Lamarque, D. Lee, B. Mendoza, T. Nakajima, A. Robock, G. Stephens, T. Takemura, and H. Zhang. 2013. Anthropogenic and Natural Radiative Forcing. In: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. T. F. Stocker, D. Qin, G.-K. Plattner, M. Tignor, S. K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, and P. M. Midgley, ed. Cambridge University Press, Cambridge, UK.

Nielsen, O.-K., M. S. Plejdrup, M. Winther, M. Nielsen, S. Gyldenkærne, M. H. Mikkelsen, R. Albrektsen, M. Thomsen, K. Hjelgaard, P. Fauser, H. G. Bruun, V. K. Johannsen, T. Nord-Larsen, L. Vesterdal, I. Callesen, E. Schou, K. Suadicani, E. Rasmussen, S. B. Petersen, L. Baunbæk, and M. G. Hansen. 2016. Denmark's National Inventory Report 2015 and 2016. Emission Inventories 1990–2014. Submitted under the United Nations Framework Convention on Climate Change and the Kyoto Protocol. Aarhus University, DCE –Danish Centre for Environment and Energy. Scientific Report from DCE–Danish Centre for Environment and Energy. http://dce2.au.dk/pub/SR189.pdf.

Nielsen, T. H., and N. P. Revsbech. 1994. Diffusion chamber for nitrogen-15 determination of coupled nitrification-denitrification around soil-manure interfaces. Soil Sci. Soc. Am. J. 58:795–800.

Oenema, O., J. Salomez, C. Branquinho, M. Budnakova, P. Cermak, P. Geupel, P. Johnes, C. Tomkins, T. Spranger, J. W. Erisman, C. Pallière, L. Maene, R. Alonso, R. Maas, J. Magid, M. A. Sutton, and H. van Grinsven. 2011. Developing integrated approaches to nitrogen management. Pages 541–550 in European Nitrogen Assessment. M. A. Sutton, C. M. Howard, J. W. Erisman, G. Billen, A. Bleeker, P. Grennfelt, H. van Grinsven, and B. Grizzetti, ed. Cambridge University Press, UK. http://centaur.reading.ac.uk/20872/.

Owen, J. J., and W. L. Silver. 2015. Greenhouse gas emissions from dairy manure management: A review of field-based studies. Glob. Change Biol. 21:550–565.

Patni, N. K., and P. Y. Jui. 1987. Changes in solids and carbon content of dairy-cattle slurry in farm tanks. Biol. Wastes 20:11–34.

Petersen, S. O., B. Amon, and A. Gattinger. 2005. Methane oxidation in slurry storage surface crusts. J. Environ. Qual. 34:455–461.

Petersen, S. O., A. J. Andersen, and J. Eriksen. 2012. Effects of slurry acidification on ammonia and methane emission during storage. J. Environ. Qual. 41:88–94.

Petersen, S. O., M. Blanchard, D. Chadwick, A. del Prado, N. Edouard, J. Mosquera, and S. G. Sommer. 2013a. Manure management for greenhouse gas mitigation. Animal 7:266–282.

Petersen, S. O., N. Dorno, S. Lindholst, A. Feilberg, and J. Eriksen. 2013b. Emissions of CH_4, N_2O, NH_3 and odorants from pig slurry during winter and summer storage. Nutr. Cycl. Agroecosyst. 95:103–113.

Petersen, S. O., and D. N. Miller. 2006. Greenhouse gas mitigation by livestock waste storage and lagoon covers. J. Sci. Food Agric. 86:1407–1411.

Petersen, S. O., T. H. Nielsen, Å. Frostegård, and T. Olesen. 1996. Oxygen uptake, carbon metabolism, and denitrification associated with manure hot-spots. Soil Biol. Biochem. 28:341–349.

Petersen, S. O., H. H. Nissen, I. Lund, and P. Ambus. 2003. Redistribution of slurry in soil as influenced by organic matter content and injection method. J. Environ. Qual. 32:2399–2409.

Petersen, S. O., A. B. Olsen, L. Elsgaard, J. M. Triolo, and S. G. Sommer. 2016. Estimation of methane emissions from slurry pits under pig and cattle confinements. PLoS One 11:e0160968.

Petersen, S. O., S. G. Sommer, O. Aaes, and K. Søegaard. 1998. Ammonia losses from urine and dung of grazing cattle: Effect of N intake. Atmos. Environ. 32:295–300.

Philibert, A., C. Loyce, and D. Makowski. 2012. Quantifying uncertainties in N_2O emission due to N fertilizer application in cultivated areas. PLoS One 7:e50950. https://doi.org/10.1371/journal.pone.0050950.

Powell, J. M., and C. A. Rotz. 2015. Measures of nitrogen use efficiency and nitrogen loss from dairy production systems. J. Environ. Qual. 44:336–344.

Prism Climate Group. 2017. Prism Climate Data. Accessed Oct. 31, 2017. http://www.prism.oregonstate.edu/normals/.

Qiao, C., L. Liu, S. Hu, J. E. Compton, T. L. Greaver, and Q. Li. 2015. How inhibiting nitrification affects nitrogen cycle and reduces environmental impacts of anthropogenic nitrogen input. Glob. Change Biol. 21:1249–1257.

Rahman, S., Y. Chen, K. Buckley, and W. Akinremi. 2004. Slurry distribution in soil as influenced by slurry application micro-rate and injection tool type. Biosyst. Eng. 89:495–504.

Schils, R., J. E. Olesen, A. del Prado, and J. F. Soussana. 2007. A review of farm level modelling approaches for mitigating greenhouse gas emissions from ruminant livestock systems. Livest. Sci. 112:240–251.

Schils, R. L. M., A. Verhagen, H. F. M. Aarts, P. J. Kuikman, and B. J. Sebek. 2006. Effect of improved nitrogen management on greenhouse gas emissions from intensive dairy systems in the Netherlands. Glob. Change Biol. 12:382–391.

Shcherbak, I., N. Millar, and G. P. Robertson. 2014. Global metaanalysis of the nonlinear response of soil nitrous oxide (N_2O) emissions to fertilizer nitrogen. Proc. Natl. Acad. Sci. USA 111:9199–9204.

Sommer, S. G., B. T. Christensen, N. E. Nielsen, and J. K. Schjorring. 1993. Ammonia volatilization during storage of cattle and pig slurry–Effect of surface cover. J. Agric. Sci. 121:63–71.

Sommer, S. G., and S. Husted. 1995. The chemical buffer system in raw and digested animal slurry. J. Agric. Sci. Camb. 124:45–53.

Sommer, S. G., J. E. Olesen, S. O. Petersen, M. R. Weisbjerg, L. Valli, L. Rodhe, and F. Béline. 2009. Region-specific assessment of greenhouse gas mitigation with different manure management strategies in four agroecological zones. Glob. Change Biol. 15:2825–2837.

Sommer, S. G., S. O. Petersen, and H. B. Møller. 2004. Algorithms for calculating methane and nitrous oxide emissions from manure management. Nutr. Cycl. Agroecosyst. 69:143–154.

Sommer, S. G., S. O. Petersen, and H. T. Søegaard. 2000. Greenhouse gas emission from stored livestock slurry. J. Environ. Qual. 29:744–750.

Sommer, S. G., S. O. Petersen, P. Sørensen, H. D. Poulsen, and H. B. Møller. 2007. Methane and carbon dioxide emissions and nitrogen turnover during liquid manure storage. Nutr. Cycl. Agroecosyst. 78:27–36.

Sørensen, C. A. G., S. G. Sommer, D. Bochtis, and A. Rotz. 2013. Technologies and logistics for handling, transport and distribution of animal manures. Pages 211–234 in Animal Manure Recycling. S. G. Sommer, M. L. Christensen, T. Schmidt, and L. S. Jensen, ed. 1st ed. J. Wiley & Sons Ltd., Chichester, UK.

Stehfest, E., and L. Bouwman. 2006. N_2O and NO emission from agricultural fields and soils under natural vegetation: Summarizing available measurement data and modeling of global annual emissions. Nutr. Cycl. Agroecosyst. 74:207–228.

Subbarao, G. V., O. Ito, K. L. Sahrawat, W. L. Berry, K. Nakahara, T. Ishikawa, T. Watanabe, K. Suenaga, M. Rondon, and I. M. Rao. 2007. Scope and strategies for regulation of nitrification in agricultural systems–Challenges and opportunities. Crit. Rev. Plant Sci. 25:303–335.

Thoma, G., J. Popp, D. Nutter, D. Shonnard, R. Ulrich, M. Matlock, D. S. Kim, Z. Neiderman, N. Kemper, C. East, and F. Adom. 2013a. Greenhouse gas emissions from milk production and consumption in the United States: A cradle-to-grave life cycle assessment circa 2008. Int. Dairy J. 31:S3–S14.

Thoma, G., J. Popp, D. Shonnard, D. Nutter, M. Matlock, R. Ulrich, W. Kellogg, D. S. Kim, Z. Neiderman, N. Kemper, F. Adom, and C. East. 2013b. Regional analysis of greenhouse gas emissions from USA dairy farms: A cradle to farm-gate assessment of the American dairy industry circa 2008. Int. Dairy J. 31:S29–S40.

Turnquist, A., J. Foltz, and C. Roth. 2006. Manure Management on Wisconsin Farms. PATS Res. Rep. No. 15.

Vadas, P. A. 2006. Distribution of phosphorus in manure slurry and its infiltration after application to soils. J. Environ. Qual. 35:542–547.

VanderZaag, A. C., J. D. MacDonald, L. Evans, X. P. C. Vergé, and R. L. Desjardins. 2013. Towards an inventory of methane emissions from manure management that is responsive to changes on Canadian farms. Environ. Res. Lett. 8:035008–035013.

Venterea, R. T., A. D. Halvorson, N. Kitchen, M. A. Liebig, M. A. Cavigelli, S. J. Del Grosso, P. P. Motavalli, K. A. Nelson, K. A. Spokas, B. P. Singh, C. E. Stewart, A. Ranaivoson, J. Strock, and H. Collins. 2012. Challenges and opportunities for mitigating nitrous oxide emissions from fertilized cropping systems. Front. Ecol. Environ. 10:562–570.

Viguria, M., D. M. López, H. Arriaga, and P. Merino. 2015. Ammonia and greenhouse gases emissions from on-farm stored pig slurry. Water Air Soil Pollut. 226:285–292.

Webb, J., S. G. Sommer, T. Kupper, K. Groenestein, N. J. Huthings, B. Eurich-Menden, L. Rodhe, T. M. Misselbrook, and B. Amon. 2011. Emissions of ammonia, nitrous oxide and methane during the management of solid manures—A review. Sust. Agric. Rev. 8:67–107.

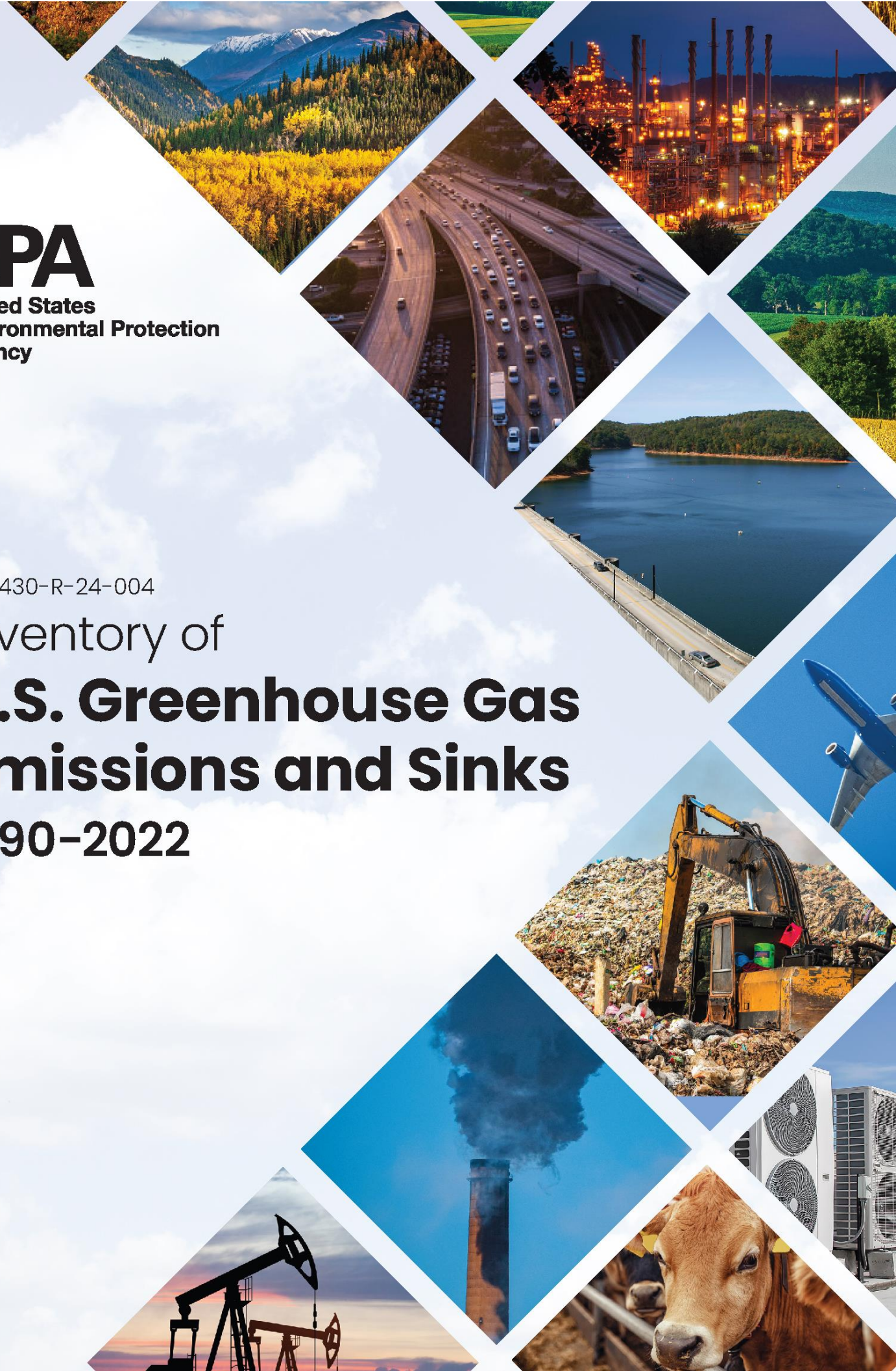
Weiske, A., A. Vabitsch, J. E. Olesen, K. Schelde, J. Michel, R. Friedrich, and M. Kaltschmitt. 2006. Mitigation of greenhouse gas emissions in European conventional and organic dairy farming. Agric. Ecosyst. Environ. 112:221–232.

Wightman, J. L., and P. B. Woodbury. 2016. New York dairy manure management greenhouse gas emissions and mitigation costs (1992–2022). J. Environ. Qual. 45:266–275.

Wood, J. D., R. J. Gordon, C. Wagner-Riddle, K. E. Dunfield, and A. Madani. 2012. Relationships between dairy slurry total solids, gas emissions, and surface crusts. J. Environ. Qual. 41:694–704.

Yiridoe, E. K., R. Gordon, and B. B. Brown. 2009. Nonmarket cobenefits and economic feasibility of on-farm biogas energy production. Energy Policy 37:1170–1179.

Zdanowicz, M., J. A. Shelford, C. B. Tucker, D. M. Weary, and M. A. G. von Keyserlingk. 2004. Bacterial populations on teat ends of dairy cows housed in free stalls and bedded with either sand or sawdust. J. Dairy Sci. 87:1694–1701.



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Inventory of
U.S. Greenhouse Gas Emissions and Sinks
1990–2022

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For more information regarding climate change and greenhouse gas emissions, see the EPA web site at https://www.epa.gov/ghgemissions.

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Preface

The United States Environmental Protection Agency (EPA) prepares the official U.S. Inventory of Greenhouse Gas Emissions and Sinks to fulfill annual existing commitments under the Paris Agreement and the United Nations Framework Convention on Climate Change (UNFCCC). National greenhouse gas (GHG) inventory reports are to be submitted each year by April 15.

In an effort to engage the public and researchers across the country, the EPA has instituted an annual public review and comment process for this document. The draft document was announced via Federal Register Notice and published for a 30-day comment period on the EPA Greenhouse Gas Emissions and Removals web site from February 14 through March 15, 2024, and comments received during the public review period are posted to the docket EPA-HQ-OAR-2024-0004. Comments received after the closure of the public comment period will be considered for the next edition of this annual report. Responses to comments are typically posted to EPA's website 2-4 weeks following publication of the final report in April 2024.

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Executive Summary

An inventory that identifies and quantifies a country's anthropogenic[1] sources and sinks of greenhouse gas emissions and removals is essential for addressing climate change. This *Inventory* adheres to both (1) a comprehensive and detailed set of methodologies for estimating national sources and sinks of anthropogenic greenhouse gases, and (2) a common and consistent format that enables Parties to the Paris Agreement and United Nations Framework Convention on Climate Change (UNFCCC) to compare the relative contribution of different greenhouse gases emissions and removals to climate change.

The United States is party to both the 1992 UNFCCC and the 2015 Paris Agreement. The Paris Agreement set a global temperature goal – holding the increase in the global average temperature to well below 2°C above pre-industrial levels and pursuing efforts to limit the increase to 1.5°C – that articulates with greater precision States' views on what is necessary to meet the UNFCCC's objective of "stabiliz[ing] … greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system.[2]

The United States is committed to submitting a national inventory of anthropogenic emission sources and removals by sinks of greenhouse gases by April 15 of each year. The United States has prepared this report, in conjunction with Common Reporting Tables (CRTs) that accompany this report, consistent with its obligations under those agreements.

This Executive Summary provides the latest information on U.S. anthropogenic greenhouse gas emission trends from 1990 through 2022. The structure of this report is consistent with requirements under the Paris Agreement and the UNFCCC on national greenhouse gas inventory reporting, as discussed in Box ES-1. Throughout this report, emission and sink estimates are grouped into five reporting sectors (i.e., chapters): Energy, IPPU, Agriculture, Land Use, Land-Use Change, and Forestry (LULUCF), and Waste. In describing trends (Chapter 2), emissions and sinks are also summarized according to commonly used economic sector categories: residential, commercial, industry, transportation, electric power, and agriculture. See Box 2-1 for more information on how economic sectors are defined.

Box ES-1: Methodological Approach for Estimating and Reporting U.S. Emissions and Removals, including Relationship to EPA's Greenhouse Gas Reporting Program

Consistent with Article 13.7(a) of the Paris Agreement and Article 4.1(a) of the UNFCCC as well as relevant decisions under those agreements, the emissions and removals presented in this report and this chapter are organized by source and sink categories and calculated using internationally accepted methods in the *2006 IPCC Guidelines for National Greenhouse Gas Inventories* (*2006 IPCC Guidelines)* and, where appropriate, its supplements and refinements. Additionally, the calculated emissions and removals in a given year for the United States are presented in a common manner in line with the reporting guidelines for the reporting of inventories

[1] The term "anthropogenic," in this context, refers to greenhouse gas emissions and removals that are a direct result of human activities or are the result of natural processes that have been affected by human activities (IPCC 2006).

[2] See Paris Agreement, Article 2.1(a); UNFCCC, Article 2.

under the Paris Agreement and the UNFCCC. The Parties' use of consistent methods to calculate emissions and removals for their inventories helps to ensure that these reports are comparable. The presentation of emissions and removals provided in this *Inventory* does not preclude alternative examinations (e.g., economic sectors). Rather, this *Inventory* presents emissions and removals in a common format consistent with how Parties are to report their national inventories under the Paris Agreement and the UNFCCC. The report itself, and this chapter, follows this common format, and provides an explanation of the application of methods used to calculate emissions and removals.

EPA also collects greenhouse gas emissions data from individual facilities and suppliers of certain fossil fuels and industrial gases through its Greenhouse Gas Reporting Program (GHGRP), which is complementary to the U.S. Inventory.[3] The GHGRP applies to direct greenhouse gas emitters, fossil fuel suppliers, industrial greenhouse gas suppliers, and facilities that inject carbon dioxide (CO_2) underground for sequestration or other reasons and requires reporting by over 8,000 sources or suppliers in 41 industrial categories.[4] Annual reporting is at the facility level, except for certain suppliers of fossil fuels and industrial greenhouse gases. In general, the threshold for reporting is 25,000 metric tons or more of CO_2 Eq. per year. Facilities in most source categories subject to GHGRP began reporting for the 2010 reporting year while additional types of industrial operations began reporting for reporting year 2011.[5] Methodologies used in EPA's GHGRP are consistent with the 2006 IPCC Guidelines. While the GHGRP does not provide full coverage of total annual U.S. greenhouse gas emissions and removals (e.g., the GHGRP excludes emissions from the agricultural, land use, and forestry sectors), it is an important input to the calculations of national-level emissions in this *Inventory*.

The GHGRP dataset provides not only annual emissions information, but also other annual information such as activity data and emission factors that can improve and refine national emission estimates over time. GHGRP data also allow EPA to disaggregate national inventory estimates in new ways that can highlight differences across regions and subcategories of emissions, along with enhancing the application of QA/QC procedures and assessment of uncertainties. See Annex 9 for more information on specific uses of GHGRP data in the Inventory (e.g., use of Subpart W data in compiling estimates for natural gas systems).

ES.1 Background Information

Greenhouse gases absorb infrared radiation, trapping heat in the atmosphere and making the planet warmer. The most important greenhouse gases directly emitted by human activities include carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and several fluorine-containing halogenated substances (HFCs, PFCs, SF_6 and NF_3). Although CO_2, CH_4, and N_2O occur naturally in the atmosphere, human activities have changed their atmospheric concentrations. From the pre-industrial era (i.e., ending about 1750) to 2022, concentrations of these greenhouse gases have increased globally by 49.5, 161.9, and 24.3 percent, respectively (IPCC 2013; NOAA/ESRL 2024a, 2024b, 2024c). This annual report estimates the total national greenhouse gas emissions and removals associated with human activities across the United States.

[3] On October 30, 2009, EPA promulgated a rule requiring annual reporting of greenhouse gas data from large greenhouse gas emissions sources in the United States. Implementation of the rule, codified at 40 CFR Part 98, is referred to as EPA's Greenhouse Gas Reporting Program (GHGRP).

[4] See http://www.epa.gov/ghgreporting and http://ghgdata.epa.gov/ghgp/main.do.

[5] See https://ccdsupport.com/confluence/pages/viewpage.action?pageId=322699300.

Global Warming Potentials

The IPCC developed the global warming potential (GWP) concept to compare the ability of a greenhouse gas to trap heat in the atmosphere relative to another gas. A GWP is a quantified measure of the relative globally averaged radiative forcing impacts of emissions of a particular greenhouse gas over time. The GWP of a greenhouse gas is defined as the ratio of the accumulated radiative forcing within a specific time horizon caused by emitting 1 kilogram of the gas, relative to that of the reference gas CO_2 (IPCC 2021); therefore, CO_2-equivalent emissions are provided in million metric tons of CO_2 equivalent (MMT CO_2 Eq.) for non-CO_2 greenhouse gases.[6,7] All estimates are provided throughout the main report in both CO_2 equivalents and unweighted units, while estimates for all gases in this Executive Summary are presented in units of MMT CO_2 Eq. Emissions by gas in unweighted mass kilotons are also provided in the Trends chapter and individual sector chapters of this report, and in the CRTs that are included in the submission to the UNFCCC.

Recent decisions under the Paris Agreement[8] and the UNFCCC[9] require Parties to use 100-year GWP values from the IPCC *Fifth Assessment Report* (AR5) for calculating CO_2-equivalents in their national reporting (IPCC 2013) by the end of 2024. This reflects updated science and ensures that national greenhouse gas inventories reported by all nations are comparable. This report reflects CO_2-equivalent greenhouse gas emission totals using 100-year AR5 GWP values. A comparison of emission values with the IPCC *Sixth Assessment Report* (AR6) (IPCC 2021) values can be found in Annex 6.1 of this report. The 100-year GWP values used in this report are listed below in Table ES-1.

Table ES-1: Global Warming Potentials (100-Year Time Horizon) Used in this Report

Gas	GWP
CO_2	1
CH_4[a]	28
N_2O	265
HFCs	up to 12,400
PFCs	up to 11,100
SF_6	23,500
NF_3	16,100
Other Fluorinated Gases	See Annex 6

[a] The GWP of CH_4 includes the direct effects and those indirect effects due to the production of tropospheric ozone and stratospheric water vapor. The indirect effect due to production of CO_2 is not included. See Annex 6 for additional information.
Source: IPCC (2013).

[6] Carbon comprises 12/44 of carbon dioxide by weight.

[7] One million metric ton is equal to 10^{12} grams or one teragram.

[8] See Annex to decision 18/CMA.1, available online at https://unfccc.int/sites/default/files/resource/CMA2018_03a02E.pdf.

[9] See paragraphs 1 and 2 of the decision on common metrics adopted at the 27th UNFCCC Conference of Parties (COP27), available online at https://unfccc.int/sites/default/files/resource/cp2022_10a01_E.pdf.

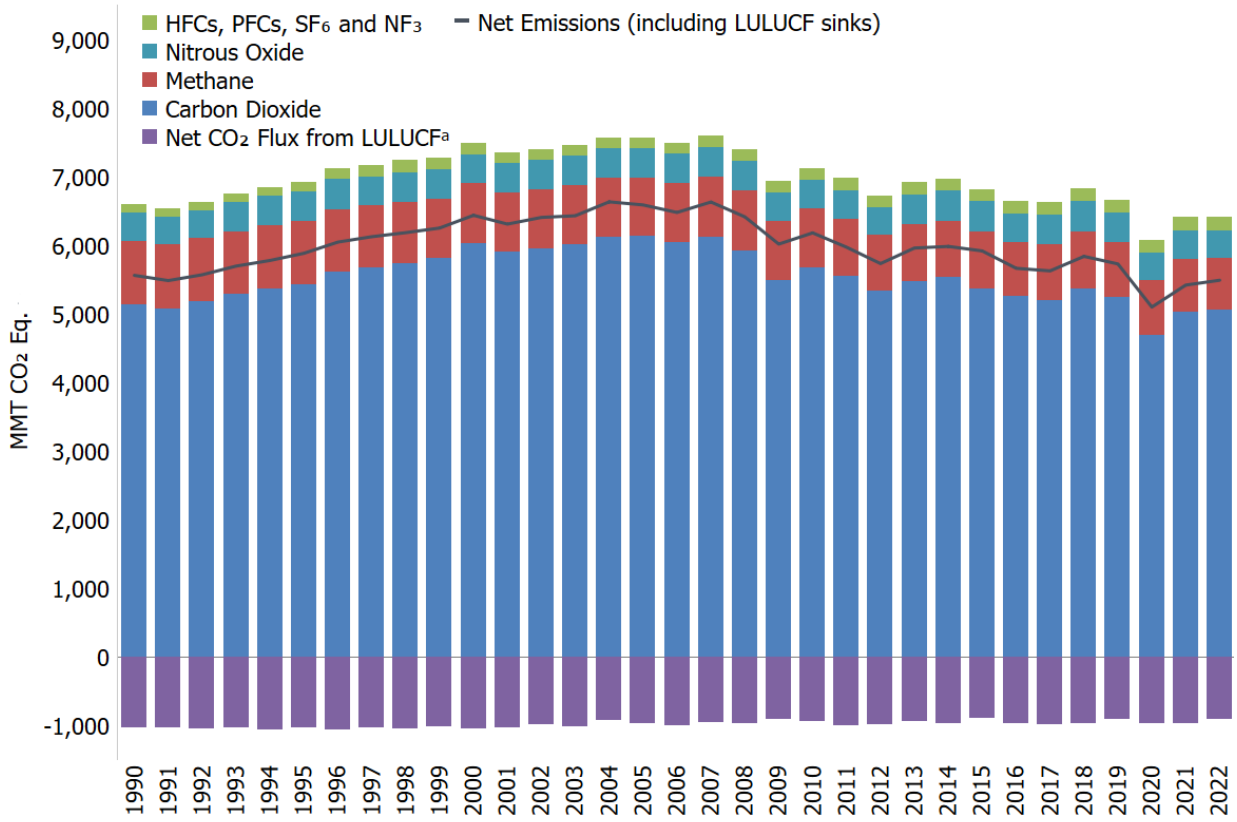
ES.2 Recent Trends in U.S. Greenhouse Gas Emissions and Sinks

In 2022, total gross U.S. greenhouse gas emissions were 6,343.2 million metric tons of carbon dioxide equivalent (MMT CO_2 Eq.).[10] Total gross U.S. emissions decreased by 3.0 percent from 1990 to 2022, down from a high of 15.2 percent above 1990 levels in 2007. Gross emissions increased from 2021 to 2022 by 0.2 percent (14.4 MMT CO_2 Eq.). Net emissions (including sinks) were 5,489.0 MMT CO_2 Eq. in 2022. Overall, net emissions increased by 1.3 percent from 2021 to 2022 and decreased by 16.7 percent from 2005 levels as shown in Table ES-2. Between 2021 and 2022, the increase in total greenhouse gas emissions was driven largely by an increase in CO_2 emissions from fossil fuel combustion across most end-use sectors due in part to increased energy use from the continued rebound of economic activity after the height of the COVID-19 pandemic. In 2022, CO_2 emissions from fossil fuel combustion increased by 1.0 percent relative to the previous year and were 1.1 percent below emissions in 1990. Carbon dioxide emissions from natural gas use increased by 5.2 percent (84.8 MMT CO_2 Eq.) from 2021, while CO_2 emissions from coal consumption decreased by 6.1 percent (58.6 MMT CO_2 Eq.) from 2021 to 2022. The increase in natural gas consumption and associated emissions in 2022 is observed across all sectors except U.S. Territories, while the coal decrease is due to reduced use in the electric power sector. Emissions from petroleum use also increased by 0.9 percent (19.0 MMT CO_2 Eq.) from 2021 to 2022. Carbon sequestration from the Land Use, Land-Use Change, and Forestry (LULUCF) sector offset 14.5 percent of total emissions in 2022.

Figure ES-1 and Figure ES-2 illustrate the overall trends in total U.S. emissions by gas and annual percent changes, and Table ES-2 provides information on trends in gross U.S. greenhouse gas emissions and sinks for 1990 through 2022. Unless otherwise stated, all tables and figures provide total gross emissions and exclude the greenhouse gas fluxes from the LULUCF sector. For more information about the LULUCF sector, see Section ES-3.

[10] The gross emissions total presented in this report for the United States excludes emissions and removals from Land Use, Land-Use Change, and Forestry (LULUCF). The net emissions total presented in this report for the United States includes emissions and removals from LULUCF.

Figure ES-1: U.S. Greenhouse Gas Emissions and Sinks by Gas



[a] The term "flux" is used to describe the exchange of CO_2 to and from the atmosphere, with net flux being either positive or negative depending on the overall balance. Removal and long-term storage of CO_2 from the atmosphere is also referred to as "carbon sequestration."

Table ES-2: Recent Trends in U.S. Greenhouse Gas Emissions and Sinks (MMT CO_2 Eq.)

Gas/Source	1990	2005	2018	2019	2020	2021	2022	Percent Change Since 1990
CO_2	5,131.6	6,126.9	5,362.2	5,234.5	4,689.0	5,017.2	5,053.0	-1.5%
CH_4 (excludes LULUCF sources)[a]	871.7	795.4	771.5	754.3	735.3	720.5	702.4	-19.4%
N_2O (excludes LULUCF sources)[a]	408.2	419.2	439.5	416.4	391.2	398.2	389.7	-4.5%
HFCs	47.7	121.7	163.9	168.2	170.3	177.0	182.8	282.9%
PFCs	39.5	10.2	7.4	7.3	6.6	6.3	6.7	-83.1%
SF_6	37.9	20.2	7.6	8.4	8.1	8.5	7.6	-80.0%
NF_3	0.3	1.0	0.7	1.1	1.3	1.1	1.1	238.3%
Total Gross Emissions (Sources)[a]	**6,536.9**	**7,494.6**	**6,752.7**	**6,590.1**	**6,001.8**	**6,328.8**	**6,343.2**	**-3.0%**
LULUCF Emissions[b]	58.0	68.9	62.8	58.0	68.4	72.9	67.6	16.5%
CH_4	53.1	58.5	55.5	52.5	59.3	62.1	58.4	10.0%
N_2O	4.8	10.3	7.3	5.5	9.1	10.7	9.1	88.3%
LULUCF Carbon Stock Change[c]	(1034.7)	(976.6)	(978.3)	(921.6)	(972.8)	(983.4)	(921.8)	-10.9%
LULUCF Sector Net Total[d]	(976.7)	(907.7)	(915.5)	(863.6)	(904.4)	(910.6)	(854.2)	-12.5%
Net Emissions (Sources and Sinks)	**5,560.2**	**6,586.9**	**5,837.3**	**5,726.6**	**5,097.4**	**5,418.2**	**5,489.0**	**-1.3%**

[a] Gross emissions totals do not include CH_4 and N_2O emissions from LULUCF. LULUCF CH_4 and N_2O emissions are included in net emission totals.

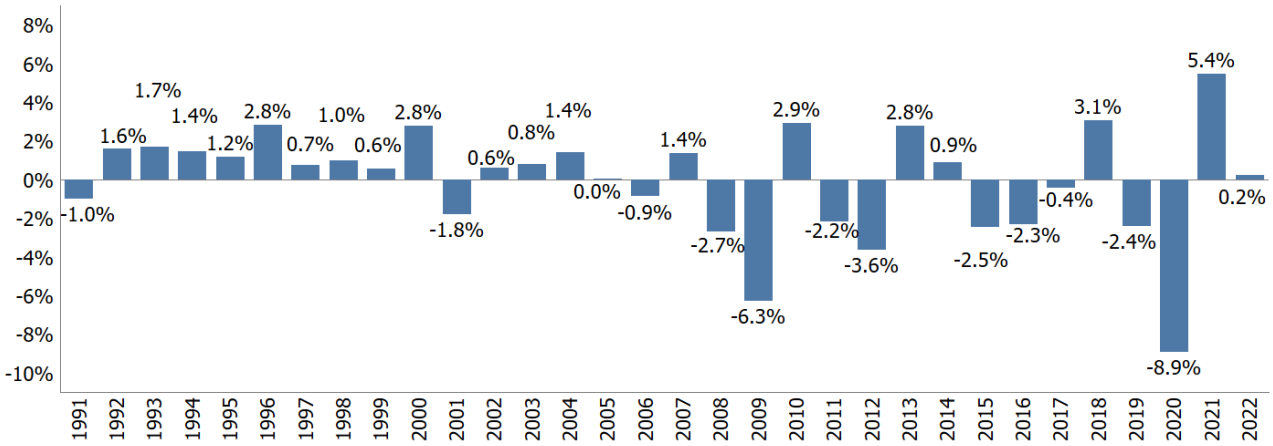
[b] LULUCF emissions subtotal of CH_4 and N_2O are reported separately from gross emissions totals. LULUCF emissions include the CH_4 and N_2O emissions reported for peatlands remaining peatlands, forest fires, drained organic soils, grassland fires, and coastal wetlands remaining coastal wetlands; CH_4 emissions from land converted to coastal wetlands, flooded land remaining flooded land, and land converted to flooded land; and N_2O emissions from forest soils and settlement soils.

[c] LULUCF carbon stock change is the net carbon stock change from the following categories: forest land remaining forest land, land converted to forest land, cropland remaining cropland, land converted to cropland, grassland remaining grassland, land converted to grassland, wetlands remaining wetlands, land converted to wetlands, settlements remaining settlements, and land converted to settlements.

[d] The LULUCF sector net total is the net sum of all LULUCF CH_4 and N_2O emissions to the atmosphere plus LULUCF net carbon stock changes.

Notes: Total (gross) are emissions presented without LULUCF. Net emissions are presented with LULUCF. Totals may not sum due to independent rounding. Parentheses indicate negative values or sequestration.

Figure ES-2: Annual Percent Change in Gross U.S. Greenhouse Gas Emissions and Sinks Relative to the Previous Year

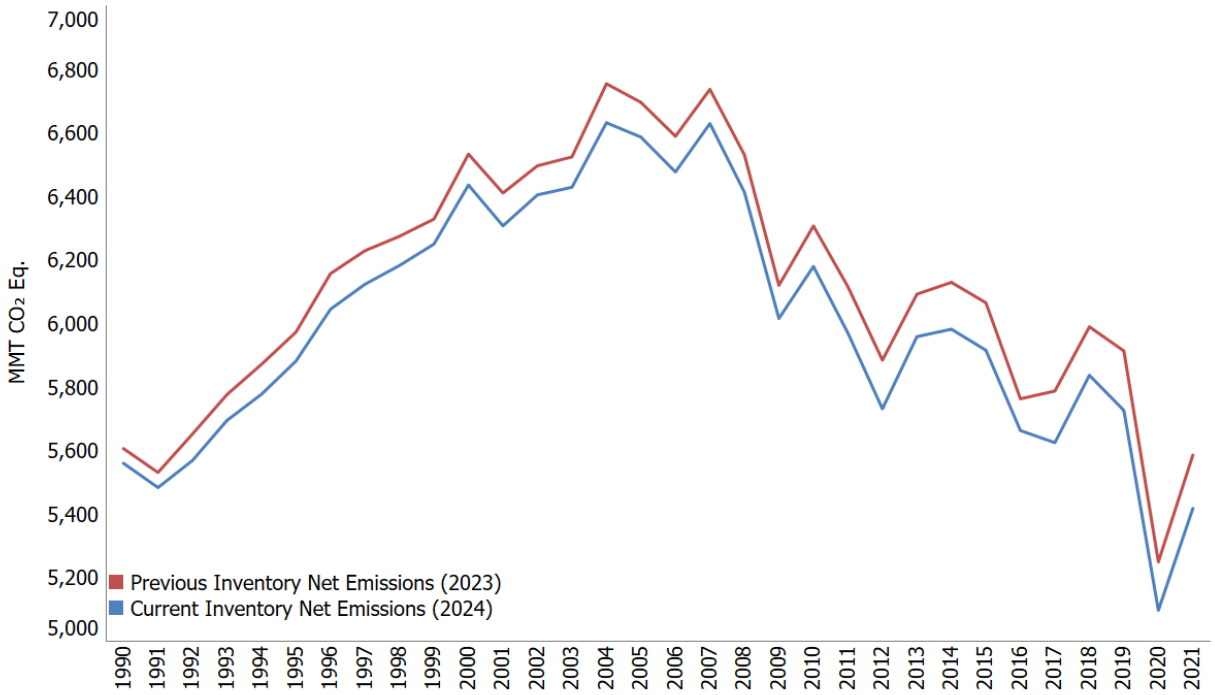


Improvements and Recalculations Relative to the Previous Inventory

Each year, some emission and removal estimates in the *Inventory* are recalculated and revised to incorporate improved methods and/or data. The most common reason for recalculating U.S. greenhouse gas emission estimates is to update recent historical data. Changes in historical data are generally the result of changes in data supplied by other U.S. government agencies or organizations, as they continue to make refinements and improvements. These improvements are implemented consistently across the previous *Inventory's* time series, as necessary, (i.e., 1990 to 2021) to ensure that the trend is accurate.

Collectively, all methodological changes and historical data updates made in the current *Inventory* resulted in an annual average decrease of 114.8 MMT CO_2 Eq. (1.9 percent) for net emissions.

Figure ES-3: Impacts of Recalculations on Net Emissions



Below are categories with methodological and data-related recalculations resulting in an average change of greater than 2.0 MMT CO_2 Eq. over the time series.

- Forest land remaining forest land: changes in forest carbon stocks (CO_2)
- Land converted to grassland: changes in all ecosystem carbon stocks (CO_2)
- Land converted to cropland: changes in all ecosystem carbon stocks (CO_2)
- Grassland remaining grassland: changes in all ecosystem carbon stocks (CO_2)
- Non-energy use of fuels (CO_2)
- Land converted to settlements: changes in all ecosystem carbon stocks (CO_2)
- Fluorochemical production (HFCs)
- Fossil fuel combustion (CO_2)
- Cropland remaining cropland: changes in all ecosystem carbon stocks (CO_2)
- Agricultural Soil Management (N_2O)
- Petroleum Systems (CH_4)
- Wetlands Remaining Wetlands: changes in soil carbon stocks in coastal wetlands (CO_2)

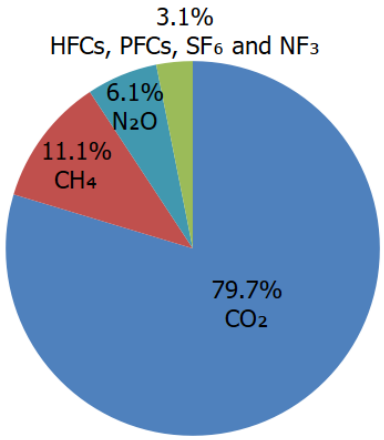
In addition, the current *Inventory* includes new categories not included in the previous *Inventory* that improve completeness of the national estimates: CO_2 emissions from ceramics production and non-metallurgical magnesia production within other process use of carbonates category, fluorinated gases from fluorochemical production other than HCFC-22 within the fluorochemical production category, and managed forest land in Hawaii and several U.S. Territories. This report also now includes SF_6 and PFCs from product uses.

In each *Inventory*, the results of all methodological changes and historical data updates and the inclusion of new sources and sink estimates are summarized in the Recalculations and Improvements chapter (Chapter 9). For more detailed descriptions of each recalculation including references for data, please see the respective source or sink category description(s) within the relevant report chapter (the Energy chapter [Chapter 3], the Industrial Processes and Product Use [IPPU] chapter [Chapter 4], the Agriculture chapter [Chapter 5], the Land Use, Land-Use Change, and Forestry [LULUCF] chapter [Chapter 6], and the Waste chapter [Chapter 7]).

Emissions and Sinks by Greenhouse Gas

Figure ES-4 illustrates the relative contribution of the greenhouse gases to total gross U.S. emissions in 2022, weighted by GWP. The primary greenhouse gas emitted by human activities in the United States is CO_2, representing 79.7 percent of total greenhouse gas emissions. The largest source of CO_2 and of overall greenhouse gas emissions is fossil fuel combustion, primarily from transportation and power generation. Methane (CH_4) emissions account for 11.1 percent of emissions. The major sources of methane include enteric fermentation associated with domestic livestock, natural gas systems, and decomposition of wastes in landfills. Agricultural soil management, wastewater treatment, stationary sources of fuel combustion, and manure management are the major sources of N_2O emissions. Emissions of substitutes for ozone depleting substances are the primary contributor to aggregate hydrofluorocarbon (HFC) emissions. Perfluorocarbon (PFC) emissions are primarily attributable to electronics manufacturing, fluorochemical production, and primary aluminum production. Electrical equipment systems account for most sulfur hexafluoride (SF_6) emissions. The electronics industry and fluorochemical production are the only sources of nitrogen trifluoride (NF_3) emissions. U.S. greenhouse gas emissions were partly offset by carbon (C) sequestration in forests, trees in urban areas, agricultural soils, landfilled yard trimmings and food scraps, and coastal wetlands, which together offset 14.5 percent of gross total emissions in 2022 (as reflected in Figure ES-1). The following sections describe each gas's contribution to total U.S. greenhouse gas emissions in more detail.

Figure ES-4: 2022 Total Gross U.S. Greenhouse Gas Emissions by Gas (Percentages based on MMT CO_2 Eq.)



Note: Emissions and removals from Land Use, Land-Use Change, and Forestry are excluded from the figure above.

Carbon Dioxide Emissions

The global carbon cycle is made up of large carbon flows and reservoirs. Billions of tons of carbon in the form of CO_2 are absorbed by oceans and living biomass (i.e., sinks) and are emitted to the atmosphere annually through natural processes (i.e., sources). When in equilibrium, global carbon fluxes among these various reservoirs are roughly balanced.[11]

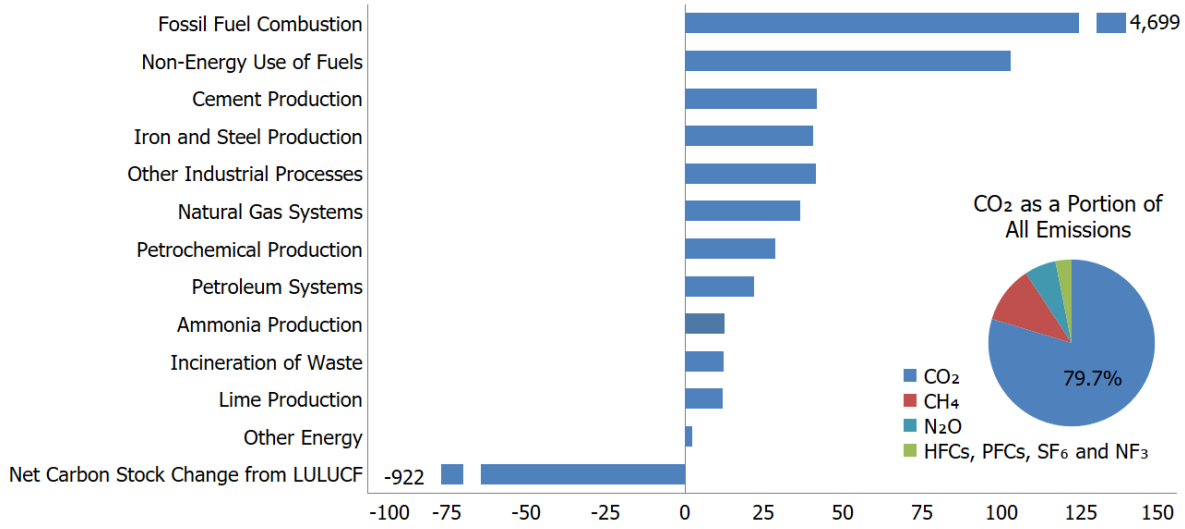
Since the Industrial Revolution (i.e., about 1750), global atmospheric concentrations of CO_2 have risen 49.5 percent (IPCC 2013; NOAA/ESRL 2024a), principally due to the combustion of fossil fuels for energy. Globally, an estimated

[11] The term "flux" is used to describe the exchange of CO_2 to and from the atmosphere, with net flux being either positive or negative depending on the overall balance. Removal and long-term storage of CO_2 from the atmosphere is also referred to as "carbon sequestration."

33,423 MMT of CO_2 were added to the atmosphere through the combustion of fossil fuels in 2022, of which the United States accounted for approximately 14.1 percent.[12]

Overall CO_2 emissions have decreased by 1.5 percent since 1990 and increased by 0.7 percent since 2021, consistent with trends in fuel combustion emissions. Within the United States, fossil fuel combustion accounted for 93.0 percent of CO_2 gross emissions in 2022. Nationally, the transportation sector was the largest emitter of CO_2 in 2022 followed by electric power generation. There are 27 additional sources of CO_2 emissions included in the *Inventory* (see [Table 2-1 in Trends]). Although not illustrated in Table ES-4, changes in land use and forestry practices can also lead to net CO_2 emissions (e.g., through conversion of forest land to agricultural or urban use) or to a net sink for CO_2 (e.g., through net additions to forest biomass). See more on these emissions and removals in Table ES-4.

Figure ES-5: 2022 Sources of CO_2 Emissions



Note: "Other Industrial Processes" includes emissions from aluminum production, carbide production and consumption, carbon dioxide consumption, ferroalloy production, glass production, lead production, magnesium production, other process uses of carbonates, phosphoric acid production, substitution of ozone depleting substances, soda ash production, titanium dioxide production, urea consumption for non-agricultural purposes, and zinc production. "Other Energy" includes emissions from abandoned oil and gas wells and coal mining.

Between 1990 and 2022, CO_2 emissions from fossil fuel combustion decreased by 1.1 percent; emissions decreased by 18.2 percent (1,044.7 MMT CO_2 Eq.) from 2005 levels; and from 2021 to 2022, these emissions increased by 1.0 percent (45.1 MMT CO_2 Eq.).

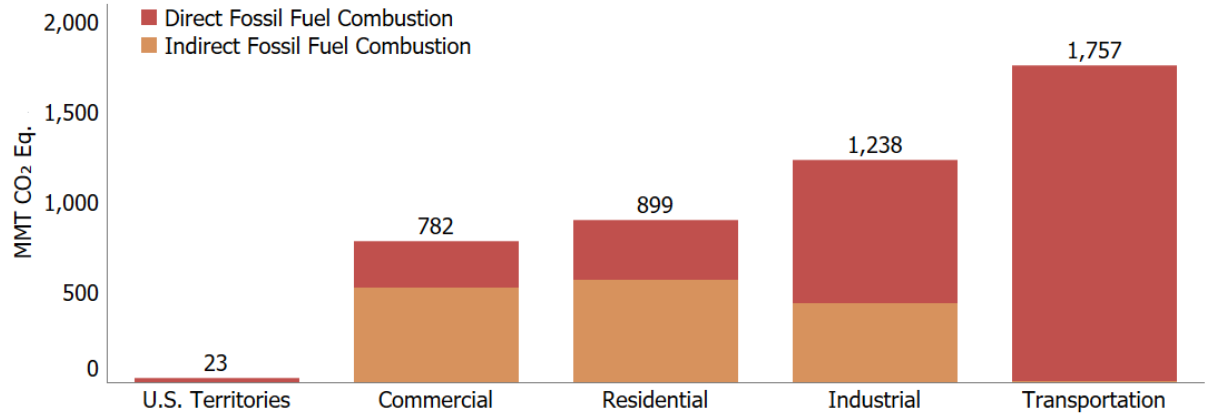
Historically, changes in emissions from fossil fuel combustion have been the driving factor affecting U.S. emission trends. Important drivers include changes in demand for energy and a general decline in the overall carbon intensity of fuels combusted for energy in recent years by non-transport sectors of the economy. Between 2019 and 2021, changes in economic activity and travel due to the COVID-19 pandemic and the subsequent recovery had significant impacts on energy use and fossil fuel combustion emissions.

The five major fuel-consuming economic sectors are transportation, electric power, industrial, residential, and commercial and are described below. Carbon dioxide emissions are produced by the electric power sector as fossil fuel is consumed to provide electricity to one of the other four economic sectors, or "end-use" sectors. In Figure

[12] Global CO_2 emissions from fossil fuel combustion were taken from International Energy Agency *Global energy-related CO_2 emissions, 1990-2022 – Charts.* Available at: https://www.iea.org/reports/co2-emissions-in-2022 (IEA 2022).

ES-6, electric power emissions have been distributed to each end-use sector on the basis of each sector's share of aggregate electricity use (i.e., indirect fossil fuel combustion). Greenhouse gas emissions from the commercial and residential and industry increase substantially when indirect emissions from electricity end-use are distributed, due to the relatively large share of electricity use by buildings (e.g., heating, ventilation, and air conditioning; lighting; and appliances) and use of electricity for powering industrial machinery.

Figure ES-6: 2022 End-Use Sector Emissions of CO_2 from Fossil Fuel Combustion



Transportation End-Use Sector. Transportation activities accounted for 37.4 percent of U.S. CO_2 emissions from fossil fuel combustion in 2022, with the largest contributors being light-duty trucks (36.8 percent), followed by medium- and heavy-duty trucks (23.0 percent) and passenger vehicles (20.6 percent). In terms of the overall trend from 1990 to 2022, total transportation CO_2 emissions increased due largely to increased demand for travel, which was a result of a confluence of factors including population growth, economic growth, urban sprawl, and low fuel prices during the beginning of this period. While an increased demand for travel has led to generally increasing CO_2 emissions since 1990, improvements in average new vehicle fuel economy since 2005 have slowed the rate of increase of CO_2 emissions. In 2022, petroleum-based products supplied 94.3 percent of the energy consumed for transportation, primarily from gasoline consumption in automobiles and other highway vehicles (51.9 percent).

Industrial End-Use Sector. Industrial CO_2 emissions, resulting both directly from the combustion of fossil fuels[13] and indirectly from the generation of electricity that is used by industry, accounted for 26.3 percent of CO_2 emissions from fossil fuel combustion in 2022. Approximately 64.7 percent of these emissions resulted from direct fossil fuel combustion to produce steam and/or heat for industrial processes. The remaining emissions resulted from the use of electricity for motors, electric furnaces, ovens, lighting, and other applications. Total direct and indirect emissions from the industrial sector have declined by 20.8 percent since 1990. This decline is due to structural changes in the U.S. economy (i.e., shifts from a manufacturing-based to a service-based economy), fuel switching, and efficiency improvements. From 2021 to 2022, total energy use in the industrial sector increased by 1.8 percent due to an increase in total industrial production and manufacturing output.

Residential and Commercial End-Use Sectors. The residential and commercial end-use sectors accounted for 19.1 and 16.6 percent, respectively, of CO_2 emissions from fossil fuel combustion in 2022 including indirect emissions from electricity. The residential and commercial sectors relied heavily on electricity for meeting energy demands, with 62.9 and 66.9 percent, respectively, of their emissions attributable to electricity use for building -related activities such as lighting, heating, cooling, and operating appliances. The remaining emissions were due to the consumption of natural gas and petroleum for heating and cooking. Total direct and indirect emissions from the residential sector have decreased by 3.4 percent since 1990, and total direct and indirect emissions from the commercial sector have increased by 2.1 percent since 1990. From 2021 to 2022, an increase in heating degree

[13] This does not include fossil fuels used as feedstocks and reductants, which are reported under IPPU emissions.

days (7.9 percent) increased energy demand for heating in the residential and commercial sectors; also, a 4.3 percent increase in cooling degree days compared to 2021 increased demand for air conditioning in the residential and commercial sectors. Combined, this resulted in a 2.5 percent increase in residential sector energy use. From 2021 to 2022, energy use in the commercial sector increased by 4.7 percent.

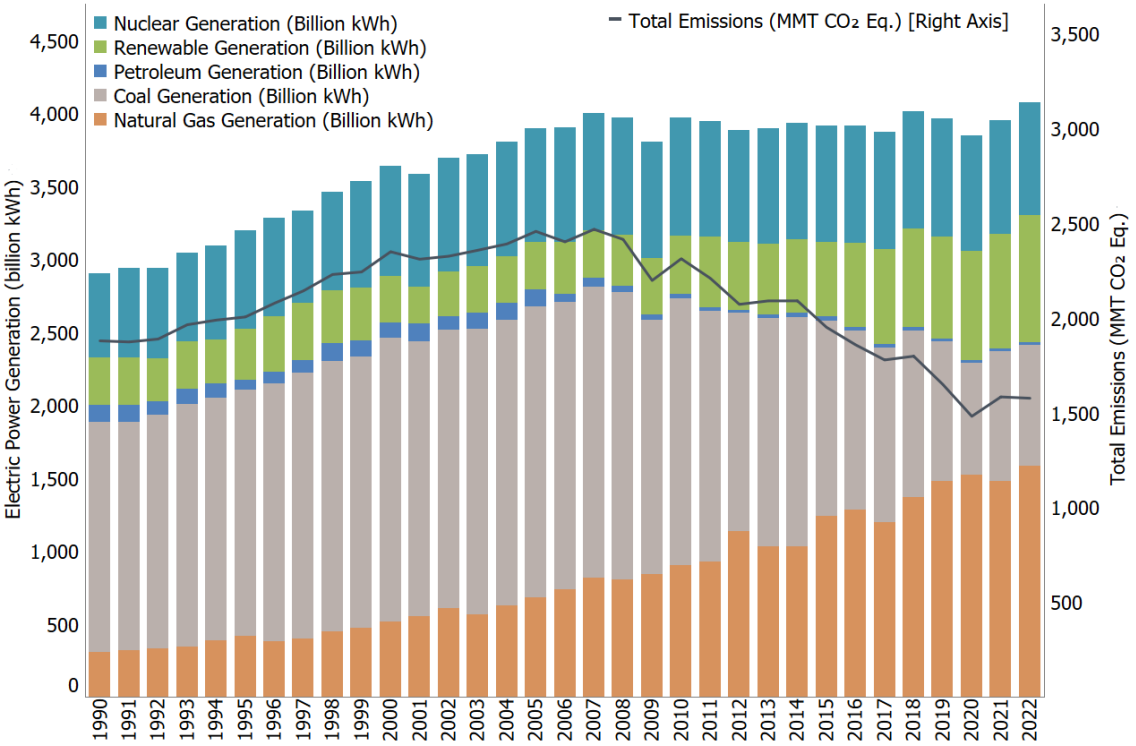
Electric Power. The United States relies on electricity to meet a significant portion of its energy demands. Electricity generators used 30.5 percent of U.S. energy from fossil fuels and emitted 32.6 percent of the CO_2 from fossil fuel combustion in 2022. The type of energy source used to generate electricity, and the mix of electric generation resources used to meet demand, are the main factors influencing emissions.[14] Coal-fired electric generation (in kilowatt-hours [kWh]) decreased from 54.1 percent of generation in 1990 to 20.3 percent in 2022.[15] This corresponded with an increase in natural gas generation and non-fossil fuel renewable energy generation, largely from wind and solar energy. Natural gas generation (in kWh) represented 10.7 percent of electric power generation in 1990 and increased over the 33-year period to represent 38.8 percent of electric power generation in 2022. Wind and solar generation (in kWh) represented 0.1 percent of electric power generation in 1990 and increased over the 33-year period to represent 14.2 percent of electric power generation in 2022. Between 2021 and 2022, coal electricity generation decreased by 10.2 percent, natural gas generation increased by 4.0 percent, and renewable energy generation increased by 7.6 percent.

Across the time series, changes in electricity generation and the carbon intensity of fuels used for electric power have a significant impact on CO_2 emissions. While CO_2 emissions from fossil fuel combustion in the electric power sector have decreased by 15.8 percent since 1990, the carbon intensity of the electric power sector, in terms of CO_2 Eq. per QBtu input, decreased by 27.6 percent during that same timeframe. This decoupling of the level of electric power generation and the resulting CO_2 emissions is shown in Figure ES-7.

[14] In line with the reporting requirements for inventories submitted under the UNFCCC, CO_2 emissions from biomass combustion have been estimated separately from fossil fuel CO_2 emissions and are not included in the electricity sector totals and trends discussed in this section. Net carbon fluxes from changes in biogenic carbon reservoirs are accounted for in the estimates for Land Use, Land-Use Change, and Forestry.

[15] Values represent electricity *net* generation from the electric power sector. See Table 7.2b Electricity Net Generation: Electric Power Sector of EIA (2024).

Figure ES-7: Electric Power Generation and Emissions



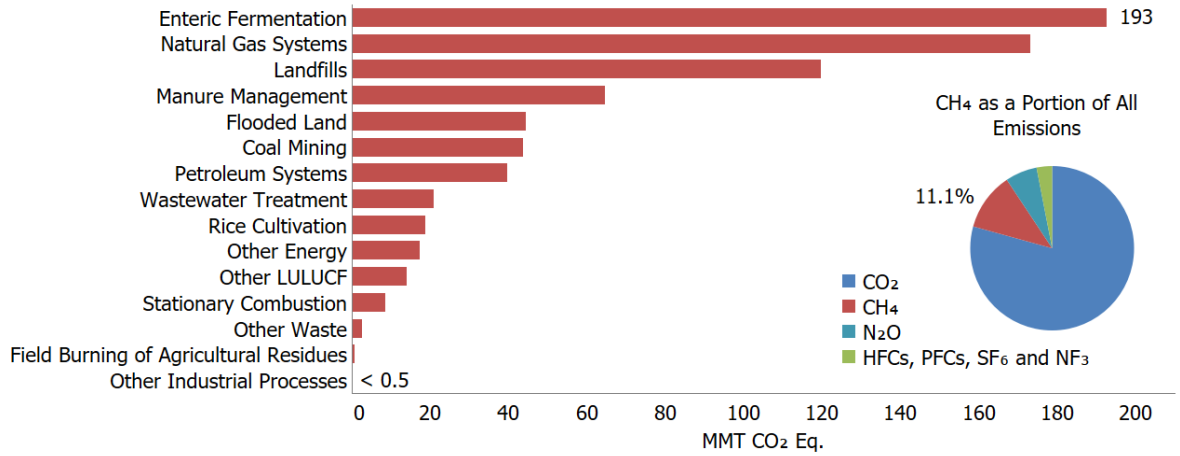
Other significant CO_2 trends included the following:

- Carbon dioxide emissions from natural gas and petroleum systems combined accounted for 1.2 percent of CO_2 emissions and 0.9 percent of total gross emissions in 2022. These emissions increased by 39.1 percent (16.4 MMT CO_2 Eq.) from 1990 to 2022. This increase is due primarily to increases in the production segment, where flaring emissions from associated gas flaring, tanks, and miscellaneous production flaring have increased over time.
- Carbon dioxide emissions from iron and steel production and metallurgical coke production accounted for 0.8 percent of CO_2 and 0.6 percent of total gross emissions. Emissions decreased by 61.2 percent (64.1 MMT CO_2 Eq.) from 1990 through 2022. This decrease was primarily due to restructuring of the industry, technological improvements, and increased scrap steel utilization.
- Total carbon stock change (i.e., net CO_2 removals) in the LULUCF sector decreased by 10.9 percent between 1990 and 2022. This decrease was primarily due to a decrease in the rate of net carbon accumulation in forest carbon stocks and cropland remaining cropland, as well as an increase in emissions from land converted to settlements.

Methane Emissions

Methane (CH_4) is significantly more effective than CO_2 at trapping heat in the atmosphere: by a factor of 28 over a 100-year time frame based on the IPCC *Fifth Assessment Report* estimate (IPCC 2013). Over the last 250 years, the concentration of CH_4 in the atmosphere increased by 161.9 percent (IPCC 2013; NOAA/ESRL 2024b). Within the United States, the main anthropogenic sources of CH_4 include enteric fermentation from domestic livestock, natural gas systems, landfills, domestic livestock manure management, flooded land, coal mining, and petroleum systems (see Figure ES-8).

Figure ES-8: 2022 Sources of CH_4 Emissions



Note: "Other Energy" includes CH_4 emissions from abandoned oil and gas wells, abandoned underground coal mines, incineration of waste, and mobile combustion. "Other Waste" includes CH_4 emissions from anaerobic digestion at biogas facilities and composting. "Other Industrial Processes" includes CH_4 emissions from carbide production and consumption, ferroalloy production, iron and steel production and metallurgical coke production, and petrochemical production. "Other LULUCF" includes the CH_4 reported for peatlands remaining peatlands, forest fires, drained organic soils, grassland fires, coastal wetlands remaining coastal wetlands, and land converted to coastal wetlands.

Overall, CH_4 emissions in the United States in 2022, including LULUCF CH_4 emissions, accounted for 760.8 MMT CO_2 Eq., representing a decrease of 17.7 percent (164.0 MMT CO_2 Eq.) since 1990 and 2.8 percent decrease (21.8 MMT CO_2 Eq.) since 2021. Significant trends for the largest sources of anthropogenic CH_4 emissions include the following:

- Enteric fermentation was the largest anthropogenic source of CH_4 emissions in the United States in 2022, accounting for 27.4 percent of total CH_4 emissions and 3.0 percent of total gross emissions. Emissions have increased by 5.2 percent (9.5 MMT CO_2 Eq.) since 1990. This increase in emissions from 1990 to 2022 generally follows the increasing trends in cattle populations.
- Natural gas systems were the second largest anthropogenic source category of CH_4 emissions in the United States in 2022, accounting for 24.6 percent of total CH_4 emissions and 2.7 percent of total gross emissions. Emissions have decreased by 20.9 percent (45.7 MMT CO_2 Eq.) since 1990, largely due to decreases in emissions from distribution, transmission, and storage.
- Landfills were the third largest anthropogenic source of CH_4 emissions in the United States in 2022, accounting for 17.1 percent of total CH_4 emissions and 1.9 percent of total gross emissions and representing a decrease of 39.4 percent (78.0 MMT CO_2 Eq.) since 1990, with small year-to-year increases. This downward trend in emissions coincided with increased landfill gas collection and control systems, and a reduction of decomposable materials (i.e., paper and paperboard, food scraps, and yard trimmings) discarded in MSW landfills over the time series.[16]

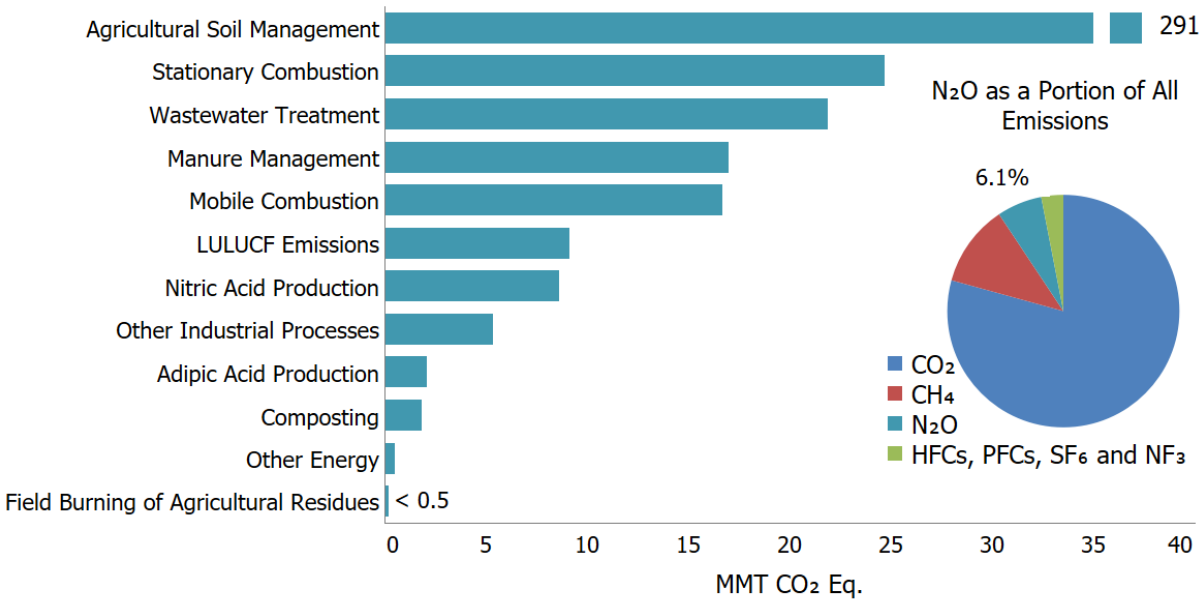
Nitrous Oxide Emissions

Nitrous oxide (N_2O) is produced by biological processes that occur in soil and water and by a variety of anthropogenic activities in the agricultural, energy, industrial, and waste management fields. While total N_2O emissions are much lower than CO_2 emissions, N_2O is 265 times more powerful than CO_2 at trapping heat in the atmosphere over a 100-year time frame (IPCC 2013). Since 1750, the global atmospheric concentration of N_2O has

[16] Carbon dioxide emissions from landfills are not included specifically in summing waste sector totals. Net carbon fluxes from changes in biogenic carbon reservoirs and decay of disposed wood products are accounted for in the estimates for LULUCF.

risen by 24.3 percent (IPCC 2013; NOAA/ESRL 2024c). The main anthropogenic activities producing N_2O in the United States are agricultural soil management, wastewater treatment, stationary fuel combustion, manure management, fuel combustion in motor vehicles, and nitric acid production (see Figure ES-9).

Figure ES-9: 2022 Sources of N_2O Emissions



Note: "Other Industrial Processes" includes N_2O emissions from caprolactam, glyoxal, and glyoxylic acid production; the electronics industry; and product uses. "Other Energy" includes N_2O emissions from petroleum systems, natural gas systems, and incineration of waste. LULUCF emissions include N_2O emissions reported for peatlands remaining peatlands, forest fires, drained organic soils, grassland fires, coastal wetlands remaining coastal wetlands, forest soils, and settlement soils.

Overall, N_2O emissions in the United States in 2022, including LULUCF N_2O emissions, accounted for 398.8 MMT CO_2 Eq., representing a decrease of 3.4 percent (14.2 MMT CO_2 Eq.) since 1990 and a decrease of 2.5 percent (10.1 MMT CO_2 Eq.) since 2021. Significant trends for the largest sources of anthropogenic N_2O emissions include the following:

- Agricultural soils were the largest anthropogenic source of N_2O emissions in 2022, accounting for 74.6 percent of N_2O emissions and 4.6 percent of total gross greenhouse gas emissions in the United States. These emissions increased by 0.7 percent (2.0 MMT CO_2 Eq.) from 1990 to 2022 but fluctuated during that period due to annual variations in weather patterns, fertilizer use, and crop production.
- Stationary combustion was the second largest source of anthropogenic N_2O emissions in 2022, accounting for 6.3 percent of N_2O emissions and 0.4 percent of total gross U.S. greenhouse gas emissions in 2022. Stationary combustion emissions peaked in 2007 and steadily decreased until 2020. Emissions increased in 2021 and 2022. Stationary combustion emissions have increased by 10.6 percent (2.4 MMT CO_2 Eq.) since 1990.
- Wastewater treatment, both domestic and industrial, was the third largest anthropogenic source of N_2O emissions in 2022, accounting for 5.6 percent of N_2O emissions and 0.3 percent of total gross greenhouse gas emissions in the United States in 2022. Emissions from wastewater treatment increased by 48.2 percent (7.1 MMT CO_2 Eq.) since 1990 as a result of growing U.S. population and protein consumption.

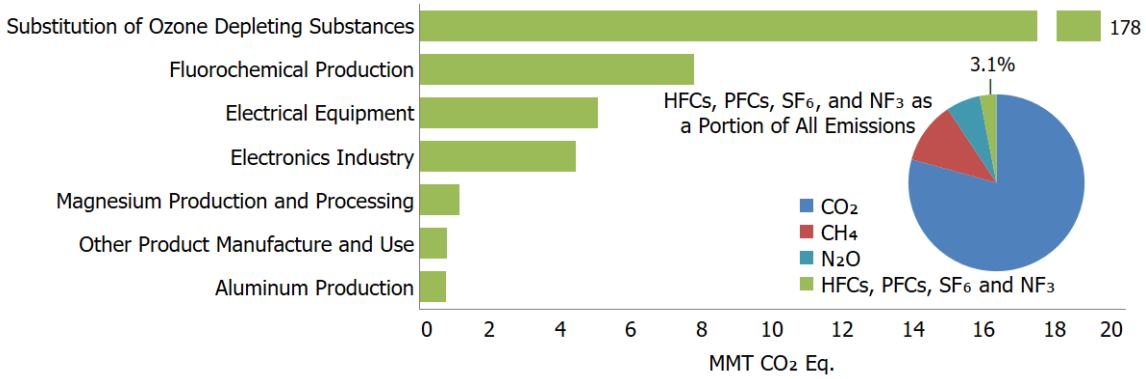
HFC, PFC, SF_6, and NF_3 Emissions

Hydrofluorocarbons (HFCs) are synthetic chemicals that are used as alternatives to ozone depleting substances (ODS), which are being phased out under the Montreal Protocol and Clean Air Act Amendments of 1990. Hydrofluorocarbons do not deplete the stratospheric ozone layer and therefore have been used as alternatives under the Montreal Protocol.

Perfluorocarbons (PFCs) are emitted from the production of electronics and aluminum and also (in smaller quantities) from their use as alternatives to ODS. Sulfur hexafluoride (SF_6) is emitted from the manufacturing and use of electrical equipment as well as the production of electronics and magnesium. NF_3 is emitted from electronics production. HFCs are also emitted during production of HCFC-22 and electronics (see Figure ES-10).

HFCs, PFCs, SF_6, and NF_3 are potent greenhouse gases. In addition to having very high GWPs, SF_6, NF_3, and PFCs have extremely long atmospheric lifetimes, resulting in their essentially irreversible accumulation in the atmosphere once emitted. Sulfur hexafluoride is the most potent greenhouse gas the IPCC has evaluated (IPCC 2021).

Figure ES-10: 2022 Sources of HFCs, PFCs, SF_6, and NF_3 Emissions



Some significant trends for the largest sources of U.S. HFC, PFC, SF_6, and NF_3 emissions include the following:

- Hydrofluorocarbon and perfluorocarbon emissions resulting from their use as substitutes for ODS (e.g., chlorofluorocarbons [CFCs]) are the largest share of fluorinated emissions (89.9 percent) in 2022 and have been consistently increasing, from small amounts since 1990. This increase over the time series was largely the result of efforts to phase out CFCs and other ODS in the United States.
- Sulfur hexafluoride emissions from electrical equipment decreased by 79.4 percent (19.6 MMT CO_2 Eq.) from 1990 to 2022. There are two factors contributing to this decrease: (1) a sharp increase in the price of SF_6 during the 1990s and (2) a growing awareness of the environmental impact of SF_6 emissions through programs such as EPA's SF_6 Emission Reduction Partnership for Electric Power Systems.
- HFC, PFC, SF_6, and NF_3 emissions from fluorochemical production decreased by 89.0 percent (63.2 MMT CO_2 Eq.) from 1990 to 2022 due to a reduction in the HFC-23 emission rate from HCFC-22 production (kg HFC-23 emitted/kg HCFC-22 produced), the imposition of emissions controls at production facilities, and a decrease in SF_6 production (due to the cessation of production at the major SF_6 production facility in 2010).
- PFC emissions from aluminum production decreased by 96.1 percent (18.5 MMT CO_2 Eq.) from 1990 to 2022, due to both industry emission reduction efforts and lower domestic aluminum production.

ES.3 Overview of Sector Emissions and Trends

Figure ES-11 and Table ES-3 aggregate emissions and sinks by the sectors defined by the UNFCCC and Paris Agreement reporting guidelines and methodological framework in the IPCC guidelines to promote comparability across countries. Over the 33-year period of 1990 to 2022, total emissions from the Energy and Waste sectors decreased by 3.4 percent (181.2 MMT CO_2 Eq.) and 29.3 percent (69.1 MMT CO_2 Eq.) respectively. Emissions from the Industrial Processes and Product Use and Agriculture sectors grew by 3.9 percent (14.4 MMT CO_2 Eq.), and 7.7 percent (42.2 MMT CO_2 Eq.), respectively. Over the same period, the overall net flux from LULUCF (i.e., the net sum of all CH_4 and N_2O emissions to the atmosphere plus LULUCF net carbon stock changes in units of MMT CO_2 Eq.) decreased by 12.5 percent (122.5 MMT CO_2 Eq.) and resulted in a removal of 854.2 MMT CO_2 Eq. in 2022.

Figure ES-11: U.S. Greenhouse Gas Emissions and Sinks by UNFCCC/IPCC Sector

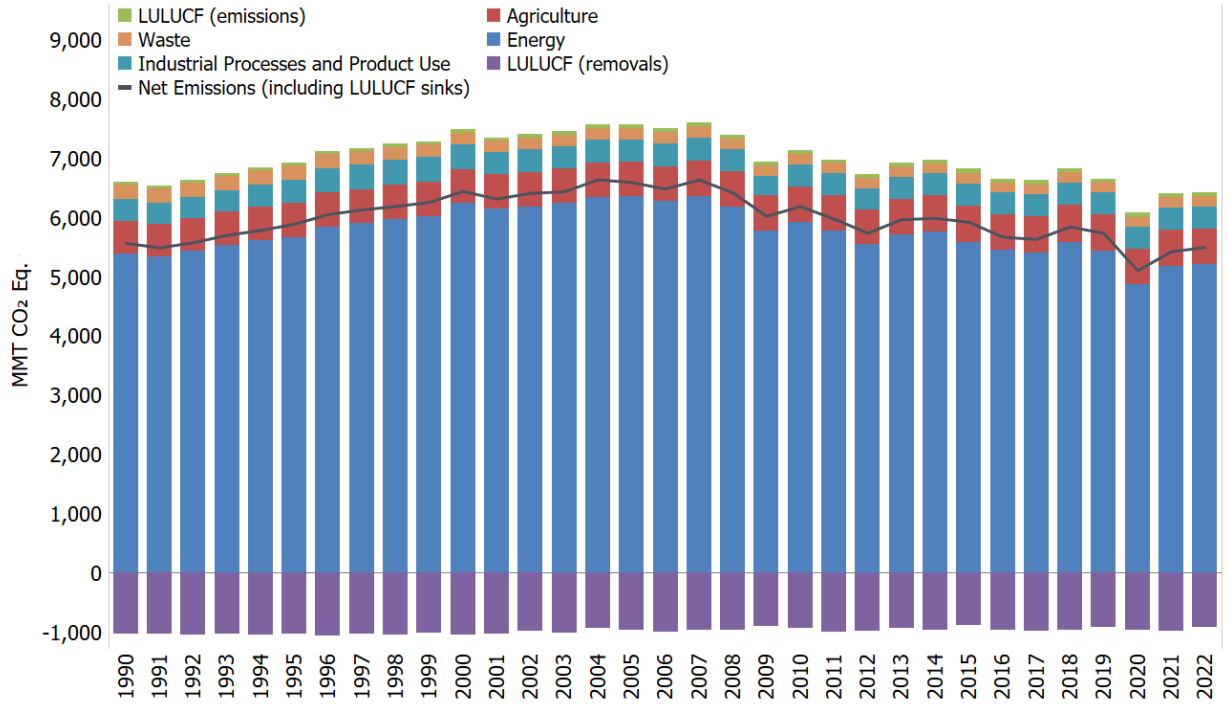


Table ES-3: Recent Trends in U.S. Greenhouse Gas Emissions and Sinks by UNFCCC/IPCC Sector (MMT CO_2 Eq.)

UNFCCC/IPCC Sector	1990	2005	2018	2019	2020	2021	2022	Percent Change Since 1990
Energy	5,381.0	6,349.5	5,570.0	5,422.4	4,862.6	5,173.3	5,199.8	-3.4%
Industrial Processes and Product Use	368.8	371.3	367.2	371.9	367.9	381.6	383.2	3.9%
Agriculture	551.1	581.8	642.4	620.1	599.7	604.8	593.4	7.7%
Waste	235.9	192.0	173.2	175.8	171.7	169.2	166.9	-29.3%
Total Gross Emissions[a] (Sources)	**6,536.9**	**7,494.6**	**6,752.7**	**6,590.1**	**6,001.8**	**6,328.8**	**6,343.2**	**-3.0%**
LULUCF Sector Net Total[b]	(976.7)	(907.7)	(915.5)	(863.6)	(904.4)	(910.6)	(854.2)	-12.5%
Net Emissions (Sources and Sinks)[c]	**5,560.2**	**6,586.9**	**5,837.3**	**5,726.6**	**5,097.4**	**5,418.2**	**5,489.0**	**-1.3%**

[a] Total emissions without LULUCF.

[b] The LULUCF sector net total is the sum of all LULUCF CH_4 and N_2O emissions to the atmosphere plus LULUCF net carbon stock changes in units of MMT CO_2 Eq.

[c] Net emissions with LULUCF.

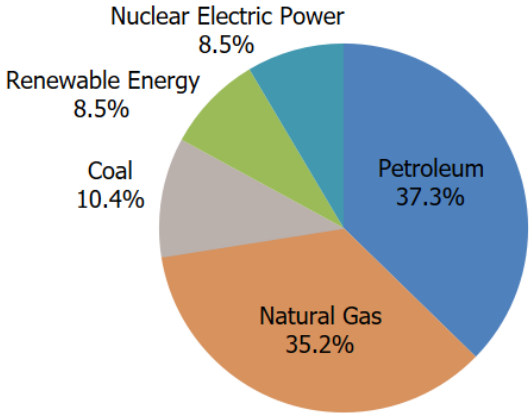
Notes: Totals may not sum due to independent rounding. Parentheses indicate negative values or sequestration.

Energy

The Energy chapter contains emissions of all greenhouse gases resulting from stationary and mobile energy activities including fuel combustion and fugitive fuel emissions, and the use of fossil fuels for non-energy purposes. Energy-related activities, primarily fossil fuel combustion, accounted for the vast majority of U.S. CO_2 emissions for the period of 1990 through 2022. Energy-related activities are also responsible for CH_4 and N_2O emissions (40.2 percent and 10.8 percent of total U.S. emissions of each gas, respectively).[17] Overall, emission sources in the Energy chapter account for a combined 82.0 percent of total gross U.S. greenhouse gas emissions in 2022. Emissions from energy increased by 0.5 percent (26.5 MMT CO_2 Eq.) since 2021, but they have decreased by 3.4 percent (181.2 MMT CO_2 Eq.) since 1990.

In 2022, 83.0 percent of the energy used in the United States (on a Btu basis) was produced through the combustion of fossil fuels. The remaining 17.0 percent came from other energy sources, such as hydropower, biomass, nuclear, wind, and solar energy (see Figure ES-12).

Figure ES-12: 2022 U.S. Energy Consumption by Energy Source (Percent)



Industrial Processes and Product Use

The Industrial Processes and Product Use (IPPU) chapter contains greenhouse gas emissions generated and emitted as the byproducts of non-energy-related industrial processes, which involve the chemical or physical transformation of raw materials and can release waste gases such as CO_2, CH_4, N_2O, and fluorinated gases (e.g., HFC-23). These processes include iron and steel production and metallurgical coke production, cement production, petrochemical production, ammonia production, lime production, other process uses of carbonates (e.g., other uses of carbonates, other uses of soda ash not associated with glass manufacturing, ceramics production, and non-metallurgical magnesia production), nitric acid production, adipic acid production, urea consumption for non-agricultural purposes, aluminum production, HCFC-22 production, other fluorochemical production, glass production, soda ash production, ferroalloy production, titanium dioxide production, caprolactam production, zinc production, phosphoric acid production, lead production, and silicon carbide production and consumption. Most of these industries also emit CO_2 from fossil fuel combustion which, in line with UNFCCC/IPCC sectoral definitions, is included in the Energy sector.

[17] The contribution of energy non-CO_2 emissions is based on gross totals and excludes LULUCF methane (CH_4) and nitrous oxide (N_2O) emissions. The contribution of energy-related CH_4 and N_2O including LULUCF non-CO_2 emissions is 37.1 percent and 9.8 percent respectively.

This chapter also contains emissions resulting from the release of HFCs, PFCs, SF_6, and NF_3 and other man-made compounds used in industrial manufacturing processes and by end-consumers (e.g., residential and mobile air conditioning). These industries include electronics manufacturing, electric power transmission and distribution, and magnesium metal production and processing. In addition, N_2O is used in and emitted by electronics industry and anesthetic and aerosol applications, PFCs and SF_6 are emitted in other product use, and CO_2 is consumed and emitted through various end-use applications. In 2022, emissions resulting from use of the substitution of ODS (e.g., chlorofluorocarbons [CFCs]) by end-consumers was the largest source of IPPU emissions and accounted for 46.5 percent of total IPPU emissions.

IPPU activities are responsible for 3.3, less than 0.5, and 4.1 percent of total U.S. CO_2, CH_4, and N_2O emissions respectively as well as for all U.S. emissions of fluorinated gases including HFCs, PFCs, SF_6 and NF_3. Overall, emission sources in the IPPU chapter accounted for 6.0 percent of U.S. greenhouse gas emissions in 2022. IPPU emissions have increased by 0.4percent (1.6 MMT CO_2 Eq.) since 2021 and by 3.9 percent (14.4 MMT CO_2 Eq.) since 1990, mostly due to increased use of ODS substitutes (e.g., HFCs).

Agriculture

The Agriculture chapter contains information on anthropogenic emissions from agricultural activities (except fuel combustion, which is addressed in the Energy chapter, and some agricultural CO_2, CH_4, and N_2O fluxes, which are addressed in the Land Use, Land-Use Change, and Forestry chapter).

Several agricultural activities contribute directly to emissions of greenhouse gases including the following sources: agricultural soil management, enteric fermentation in domestic livestock, livestock manure management, rice cultivation, urea fertilization, liming, and field burning of agricultural residues.

In 2022, agricultural activities were responsible for 9.4 percent of total gross U.S. greenhouse gas emissions. Agriculture sector emissions decreased by 11.4 MMT CO_2 Eq. (1.9 percent) since 2021 and have increased by 42.2 MMT CO_2 Eq. (7.7 percent) since 1990, mostly from trends in enteric fermentation and manure management. Methane, N_2O, and CO_2 are greenhouse gases emitted by agricultural activities. Methane emissions from enteric fermentation and manure management represented 36.6 percent of total CH_4 emissions from anthropogenic activities in 2022. Agricultural soil management activities, such as application of synthetic and organic fertilizers, deposition of livestock manure, and growing N-fixing plants, were the largest contributors to U.S. N_2O emissions in 2022, accounting for 74.6 percent of total N_2O emissions. Carbon dioxide emissions from the application of crushed limestone and dolomite (i.e., soil liming) and urea fertilization represented 0.2 percent of total CO_2 emissions from anthropogenic activities.

Land Use, Land-Use Change, and Forestry

The LULUCF chapter contains emissions and removals of CO_2 and emissions of CH_4 and N_2O from managed lands in the United States. Consistent with the *2006 IPCC Guidelines*, emissions and removals from managed lands are considered to be anthropogenic, while emissions and removals from unmanaged lands are considered to be natural.[18] The share of managed land in the United States is approximately 95 percent of total land included in the Inventory.[19] More information on the definition of managed land used in the *Inventory* is provided in Chapter 6.

Overall, the *Inventory* results show that managed land is a net sink for CO_2 (C sequestration). The primary drivers of fluxes on managed lands include forest management practices, tree planting in urban areas, the management of agricultural soils, lands remaining and lands converted to reservoirs and other constructed waterbodies, landfilling

[18] See http://www.ipcc-nggip.iges.or.jp/public/2006gl/pdf/4_Volume4/V4_01_Ch1_Introduction.pdf.

[19] The current land representation does not include land in U.S. Territories, but there are planned improvements to include these regions in future *Inventories*. U.S. Territories represent approximately 0.1 percent of the total land base for the United States. See Box 6-2 in Chapter 6 of this report.

of yard trimmings and food scraps, and activities that cause changes in carbon stocks in coastal wetlands. The main drivers for forest carbon sequestration include forest growth and increasing forest area (i.e., afforestation), as well as a net accumulation of carbon stocks in harvested wood pools. The net sequestration in settlements remaining settlements, which occurs predominantly from urban forests (i.e., settlement trees) and landfilled yard trimmings and food scraps, is a result of net tree growth and increased urban forest area, as well as long-term accumulation of carbon from yard trimmings and food scraps in landfills.

The LULUCF sector in 2022 resulted in a net increase in carbon stocks (i.e., net CO_2 removals) of 921.8 CO_2 Eq.[20] The removals of carbon offset 14.5 percent of total gross greenhouse gas emissions in 2022. Emissions of CH_4 and N_2O from LULUCF activities in 2022 represented 1.2 percent of net greenhouse gas emissions.[21] Carbon dioxide removals from carbon stock changes are presented in Table ES-4 along with CH_4 and N_2O emissions for LULUCF source categories.

Between 1990 and 2022, total carbon sequestration in the LULUCF sector decreased by 10.9 percent, primarily due to a decrease in the rate of net carbon accumulation in forests and in cropland remaining cropland, as well as an increase in CO_2 emissions from land converted to settlements. The overall net flux from LULUCF (i.e., net sum of all CH_4 and N_2O emissions to the atmosphere plus LULUCF net carbon stock changes in units of MMT CO_2 Eq.) resulted in a removal of 854.2 MMT CO_2 Eq. in 2022.

Flooded lands were the largest source of CH_4 emissions from the LULUCF sector and the fifth largest source overall net CH_4 emissions in 2022. Forest fires were the second largest source of CH_4 emissions, followed by coastal wetlands remaining coastal wetlands. Forest fires were the largest source of N_2O emissions from the LULUCF sector in 2022.

Table ES-4: U.S. Greenhouse Gas Emissions and Removals (Net Flux) from Land Use, Land-Use Change, and Forestry (MMT CO_2 Eq.)

Land-Use Category	1990	2005	2018	2019	2020	2021	2022
Forest Land Remaining Forest Land[a]	(968.8)	(860.1)	(863.4)	(807.0)	(846.3)	(823.9)	(771.7)
Land Converted to Forest Land[b]	(100.2)	(100.2)	(100.4)	(100.3)	(100.3)	(100.3)	(100.3)
Cropland Remaining Cropland	(5.0)	(31.6)	(17.8)	(19.4)	(8.8)	(32.0)	(31.7)
Land Converted to Cropland[c]	45.4	34.5	31.9	31.4	29.3	34.9	35.1
Grassland Remaining Grassland[d]	24.6	24.9	29.7	28.9	17.1	11.5	14.0
Land Converted to Grassland[c]	35.3	21.8	25.2	25.4	28.7	24.5	25.6
Wetlands Remaining Wetlands[e]	36.8	39.4	38.2	38.1	38.1	38.1	38.1
Land Converted to Wetlands[e]	7.2	1.8	0.7	0.7	0.7	0.7	0.7
Settlements Remaining Settlements[f]	(109.1)	(115.2)	(131.0)	(131.5)	(131.8)	(132.3)	(132.3)
Land Converted to Settlements[c]	57.2	77.1	71.4	70.2	68.8	68.2	68.2
LULUCF Carbon Stock Change[g]	**(1,034.7)**	**(976.6)**	**(978.3)**	**(921.6)**	**(972.8)**	**(983.4)**	**(921.8)**
LULUCF Emissions[h]	**58.0**	**68.9**	**62.8**	**58.0**	**68.4**	**72.9**	**67.6**
CH_4	53.1	58.5	55.5	52.5	59.3	62.1	58.4
N_2O	4.8	10.3	7.3	5.5	9.1	10.7	9.1
LULUCF Sector Net Total[i]	**(976.7)**	**(907.7)**	**(915.5)**	**(863.6)**	**(904.4)**	**(910.6)**	**(854.2)**

[a] Includes the net changes to carbon stocks stored in all forest ecosystem pools and harvested wood products, emissions from fires on both forest land remaining forest land and land converted to forest land, emissions from N fertilizer additions on both forest land remaining forest land and land converted to forest land, and CH_4 and N_2O emissions from drained organic soils on both forest land remaining forest land and land converted to forest land.

[20] LULUCF carbon stock change is the net C stock change from the following categories: forest land remaining forest land, land converted to forest land, cropland remaining cropland, land converted to cropland, grassland remaining grassland, land converted to grassland, wetlands remaining wetlands, land converted to wetlands, settlements remaining settlements, and land converted to settlements.

[21] LULUCF emissions include the CH_4 and N_2O emissions reported for peatlands remaining peatlands, forest fires, drained organic soils, grassland fires, and coastal wetlands remaining coastal wetlands; CH_4 emissions from land converted to coastal wetlands; and N_2O emissions from forest soils and settlement soils.

[b] Includes the net changes to carbon stocks stored in all forest ecosystem pools.
[c] Includes changes in mineral and organic soil carbon stocks for all land use conversions to cropland, grassland, and settlements, respectively. Also includes aboveground/belowground biomass, dead wood, and litter carbon stock changes for conversion of forest land to cropland, grassland, and settlements, respectively.
[d] Estimates include CH_4 and N_2O emissions from fires on both grassland remaining grassland and land converted to grassland.
[e] Estimates include CH_4 emissions from flooded land remaining flooded land and land converted to flooded land.
[f] Estimates include N_2O emissions from N fertilizer additions on both settlements remaining settlements and land converted to settlements because it is not possible to separate the activity data at this time.
[g] LULUCF carbon stock change includes any carbon stock gains and losses from all land use and land use conversion categories.
[h] LULUCF emissions subtotal includes the CH_4 and N_2O emissions reported for peatlands remaining peatlands, forest fires, drained organic soils, grassland fires, and coastal wetlands remaining coastal wetlands; CH_4 emissions from land converted to coastal wetlands, flooded land remaining flooded land, and land converted to flooded land; and N_2O emissions from forest soils and settlement soils. Emissions values are included in land-use category rows.
[i] The LULUCF sector net total is the net sum of all LULUCF CH_4 and N_2O emissions to the atmosphere plus LULUCF net carbon stock changes in units of MMT CO_2 Eq.
Notes: Totals may not sum due to independent rounding. Parentheses indicate net sequestration.

Waste

The Waste chapter contains emissions from waste management activities (except the incineration of waste, which is addressed in the Energy chapter). Landfills were the largest source of anthropogenic greenhouse gas emissions from waste management activities, accounting for 71.8 percent of total greenhouse gas emissions from waste management activities, and 17.1 percent of total U.S. CH_4 emissions.[22] Additionally, wastewater treatment accounted for 25.6 percent of total Waste sector greenhouse gas emissions, 3.0 percent of U.S. CH_4 emissions, and 5.6 percent of U.S. N_2O emissions in 2022. Emissions of CH_4 and N_2O from commercial composting are also included in this chapter, accounting for 1.5 percent (2.6 MMT CO_2 Eq.) and 1.1 percent (1.8 MMT CO_2 Eq.) of overall waste sector emissions, respectively. Anaerobic digestion at biogas facilities generated CH_4 emissions, accounting for less than 0.05 percent of emissions from the Waste sector. Overall, emission sources in the Waste chapter accounted for 2.6 percent of total gross U.S. greenhouse gas emissions in 2022. Waste sector emissions decreased by 1.4 percent (2.3 MMT CO_2 Eq.) since 2021 and by 29.3 percent (69.1 MMT CO_2 Eq.) since 1990.

ES.4 Other Information

Emissions and Sinks by Economic Sector

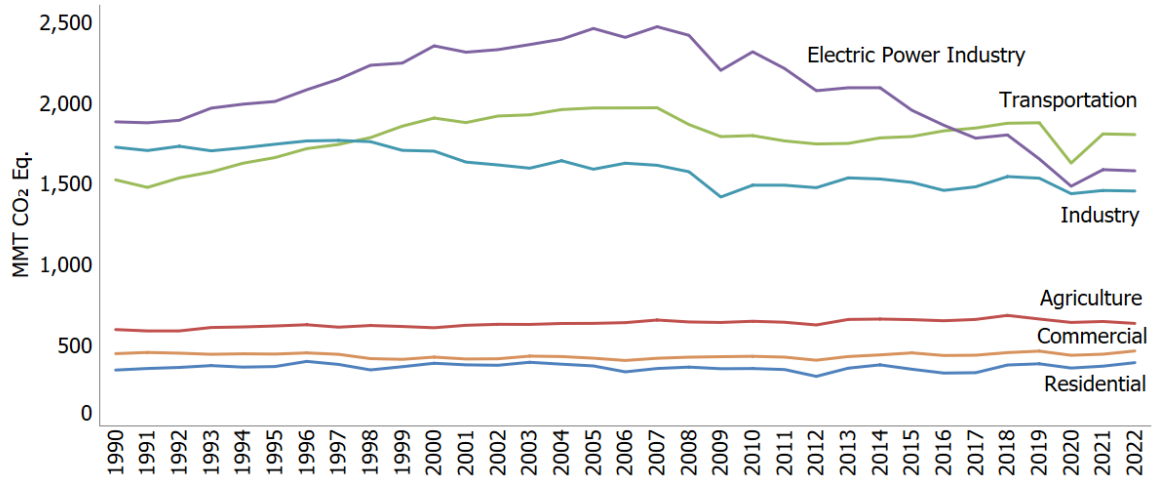
In addition to the Paris Agreement and UNFCCC sectors and methods defined by the IPCC, this report also characterizes emissions according to commonly used economic sector categories: residential, commercial, industry, transportation, electric power, and agriculture.[23] Emissions from U.S. Territories are reported as their own end-use sector due to a lack of specific consumption data for the individual end-use sectors within U.S. Territories. For more information on trends in the Land Use, Land-Use Change, and Forestry sector, see Section ES.2 Recent Trends in U.S. Greenhouse Gas Emissions and Sinks.

[22] Landfills also store carbon, due to incomplete degradation of organic materials such as harvest wood products, yard trimmings, and food scraps, as described in the Land Use, Land-Use Change, and Forestry chapter of the Inventory report. Also, the estimated total methane emissions used to estimate contribution excludes methane emissions from the LULUCF sector.

[23] The agriculture economic sector includes emissions from fossil fuel combustion and electricity use within the agricultural sector.

Figure ES-13 shows the trend in emissions by economic sector from 1990 to 2022, and Table ES-5 summarizes emissions from each of these economic sectors.

Figure ES-13: U.S. Greenhouse Gas Emissions Allocated to Economic Sectors



Note: Emissions and removals from Land Use, Land-Use Change, and Forestry are excluded from figure above. Excludes U.S. Territories.

Table ES-5: U.S. Greenhouse Gas Emissions Allocated to Economic Sectors (MMT CO_2 Eq.)

Economic Sectors	1990	2005	2018	2019	2020	2021	2022	Percent Change Since 1990
Transportation	1,521.4	1,965.9	1,871.6	1,874.6	1,625.3	1,805.5	1,801.5	18.4%
Electric Power Industry	1,880.2	2,457.4	1,799.2	1,650.8	1,482.2	1,584.4	1,577.5	-16.1%
Industry	1,723.3	1,587.3	1,541.9	1,531.8	1,435.9	1,455.8	1,452.5	-15.7%
Agriculture	595.9	634.3	683.5	661.0	640.0	645.9	634.0	6.4%
Commercial	447.0	418.9	453.5	462.6	436.9	443.7	463.7	3.7%
Residential	345.6	371.2	376.8	384.2	358.0	369.6	391.3	13.2%
U.S. Territories	23.4	59.7	26.3	25.1	23.4	23.9	22.7	-3.1%
Total Gross Emissions (Sources)	**6,536.9**	**7,494.6**	**6,752.7**	**6,590.1**	**6,001.8**	**6,328.8**	**6,343.2**	**-3.0%**
LULUCF Sector Net Total[a]	(976.7)	(907.7)	(915.5)	(863.6)	(904.4)	(910.6)	(854.2)	-12.5%
Net Emissions (Sources and Sinks)	**5,560.2**	**6,586.9**	**5,837.3**	**5,726.6**	**5,097.4**	**5,418.2**	**5,489.0**	**-1.3%**

[a] The LULUCF sector net total is the net sum of all LULUCF CH_4 and N_2O emissions to the atmosphere plus LULUCF net carbon stock changes.

Notes: Total (gross) emissions are presented without LULUCF. Total net emissions are presented with LULUCF. Totals may not sum due to independent rounding. Parentheses indicate negative values or sequestration.

Using this categorization, emissions from transportation activities accounted for the largest portion (28.4 percent) of total gross U.S. greenhouse gas emissions in 2022. Electric power accounted for the second largest portion (24.9 percent) of U.S. greenhouse gas emissions in 2022, while emissions from industry accounted for the third largest portion (22.9 percent). Emissions from industry have in general declined over the past decade, due to a number of factors, including structural changes in the U.S. economy (i.e., shifts from a manufacturing-based to a service-based economy), fuel switching, and energy efficiency improvements.

The remaining 23.8 percent of U.S. greenhouse gas emissions were contributed by, in order of magnitude, the agriculture, commercial, and residential sectors, plus emissions from U.S. Territories. Activities related to agriculture accounted for 10.0 percent of U.S. emissions; unlike other economic sectors, agricultural sector

emissions were dominated by N_2O emissions from agricultural soil management and CH_4 emissions from enteric fermentation. An increasing amount of carbon is stored in agricultural soils each year, but this CO_2 sequestration is assigned to the LULUCF sector rather than the agriculture economic sector. The commercial and residential sectors accounted for 7.3 percent and 6.2 percent of emissions, respectively, and U.S. Territories accounted for 0.4 percent of emissions; emissions from these sectors primarily consisted of CO_2 emissions from fossil fuel combustion. Carbon dioxide was also emitted and sequestered by a variety of activities related to forest management practices, tree planting in urban areas, the management of agricultural soils, landfilling of yard trimmings, and changes in carbon stocks in coastal wetlands.

Electricity is ultimately used in the economic sectors described above. Table ES-6 presents greenhouse gas emissions from economic sectors with emissions related to electric power distributed into end-use categories (i.e., emissions from electric power generation are allocated to the economic sectors in which the electricity is used). To distribute electricity emissions among end-use sectors, emissions from the source categories assigned to electric power were allocated to the residential, commercial, industry, transportation, and agriculture economic sectors according to retail sales of electricity for each end-use sector (EIA 2024).[24] These source categories include CO_2 from fossil fuel combustion and the use of limestone and dolomite for flue gas desulfurization, CO_2 and N_2O from incineration of waste, CH_4 and N_2O from stationary sources, and SF_6 from electrical equipment systems.

When emissions from electricity use are distributed among these end-use sectors, industrial activities and transportation account for the largest shares of U.S. greenhouse gas emissions (29.5 percent and 28.5 percent, respectively) in 2022. The commercial and residential sectors contributed the next largest shares of total gross U.S. greenhouse gas emissions in 2022 (15.8and 15.3 percent, respectively). Emissions from the commercial and residential sectors increase substantially when emissions from electricity use are included, due to their relatively large share of electricity use for energy (e.g., lighting, cooling, appliances). Figure ES-14 shows the trends in these emissions by sector from 1990 to 2022.

Table ES-6: U.S. Greenhouse Gas Emissions with Electricity-Related Emissions Distributed by Economic Sector (MMT CO_2 Eq.)

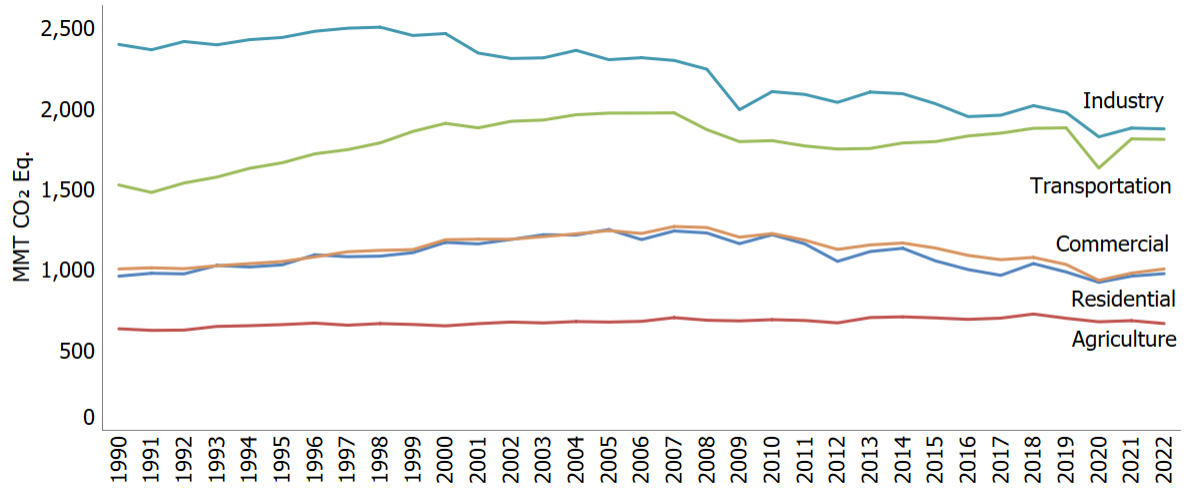
Economic Sectors	1990	2005	2018	2019	2020	2021	2022	Percent Change Since 1990
Industry	2,397.3	2,302.9	2,017.1	1,974.8	1,823.5	1,877.8	1,872.9	-21.9%
Transportation	1,524.6	1,970.8	1,876.5	1,879.5	1,629.5	1,810.6	1,807.8	18.6%
Commercial	1,002.5	1,241.1	1,074.3	1,030.5	931.5	976.8	1,002.6	0.0%
Residential	958.0	1,247.7	1,035.9	984.0	919.5	958.0	973.5	1.6%
Agriculture	631.1	672.6	722.7	696.3	674.4	681.6	663.6	5.2%
U.S. Territories	23.4	59.7	26.3	25.1	23.4	23.9	22.7	-3.1%
Total Gross Emissions (Sources)	**6,536.9**	**7,494.6**	**6,752.7**	**6,590.1**	**6,001.8**	**6,328.8**	**6,343.2**	**-3.0%**
LULUCF Sector Net Total[a]	(976.7)	(907.7)	(915.5)	(863.6)	(904.4)	(910.6)	(854.2)	-12.5%
Net Emissions (Sources and Sinks)	**5,560.2**	**6,586.9**	**5,837.3**	**5,726.6**	**5,097.4**	**5,418.2**	**5,489.0**	**-1.3%**

[a] The LULUCF sector net total is the net sum of all LULUCF CH_4 and N_2O emissions to the atmosphere plus LULUCF net carbon stock changes.

Notes: Emissions from electric power are allocated based on aggregate electricity use in each end-use sector. Totals may not sum due to independent rounding. Parentheses indicate negative values or sequestration.

[24] U.S. Territories consumption data that are obtained from EIA are only available at the aggregate level and cannot be broken out by end-use sector. The distribution of emissions to each end-use sector for the 50 states does not apply to Territories data.

Figure ES-14: U.S. Greenhouse Gas Emissions with Electricity-Related Emissions Distributed to Economic Sectors



Note: Emissions and removals from Land Use, Land-Use Change, and Forestry are excluded from figure above. Excludes U.S. Territories.

Box ES-2: Trends in Various U.S. Greenhouse Gas Emissions-Related Data

Total (gross) greenhouse gas emissions can be compared to other economic and social indices to highlight changes over time. These comparisons include: (1) aggregate energy use, because energy-related activities are the largest sources of emissions; (2) energy use per capita as a measure of efficiency; (3) emissions per unit of total gross domestic product as a measure of national economic activity; and (4) emissions per capita.

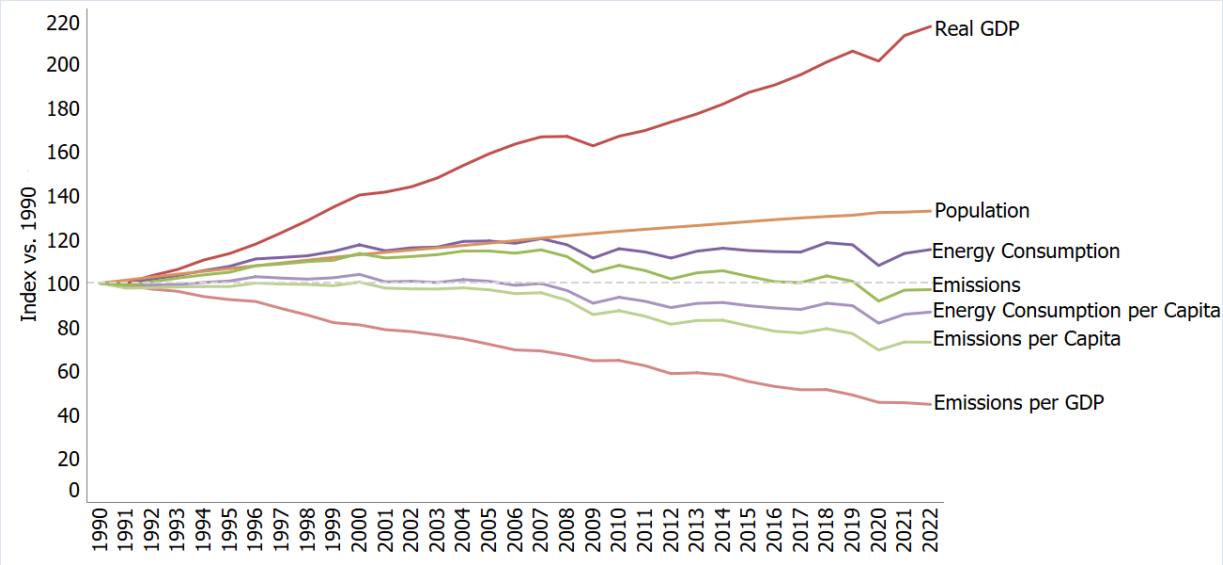
Table ES-7 provides data on various statistics related to U.S. greenhouse gas emissions normalized to 1990 as a baseline year. These values represent the relative change in each statistic since 1990. Greenhouse gas emissions in the United States have declined at an average annual rate of 0.01 percent since 1990, although changes from year to year have been significantly larger. This growth rate is slightly slower than that for total energy use and fossil fuel consumption, and overall gross domestic product (GDP), and national population (see Figure ES-15). The direction of these trends started to change after 2005, when greenhouse gas emissions, total energy use, and fossil fuel consumption began to peak. Greenhouse gas emissions in the United States have decreased at an average annual rate of 0.9 percent since 2005. Since 2005, GDP and national population, generally, continued to increase while energy has decreased slightly—noting 2020 was impacted by the COVID-19 pandemic.

Table ES-7: Recent Trends in Various U.S. Data (Index 1990 = 100)

Variable	1990	2005	2018	2019	2020	2021	2022	Avg. Annual Growth Rate Since 1990[a]	Avg. Annual Growth Rate Since 2005[a]
Greenhouse Gas Emissions[b]	100	115	103	101	92	97	97	-0.1%	-0.9%
Energy Use[c]	100	119	118	117	107	113	115	0.5%	-0.2%
GDP[d]	100	159	201	206	201	213	217	2.5%	1.9%
Population[e]	100	118	130	131	132	132	133	0.9%	0.7%

+ Absolute value does not exceed 0.05 percent.
[a] Average annual growth rate.
[b] Gross total GWP-weighted values.
[c] Energy content-weighted values (EIA 2024).
[d] GDP in chained 2017 dollars (BEA 2024).
[e] U.S. Census Bureau (2024).

Figure ES-15: U.S. Greenhouse Gas Emissions Per Capita and Per Dollar of Gross Domestic Product (GDP)



Source: BEA (2024), U.S. Census Bureau (2024), and emission estimates in this report.

Key Categories

The *2006 IPCC Guidelines for National Greenhouse Gas Inventories* (IPCC 2006) and *2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories* (IPCC 2019) defines key categories as "inventory categories which individually, or as a group of categories (for which a common method, emission factor and activity data are applied) are prioritized within the national inventory system because their estimates have a significant influence on a country's total inventory of greenhouse gases in terms of the absolute level, the trend, or

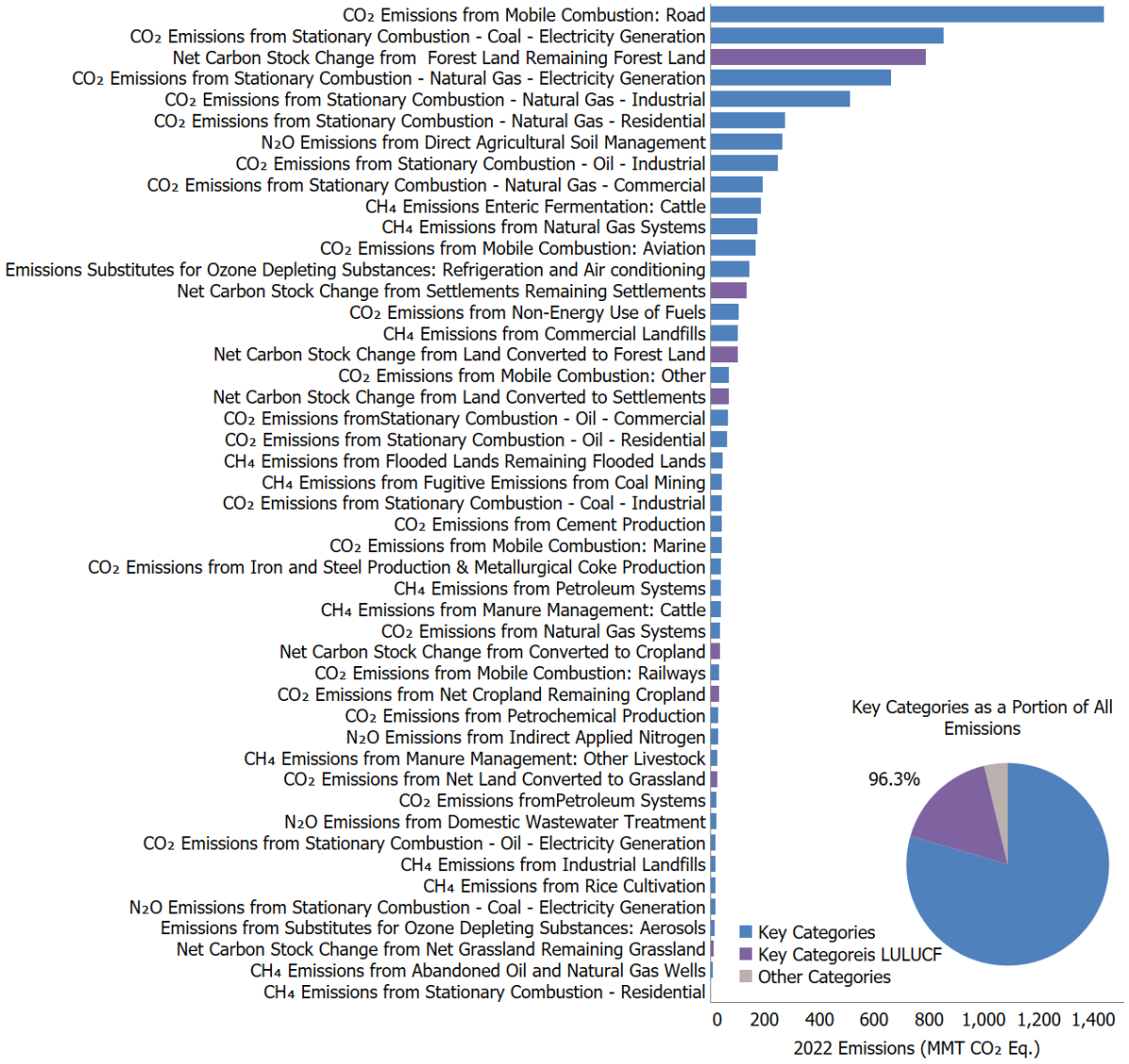
the level of uncertainty in emissions or removals."[25] A key category analysis identifies priority source or sink categories for focusing efforts to improve overall Inventory quality. In addition, a qualitative review of key categories and non-key categories can also help identify additional source and sink categories to consider for improvement efforts, including reducing uncertainty.

Figure ES-16 presents the 2022 key categories identified by the Approach 1 level assessment, including the LULUCF sector. A level assessment using Approach 1 identifies all source and sink categories that cumulatively account for 95 percent of total (i.e., gross) emissions in a given year when assessed in descending order of absolute magnitude.

For a complete list of key categories and more information regarding the overall key category analysis, including approaches accounting for uncertainty and the influence of trends of individual source and sink categories, see the Introduction chapter, Section 1.5, and Annex 1.

[25] See Chapter 4 "Methodological Choice and Identification of Key Categories" in IPCC (2006) and IPCC (2019). See http://www.ipcc-nggip.iges.or.jp/public/2006gl/vol1.html and https://www.ipcc-nggip.iges.or.jp/public/2019rf/pdf/1_Volume1/19R_V1_Ch04_MethodChoice.pdf.

Figure ES-16: 2022 Key Categories (Approach 1 including LULUCF)[a]



Note: For a complete list of key categories and detailed discussion of the underlying key category analysis, see Annex 1. Bars indicate key categories identified using Approach 1 level assessment including the LULUCF sector. The absolute values of net CO_2 emissions from LULUCF are presented in this figure but reported separately from gross emissions totals. Refer to Table ES-4 for a breakout of emissions and removals for LULUCF by source/sink category.

Quality Assurance and Quality Control (QA/QC)

The United States seeks continuous improvements to the quality, transparency, and usability of the *Inventory of U.S. Greenhouse Gas Emissions and Sinks*. To assist in these efforts, the United States implemented a systematic approach to QA/QC. The procedures followed for the Inventory have been formalized in accordance with the U.S. Inventory QA/QC plan, and the UNFCCC reporting guidelines and *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The QA process includes expert and public reviews for the Inventory estimates and this report.

Box ES-3: Use of Ambient Measurements Systems for Validation of Emission Inventories

In following Article 13.7(a) of the Paris Agreement and Article 4.1(a) of the UNFCCC, as well as relevant decisions under those agreements to develop and submit national greenhouse gas emission inventories, the emissions and sinks presented in this report are organized by source and sink categories and calculated using internationally accepted methods in the 2006 IPCC Guidelines for National Greenhouse Gas Inventories (2006 IPCC Guidelines) and, where appropriate, its supplements and refinements.[26] Several recent studies have estimated emissions at the national or regional level with estimated results that sometimes differ from EPA's estimate of emissions. EPA has engaged with researchers on how remote sensing, ambient measurement, and inverse modeling techniques for estimating greenhouse gas emissions could assist in improving the understanding of inventory estimates. In working with the research community to improve national greenhouse gas inventories, EPA follows guidance from the IPCC on the use of measurements and modeling to validate emission inventories.[27] An area of particular interest in EPA's outreach efforts is how ambient measurement data can be used to assess estimates or potentially be incorporated into the Inventory in a manner consistent with this *Inventory* report's transparency of its calculation methodologies, and the ability of inverse modeling techniques to attribute emissions and removals from remote sensing to anthropogenic sources, as defined by the IPCC for this report, versus natural sources and sinks.

The *2019 Refinement to the IPCC 2006 Guidelines for National Greenhouse Gas Inventories* (IPCC 2019) Volume 1 General Guidance and Reporting, Chapter 6: Quality Assurance, Quality Control and Verification notes that emission estimates derived from atmospheric concentration measurements can provide independent data sets as a basis for comparison with inventory estimates. The *2019 Refinement* provides guidance on conducting such comparisons (as summarized in Table 6.2 of IPCC [2019] Volume 1, Chapter 6) and provides guidance on using such comparisons to identify areas of improvement in national inventories (as summarized in Box 6.5 of IPCC [2019] Volume 1, Chapter 6). Further, it identified fluorinated gases as particularly suitable for such comparisons due their limited natural sources, their generally long atmospheric lifetimes, and well-understood loss mechanisms, which makes it relatively more straightforward to model their emission fluxes from observed mass quantities. Unlike emissions of CO_2, CH_4, and N_2O, emissions of fluorinated greenhouse gases are almost exclusively anthropogenic, meaning that the fluorinated greenhouse gas emission sources included in this Inventory account for the majority of the total U.S. emissions of these gases detectable in the atmosphere. This evaluation approach is also useful for gases and sources with larger uncertainties in available bottom-up inventory methods and data, such as emissions of CH_4, which are primarily from uncertain biological (e.g., enteric fermentation) and fugitive (e.g., natural gas production) activities.

In this *Inventory*, EPA includes the results from current and previous comparisons between fluorinated gas emissions inferred from atmospheric measurements and fluorinated gas emissions estimated based on bottom-up measurements and modeling. These comparisons, performed for HFCs and SF_6 respectively, are described under the QA/QC and Verification discussions in Chapter 4, Sections 4.25 Substitution of Ozone Depleting Substances and 4.26 Electrical Equipment, in the IPPU chapter of this report.

Consistent with the *2019 Refinement*, a key element to facilitate such comparisons is a spatially-explicit (or gridded inventory as an input to inverse modeling. To improve the ability to compare methane emissions from the national-level greenhouse gas inventory with observation-based estimates , a team of researchers from U.S. EPA, SRON Netherlands Institute for Space Research, Harvard University, and Lawrence Berkely National Laboratory and other coauthors developed a time series of anthropogenic methane emissions maps with 0.1° x 0.1° (10 km x 10 km) spatial resolution and monthly temporal resolution for the contiguous United States.[28] The gridded methane inventory is designed to be consistent with the U.S. EPA *Inventory of U.S. Greenhouse Gas*

[26] See http://www.ipcc-nggip.iges.or.jp/public/index.html.

[27] See http://www.ipcc-nggip.iges.or.jp/meeting/pdfiles/1003_Uncertainty%20meeting_report.pdf.

[28] See https://www.epa.gov/ghgemissions/us-gridded-methane-emissions.

Emissions and Sinks estimates, which presents national totals for different source types.[29] The development of this gridded inventory is consistent with the recommendations contained in two National Academies of Science reports examining greenhouse gas emissions data (National Research Council 2010; National Academies of Sciences, Engineering, and Medicine 2018).

Finally, in addition to the use of atmospheric concentration measurement data for comparison with Inventory data, information from top-down studies is directly incorporated in the natural gas systems calculations to quantify emissions from certain well blowout events.

Uncertainty Analysis of Emission and Sink Estimates

Uncertainty assessment is an essential element of a complete inventory of greenhouse gas emissions and removals because it helps to inform and prioritize inventory improvements. Recognizing the benefit of conducting an uncertainty analysis, the UNFCCC reporting guidelines follow the recommendations of the *2006 IPCC Guidelines for National Greenhouse Gas Inventories* (IPCC 2006), Volume 1, Chapter 3 and require that countries provide single estimates of uncertainty for source and sink categories. In addition to quantitative uncertainty assessments, a qualitative discussion of uncertainty is presented for each source and sink category identifying specific factors affecting the uncertainty surrounding the estimates provided in accordance with UNFCCC reporting guidelines. Some of the current estimates, such as those for CO_2 emissions from energy-related combustion activities, are considered to have low uncertainties. This is because the amount of CO_2 emitted from energy-related combustion activities is directly related to the amount of fuel consumed, the fraction of the fuel that is oxidized, and the carbon content of the fuel, and for the United States, the uncertainties associated with estimating those factors are relatively small. For some other categories of emissions and sinks, however, inherent variability or a lack of data increases the uncertainty or systematic error associated with the estimates presented. Finally, an analysis is conducted to assess uncertainties associated with the overall emissions, sinks, and trends estimates. The overall uncertainty surrounding total net greenhouse gas emissions is estimated to be -6 to +6 percent in 1990 and -5 to +6 percent in 2022. When the LULUCF sector is excluded from the analysis the uncertainty is estimated to be -3 to +4 percent in 1990 and -2 to +4 percent in 2022.

[29] See https://www.epa.gov/ghgemissions/inventory-us-greenhouse-gas-emissions-and-sinks.

1. Introduction

This report presents an inventory of U.S. anthropogenic greenhouse gas emissions and sinks for the years 1990 through 2022 compiled by the United States government. A summary of source and sink category estimates is provided in Table 2-1, Table 2-2, andTable 2-4 by gas and IPCC sector in the Trends in Greenhouse Gas Emissions and Sinks chapter. The emission and sink estimates in these tables are presented throughout the main report in both CO_2 equivalents (CO_2 Eq.[30] and unweighted units). This report also discusses the methods and data used to calculate the emission and sink estimates.

The United States is party to both the 1992 UNFCCC and the 2015 Paris Agreement. The Paris Agreement set a global temperature goal–holding the increase in the global average temperature to well below 2°C above pre-industrial levels and pursuing efforts to limit the increase to 1.5°C–that articulates with greater precision States' views on what is necessary to meet the UNFCCC's objective of "stabiliz[ing] … greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system.[31]

The United States is committed to submitting a national inventory of anthropogenic emissions sources and removals by sinks of greenhouse gases by April 15 of each year. The United States has prepared this report, in conjunction with Common Reporting Tables (CRTs) that accompany this report, consistent with its obligations under those agreements.

In 1988, preceding the creation of the UNFCCC, the World Meteorological Organization (WMO) and the United Nations Environment Programme (UNEP) jointly established the Intergovernmental Panel on Climate Change (IPCC). The role of the IPCC is to assess on a comprehensive, objective, open and transparent basis the scientific, technical and socio-economic information relevant to understanding the scientific basis of risk of human-induced climate change, its potential impacts and options for adaptation and mitigation (IPCC 2021). The Paris Agreement and the UNFCCC require use of methods from the *2006 IPCC Guidelines for National Greenhouse Gas Inventories* and encourages Parties to use the *2013 Supplement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories: Wetlands* and *the 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The recently released *2019 Refinement* clarify and elaborate on the existing guidance in the *2006 IPCC Guidelines*, along with providing updates to default values of emission factors and other parameters based on updated science. This report applies both the *2013 Supplement* and updated guidance in the *2019 Refinement* to improve accuracy and completeness of the *Inventory*. For more information on specific uses, see Section 1.4 of this chapter on Methodology and Data Sources.

[30] More information is provided in the Global Warming Potentials section of this chapter on the use of IPCC *Fifth Assessment Report* (AR5) GWP values.

[31] See Paris Agreement, Article 2.1(a); UNFCCC, Article 2.

Box 1-1: Methodological Approach for Estimating and Reporting U.S. Emissions and Removals, including Relationship to EPA's Greenhouse Gas Reporting Program

Consistent with Article 13.7(a) of the Paris Agreement and Article 4.1(a) of the UNFCCC, as well as relevant decisions under those agreements, the emissions and removals presented in this report and this chapter are organized by source and sink categories and calculated using internationally accepted methods in the *2006 IPCC Guidelines for National Greenhouse Gas Inventories* (*2006 IPCC Guidelines*) and, where appropriate, its supplements and refinements. Additionally, the calculated emissions and removals in a given year for the United States are presented in a common manner in line with the reporting guidelines for the reporting of inventories under the Paris Agreement and the UNFCCC. The Parties' use of consistent methods to calculate emissions and removals for their inventories helps to ensure that these reports are comparable. The presentation of emissions and removals provided in this *Inventory* does not preclude alternative examinations (e.g., economic sectors). Rather, this *Inventory* presents emissions and removals in a common format consistent with how Parties are to report their national inventories under the Paris Agreement and the UNFCCC. The report itself, and this chapter, follows this common format, and provides an explanation of the application of methods used to calculate emissions and removals.

EPA also collects greenhouse gas emissions data from individual facilities and suppliers of certain fossil fuels and industrial gases through its Greenhouse Gas Reporting Program (GHGRP), which is complementary to the U.S. *Inventory*.[32] The GHGRP applies to direct greenhouse gas emitters, fossil fuel suppliers, industrial greenhouse gas suppliers, and facilities that inject carbon dioxide (CO_2) underground for sequestration or other reasons and requires reporting by over 8,000 sources or suppliers in 41 industrial categories.[33] Annual reporting is at the facility level, except for certain suppliers of fossil fuels and industrial greenhouse gases. In general, the threshold for reporting is 25,000 metric tons or more of CO_2 Eq. per year. Facilities in most source categories[34] subject to GHGRP began reporting for the 2010 reporting year while additional types of industrial operations began reporting for the 2011 reporting year. Methodologies used in EPA's GHGRP are consistent with the *2006 IPCC Guidelines*. While the GHGRP does not provide full coverage of total annual U.S. greenhouse gas emissions and removals (e.g., the GHGRP excludes emissions from the Agriculture and Land Use, Land-Use Change, and Forestry sectors), it is an important input to the calculations of national-level emissions in this *Inventory*.

Data presented in this *Inventory* report and EPA's GHGRP are complementary. The GHGRP dataset continues to be an important resource for the *Inventory*, providing not only annual emissions information, but also other annual information such as activity data and emission factors that can improve and refine national emission estimates and trends over time. Methodologies used in EPA's GHGRP are consistent with the *2006 IPCC Guidelines* (e.g., higher tier methods). GHGRP data also allow EPA to disaggregate national inventory estimates in new ways that can highlight differences across regions and sub-categories of emissions, along with enhancing the application of QA/QC procedures and assessment of uncertainties. EPA uses annual GHGRP data in several categories to improve the national estimates presented in this *Inventory*, consistent with IPCC methodological guidance. See Annex 9 for more information on specific uses of GHGRP data in the *Inventory* (e.g., natural gas systems).

1.1 Background Information

Science

For over the past 200 years, the burning of fossil fuels such as coal, oil, and natural gas, along with deforestation, land-use changes, and other activities have caused the concentrations of heat-trapping "greenhouse gases" to increase significantly in our atmosphere (IPCC 2021). These gases in the atmosphere absorb some of the energy

being radiated from the surface of the Earth that would otherwise be lost to space, essentially acting like a blanket that makes the Earth's surface warmer than it would be otherwise.

Greenhouse gases are necessary to life as we know it. Without greenhouse gases to create the natural heat-trapping properties of the atmosphere, the planet's surface would be about 60 degrees Fahrenheit cooler than present (USGCRP 2017). Carbon dioxide is also necessary for plant growth. With emissions from biological and geological sources, there is a natural level of greenhouse gases that is maintained in the atmosphere. Human emissions of greenhouse gases and subsequent changes in atmospheric concentrations alter the balance of energy transfers between space and the earth system (IPCC 2021). A gauge of these changes is called radiative forcing, which is a measure of a substance's total net effect on the global energy balance for which a positive number represents a warming effect, and a negative number represents a cooling effect (IPCC 2021). IPCC concluded in its most recent scientific assessment report that it is "unequivocal that human influence has warmed the atmosphere, ocean and land" (IPCC 2021).

As concentrations of greenhouse gases continue to increase from man-made sources, the Earth's temperature is climbing above past levels. The Earth's average land and ocean surface temperature has increased by about 2.0 degrees Fahrenheit from the 1850 to 1900 period to the decade of 2011 to 2020 (IPCC 2021). The last four decades have each been the warmest decade successively at the Earth's surface since at least 1850 (IPCC 2021). Other aspects of the climate are also changing, such as rainfall patterns, snow and ice cover, and sea level. If greenhouse gas concentrations continue to increase, climate models predict that the average temperature at the Earth's surface is likely to increase between 0.27 to 9.99 degrees Fahrenheit (0.15 to 5.55 degrees Celsius) relative to 1995 to 2014 levels by the end of this century, depending on the emissions scenario and the responsiveness of the climate system (IPCC 2021).

For further information on greenhouse gases, radiative forcing, and implications for climate change, see the recent scientific assessment reports from the IPCC,[35] the U.S. Global Change Research Program (USGCRP),[36] and the National Academies of Sciences, Engineering, and Medicine (NAS).[37]

Greenhouse Gases

Although the Earth's atmosphere consists mainly of oxygen and nitrogen, neither plays a significant role in enhancing the greenhouse effect because both are essentially transparent to terrestrial radiation. The greenhouse effect is primarily a function of the concentration of water vapor, carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and other trace gases in the atmosphere that absorb the terrestrial radiation leaving the surface of the Earth (IPCC 2021).

Naturally occurring greenhouse gases include water vapor, CO_2, CH_4, N_2O, and ozone (O_3). Several classes of halogenated substances that contain fluorine, chlorine, or bromine are also greenhouse gases, but they are, for the most part, solely a product of industrial activities. Chlorofluorocarbons (CFCs) and hydrochlorofluorocarbons (HCFCs) are halocarbons that contain chlorine, while halocarbons that contain bromine are referred to as bromofluorocarbons (i.e., halons). As stratospheric ozone depleting substances, CFCs, HCFCs, and halons are covered under the Montreal Protocol on Substances that Deplete the Ozone Layer. The UNFCCC defers to this earlier international treaty. Consequently, Parties to the UNFCCC are not required to include these gases in

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[32] On October 30, 2009, EPA promulgated a rule requiring annual reporting of greenhouse gas data from large greenhouse gas emissions sources in the United States. Implementation of the rule, codified at 40 CFR Part 98, is referred to as EPA's Greenhouse Gas Reporting Program (GHGRP).

[33] See http://www.epa.gov/ghgreporting and http://ghgdata.epa.gov/ghgp/main.do.

[34] See https://www.ccdsupport.com/confluence/pages/viewpage.action?pageId=322699300

[35] See https://www.ipcc.ch/report/ar6/wg1/.

[36] See https://nca2018.globalchange.gov/.

[37] See https://www.nationalacademies.org/topics/climate.

national greenhouse gas inventories.[38] Some other fluorine-containing halogenated substances—hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), sulfur hexafluoride (SF_6), and nitrogen trifluoride (NF_3)—do not deplete stratospheric ozone but are potent greenhouse gases. These latter substances are addressed by the UNFCCC and accounted for in national greenhouse gas inventories.

There are also several other substances that influence the global radiation budget but are short-lived and therefore not well-mixed, leading to spatially variable radiative forcing effects. These substances include carbon monoxide (CO), nitrogen dioxide (NO_2), sulfur dioxide (SO_2), and tropospheric (ground level) ozone (O_3). Tropospheric ozone is formed from chemical reactions in the atmosphere of precursor pollutants, which include volatile organic compounds (VOCs), CH_4, and nitrogen oxides (NO_x), in the presence of ultraviolet light (sunlight).

Aerosols are extremely small particles or liquid droplets suspended in the Earth's atmosphere that are often composed of sulfur compounds, carbonaceous combustion products (e.g., black carbon), crustal materials (e.g., dust) and other human-induced pollutants. They can affect the absorptive characteristics of the atmosphere (e.g., scattering incoming sunlight away from the Earth's surface, or, in the case of black carbon, absorbing sunlight) and can play a role in affecting cloud formation and lifetime, as well as the radiative forcing of clouds and precipitation patterns.

CO_2, CH_4, and N_2O are continuously emitted to and removed from the atmosphere by natural processes on Earth. Anthropogenic activities (such as fossil fuel combustion, cement production, land-use, land-use change, and forestry, agriculture, or waste management), however, can cause additional quantities of these and other greenhouse gases to be emitted or sequestered, thereby changing their global average atmospheric concentrations. Natural activities such as respiration by plants or animals and seasonal cycles of plant growth and decay are examples of processes that only cycle carbon or nitrogen between the atmosphere and organic biomass. Such processes, except when directly or indirectly perturbed out of equilibrium by anthropogenic activities, generally do not alter average atmospheric greenhouse gas concentrations over decadal timeframes. Climatic changes resulting from anthropogenic activities, however, could have positive or negative feedback effects on these natural systems. Atmospheric concentrations of these gases, along with their rates of growth and atmospheric lifetimes, are presented in Table 1-1.

Table 1-1: Global Atmospheric Concentration, Rate of Concentration Change, and Atmospheric Lifetime of Selected Greenhouse Gases

Atmospheric Variable	CO_2	CH_4	N_2O	SF_6	CF_4
Pre-industrial atmospheric concentration	280 ppm	0.730 ppm	0.270 ppm	0.01 ppt	34.1 ppt
Atmospheric concentration	419 ppm[a]	1.912 ppm[b]	0.336 ppm[c]	11.02 ppt[d]	85.5 ppt[e]
Rate of concentration change	2.28 ppm/yr[f]	8.83 ppb/yr[f,g]	1.01 ppb/yr[f]	0.32 ppt/yr[f]	0.81 ppt/yr[f]
Atmospheric lifetime (years)	See footnote[h]	11.8	109[i]	About 1,000[j]	50,000

[a] The atmospheric CO_2 concentration is the 2022 annual average at the Mauna Loa, HI station (NOAA/ESRL 2024a). The global atmospheric CO_2 concentration, computed using an average of sampling sites across the world, was 417 ppm in 2022.

[b] The values presented are global 2022 annual average mole fractions (NOAA/ESRL 2024b).

[c] The values presented are global 2022 annual average mole fractions (NOAA/ESRL 2024c).

[d] The values presented are global 2022 annual average mole fractions (NOAA/ESRL 2024d).

[e] The 2019 CF_4 global mean atmospheric concentration is from the Advanced Global Atmospheric Gases Experiment (IPCC 2021).

[f] The rate of concentration change for CO_2 is an average of the rates from 2007 through 2022 and has fluctuated between 1.5 to 3.0 ppm per year over this period (NOAA/ESRL 2024a). The rate of concentration change for CH_4, N_2O, and SF_6, is the average rate of change between 2007 and 2022 (NOAA/ESRL 2024b; NOAA/ESRL 2024c; NOAA/ESRL 2024d). The rate of concentration change for CF_4 is the average rate of change between 2011 and 2019 (IPCC 2021).

[g] The growth rate for atmospheric CH_4 decreased from over 10 ppb/year in the 1980s to nearly zero in the early 2000s; recently, the growth rate has been about 13.22 ppb/year (NOAA/ESRL 2024b).

[38] Emissions estimates of CFCs, HCFCs, halons and other ozone-depleting substances are included in this document for informational purposes.

[h] For a given amount of CO_2 emitted, some fraction of the atmospheric increase in concentration is quickly absorbed by the oceans and terrestrial vegetation, some fraction of the atmospheric increase will only slowly decrease over a number of years, and a small portion of the increase will remain for many centuries or more.

[i] This table reports the "perturbation lifetime" for both CH_4 and N_2O, which takes into account the interactions between emissions of the gas and its own atmospheric residence time.

[j] The lifetime for SF_6 was revised from 3,200 years to about 1,000 years based on recent studies (IPCC 2021).

Source: Pre-industrial atmospheric concentrations and atmospheric lifetimes for CH_4, and N_2O, are from IPCC (2021), pre-industrial atmospheric concentration for SF_6, is from Rigby (2010), and pre-industrial atmospheric concentration for CF_4 is from Meinhausen (2017).

A brief description of each greenhouse gas, its sources, and its role in the atmosphere is given below. The following section then explains the concept of global warming potentials (GWPs), which are assigned to individual gases as a measure of their relative average global radiative forcing effect.

Water Vapor (H_2O). Water vapor is the largest contributor to the natural greenhouse effect. Water vapor is fundamentally different from other greenhouse gases in that it can condense and rain out when it reaches high concentrations, and the total amount of water vapor in the atmosphere is in part a function of the Earth's temperature. While some human activities such as evaporation from irrigated crops or power plant cooling release water vapor into the air, these activities have been determined to have a negligible effect on global climate (IPCC 2021). The lifetime of water vapor in the troposphere is on the order of 10 days. Water vapor can also contribute to cloud formation, and clouds can have both warming and cooling effects by either trapping or reflecting heat. Because of the relationship between water vapor levels and temperature, water vapor and clouds serve as a feedback to climate change, such that for any given change in other greenhouse gas concentrations, the total temperature change is greater than would happen in the absence of water vapor. Aircraft emissions can create contrails, which may also develop into contrail-induced cirrus clouds, with complex regional and temporal net radiative forcing effects that currently have a low level of scientific certainty (IPCC 2021).

Carbon Dioxide (CO_2). In nature, carbon is cycled between various atmospheric, oceanic, land biotic, marine biotic, and mineral reservoirs. The largest fluxes occur between the atmosphere and terrestrial biota, and between the atmosphere and surface water of the oceans. In the atmosphere, carbon predominantly exists in its oxidized form as CO_2. Atmospheric CO_2 is part of this global carbon cycle, and therefore its fate is a complex function of geochemical and biological processes. Carbon dioxide concentrations in the atmosphere increased from approximately 280 parts per million by volume (ppmv) in pre-industrial times to 419 ppmv in 2022, a 50 percent increase (IPCC 2021; NOAA/ESRL 2024a).[39, 40] The IPCC states that "Observed increases in well-mixed greenhouse gas (GHG) concentrations since around 1750 are unequivocally caused by human activities" (IPCC 2021). The predominant source of anthropogenic CO_2 emissions is the combustion of fossil fuels. Forest clearing, other biomass burning, and some non-energy production processes (e.g., cement production) also emit notable quantities of CO_2. In its *Sixth Assessment Report*, the IPCC determined that of the 2.0 degrees of observed warming, the best estimate is that 1.9 degrees of that are due to human influence, with elevated CO_2 concentrations being the most important contributor to that warming (IPCC 2021).

Methane (CH_4). Methane is primarily produced through anaerobic decomposition of organic matter in biological systems. Agricultural processes such as wetland rice cultivation, enteric fermentation in animals, and the decomposition of animal wastes emit CH_4, as does the decomposition of municipal solid wastes and treatment of wastewater. Methane is also emitted during the production and distribution of natural gas and petroleum, and is released as a byproduct of coal mining and incomplete fossil fuel combustion. Atmospheric concentrations of CH_4 have increased by about 162 percent since 1750, from a pre-industrial value of about 730 ppb to 1,912 ppb in 2022[41] although the rate of increase decreased to near zero in the early 2000s, and has recently increased again to

[39] The pre-industrial period is considered as the time preceding the year 1750 (IPCC 2021).

[40] Carbon dioxide concentrations during the last 1,000 years of the pre-industrial period (i.e., 750 to 1750), a time of relative climate stability, fluctuated by about ±10 ppmv around 280 ppmv (IPCC 2021).

[41] This value is the global 2022 annual average mole fraction (NOAA/ESRL 2024b).

about 8.83 ppb/year. The IPCC has estimated that about half of the current CH_4 flux to the atmosphere (and the entirety of the increase in concentration) is anthropogenic, from human activities such as agriculture, fossil fuel production and use, and waste disposal (IPCC 2021).

Methane is primarily removed from the atmosphere through a reaction with the hydroxyl radical (OH) and is ultimately converted to CO_2. Minor removal processes also include reaction with chlorine in the marine boundary layer, a soil sink, and stratospheric reactions. Increasing emissions of CH_4 reduce the concentration of OH, creating a feedback that increases the atmospheric lifetime of CH_4 (IPCC 2021). Methane's reactions in the atmosphere also lead to production of tropospheric ozone and stratospheric water vapor, both of which also contribute to climate change. Tropospheric ozone also has negative effects on human health and plant productivity.

Nitrous Oxide (N_2O). Anthropogenic sources of N_2O emissions include agricultural soils, especially production of nitrogen-fixing crops and forages, the use of synthetic and manure fertilizers, and manure deposition by livestock; fossil fuel combustion, especially from mobile combustion; adipic (nylon) and nitric acid production; wastewater treatment and waste incineration; and biomass burning. The atmospheric concentration of N_2O has increased by 24 percent since 1750, from a pre-industrial value of about 270 ppb to 336 ppb in 2022,[42] a concentration that has not been exceeded during at least the last 800 thousand years. Nitrous oxide is primarily removed from the atmosphere by the photolytic action of sunlight in the stratosphere (IPCC 2021).

Ozone (O_3). Ozone is present in both the upper stratosphere,[43] where it shields the Earth from harmful levels of ultraviolet radiation, and at lower concentrations in the troposphere,[44] where it is the main component of anthropogenic photochemical "smog." During the last two decades, emissions of anthropogenic chlorine and bromine-containing halocarbons, such as CFCs, have depleted stratospheric ozone concentrations. This loss of ozone in the stratosphere has resulted in negative radiative forcing, representing an indirect effect of anthropogenic emissions of chlorine and bromine compounds (IPCC 2021). The depletion of stratospheric ozone and its radiative forcing remained relatively unchanged since 2000 for the last two decades and is starting to decline; recovery is expected to occur shortly after the middle of the twenty-first century (WMO/UNEP 2018).

The past increase in tropospheric ozone, which is also a greenhouse gas, is estimated to provide the third largest increase in direct radiative forcing since the pre-industrial era, behind CO_2 and CH_4. Tropospheric ozone is produced from complex chemical reactions of volatile organic compounds and CH_4 mixing with NO_x in the presence of sunlight. The tropospheric concentrations of ozone and these other pollutants are short-lived and, therefore, spatially variable (IPCC 2021).

Halocarbons, Sulfur Hexafluoride (SF_6), and Nitrogen Trifluoride (NF_3). Halocarbons are, for the most part, man-made chemicals that have direct radiative forcing effects and could also have an indirect effect. Halocarbons that contain chlorine (CFCs, HCFCs, methyl chloroform, and carbon tetrachloride) and bromine (halons, methyl bromide, and hydrobromofluorocarbons) result in stratospheric ozone depletion and are therefore controlled under the Montreal Protocol on Substances that Deplete the Ozone Layer. Although most CFCs and HCFCs are potent global warming gases, their net radiative forcing effect on the atmosphere is reduced because they cause stratospheric ozone depletion, which itself is a greenhouse gas but which also shields the Earth from harmful levels of ultraviolet radiation. Under the Montreal Protocol, the United States phased out the production and importation of halons by 1994 and of CFCs by 1996. Under the Copenhagen Amendments to the Protocol, a cap

[42] This value is the global 2022 annual average (NOAA/ESRL 2024c).

[43] The stratosphere is the layer from the troposphere up to roughly 50 kilometers. In the lower regions the temperature is nearly constant but in the upper layer the temperature increases rapidly because of sunlight absorption by the ozone layer. The ozone-layer is the part of the stratosphere from 19 kilometers up to 48 kilometers where the concentration of ozone reaches up to 10 parts per million.

[44] The troposphere is the layer from the ground up to 11 kilometers near the poles and up to 16 kilometers in equatorial regions (i.e., the lowest layer of the atmosphere where people live). It contains roughly 80 percent of the mass of all gases in the atmosphere and is the site for most weather processes, including most of the water vapor and clouds.

was placed on the production and importation of HCFCs by non-Article 5 countries, including the United States,[45] beginning in 1996, and then followed by intermediate requirements and a complete phase-out by the year 2030. While ozone depleting gases covered under the Montreal Protocol and its Amendments are not covered by the UNFCCC, they are reported in this Inventory under Annex 6.2 for informational purposes.

HFCs, PFCs, SF_6, and NF_3 are not ozone depleting substances. The most common HFCs are, however, powerful greenhouse gases. Hydrofluorocarbons are primarily used as replacements for ozone depleting substances but are also emitted as a byproduct of the HCFC-22 (chlorodifluoromethane) manufacturing process. Other contributing sources to HFC emissions include the electronics industry and magnesium production and processing. Currently, these emissions have a small aggregate radiative forcing impact, but it was anticipated that without further controls their contribution to overall radiative forcing would increase, the ERF (effective radiative forcing) of halogenated gases increased by 3.5 percent between 2011 and 2019 primarily due to a decrease in atmospheric mixing-ratios of CFCs and an increase in their replacements (IPCC 2021). On December 27, 2020, the American Innovation and Manufacturing (AIM) Act was enacted by Congress and which gives EPA authority to phase down HFC production and consumption (i.e., production plus import, minus export), through an allowance allocation program, promulgate certain regulations for purposes of maximizing reclamation and minimizing releases of HFCs and their substitutes from equipment, and facilitate the transition to next-generation technologies through sector-based restrictions, which will lead to lower HFC emissions over time. On October 31, 2022, the United States also ratified the Kigali Amendment to the Montreal Protocol, committing to continued phase down of HFCs. Perfluorocarbons, SF_6, and NF_3 are predominantly emitted from various industrial processes including aluminum smelting, semiconductor manufacturing, electric power transmission and distribution, and magnesium casting. Currently, the radiative forcing impact of PFCs, SF_6, and NF_3 is also small, but they have a significant growth rate, extremely long atmospheric lifetimes, and are strong absorbers of infrared radiation, and therefore have the potential to influence climate far into the future (IPCC 2021).

Carbon Monoxide (CO). Carbon monoxide has an indirect radiative forcing effect by elevating concentrations of CH_4 and tropospheric ozone through chemical reactions with other atmospheric constituents (e.g., the hydroxyl radical, OH) that would otherwise assist in destroying CH_4 and tropospheric ozone. Carbon monoxide is created when carbon-containing fuels are burned incompletely. Through natural processes in the atmosphere, it is eventually oxidized to CO_2. Carbon monoxide concentrations are both short-lived in the atmosphere and spatially variable.

Nitrogen Oxides (NO_x). The primary climate change effects of nitrogen oxides (i.e., NO and NO_2) are indirect. Warming effects can occur due to reactions leading to the formation of ozone in the troposphere, but cooling effects can occur due to the role of NO_x as a precursor to nitrate particles (i.e., aerosols) and due to destruction of stratospheric ozone when emitted from very high-altitude aircraft.[46] Additionally, NO_x emissions are also likely to decrease CH_4 concentrations, thus having a negative radiative forcing effect (IPCC 2021). Nitrogen oxides are created from lightning, soil microbial activity, biomass burning (both natural and anthropogenic fires) fuel combustion, and, in the stratosphere, from the photo-degradation of N_2O. Concentrations of NO_x are both relatively short-lived in the atmosphere and spatially variable.

Non-methane Volatile Organic Compounds (NMVOCs). Non-methane volatile organic compounds include substances such as propane, butane, and ethane. These compounds participate, along with NO_x, in the formation of tropospheric ozone and other photochemical oxidants. NMVOCs are emitted primarily from transportation and industrial processes, as well as biomass burning and non-industrial consumption of organic solvents. Concentrations of NMVOCs tend to be both short-lived in the atmosphere and spatially variable.

[45] Article 5 of the Montreal Protocol covers several groups of countries, especially developing countries, with low consumption rates of ozone depleting substances. Developing countries with per capita consumption of less than 0.3 kg of certain ozone depleting substances (weighted by their ozone depleting potential) receive financial assistance and a grace period of ten additional years in the phase-out of ozone depleting substances.

[46] NO_x emissions injected higher in the stratosphere, primarily from fuel combustion emissions from high altitude supersonic aircraft, can lead to stratospheric ozone depletion.

Aerosols. Aerosols are extremely small particles or liquid droplets found in the atmosphere that are either directly emitted into or are created through chemical reactions in the Earth's atmosphere. Aerosols or their chemical precursors can be emitted by natural events such as dust storms, biogenic or volcanic activity, or by anthropogenic processes such as transportation, coal combustion, cement manufacturing, waste incineration, or biomass burning. Various categories of aerosols exist from both natural and anthropogenic sources, such as soil dust, sea salt, biogenic aerosols, sulfates, nitrates, volcanic aerosols, industrial dust, and carbonaceous[47] aerosols (e.g., black carbon, organic carbon). Aerosols can be removed from the atmosphere relatively rapidly by precipitation or through more complex processes under dry conditions.

Aerosols affect radiative forcing differently than greenhouse gases. Their radiative effects occur through direct and indirect mechanisms: directly by scattering and absorbing solar radiation (and to a lesser extent scattering, absorption, and emission of terrestrial radiation); and indirectly by increasing cloud droplets and ice crystals that modify the formation, precipitation efficiency, and radiative properties of clouds (IPCC 2021). Despite advances in understanding of cloud-aerosol interactions, the contribution of aerosols to radiative forcing are difficult to quantify because aerosols generally have short atmospheric lifetimes, and have number concentrations, size distributions, and compositions that vary regionally, spatially, and temporally (IPCC 2021).

The net effect of aerosols on the Earth's radiative forcing is believed to be negative (i.e., net cooling effect on the climate). In fact, aerosols contributed a cooling influence of up to 1.4 degrees, offsetting a substantial portion of greenhouse gas warming (IPCC 2021). Because aerosols remain in the atmosphere for only days to weeks, their concentrations respond rapidly to changes in emissions.[48] Not all aerosols have a cooling effect. Current research suggests that another constituent of aerosols, black carbon, has a positive radiative forcing by heating the Earth's atmosphere and causing surface warming when deposited on ice and snow (IPCC 2021). Black carbon also influences cloud development, but the direction and magnitude of this forcing is an area of active research.

Global Warming Potentials

A GWP is a quantified measure of the relative globally averaged radiative forcing impacts of emissions of a particular greenhouse gas over time (see Table 1-2). It is defined as the accumulated radiative forcing within a specific time horizon caused by emitting 1 kilogram (kg) of the gas, relative to that of the reference gas CO_2 (IPCC 2021). Direct radiative effects occur when the gas itself absorbs radiation. Indirect radiative forcing occurs when chemical transformations involving the original gas produce a gas or gases that are greenhouse gases, or when a gas influences other radiatively important processes such as the atmospheric lifetimes of other gases. The reference gas used is CO_2, and therefore GWP-weighted emissions are measured in CO_2 equivalent (CO_2 Eq.).[49] For example, the relationship between a kg of emissions of a gas and a kg of CO_2 Eq. emissions can be expressed as follows and also adapted to other units (e.g. metric tons, etc.):

[47] Carbonaceous aerosols are aerosols that are comprised mainly of carbon and hydrogen. Those carbonaceous aerosols with more hydrogen are classified as "organic carbon", and are generally reflective, while the aerosols that are nearly pure carbon are classified as "black carbon" (also referred to as "soot") and can absorb light (IPCC 2021).

[48] Volcanic activity can inject significant quantities of aerosol producing sulfur dioxide and other sulfur compounds into the stratosphere, which can result in a longer lasting negative forcing effect (i.e., a few years) (IPCC 2021).

[49] Carbon comprises 12/44^{ths} of carbon dioxide by weight.

Equation 1-1: Calculating CO_2 Equivalent Emissions

$$\text{kg } CO_2 \text{ Eq.} = (\text{kg emission of gas}) \times (\text{GWP})$$

where,

kg CO_2 Eq.	= kilograms of CO_2 equivalent
kt	= kilograms (equivalent to a thousand metric grams)
GWP	= Global warming potential

GWP values allow for a comparison of the impacts of emissions and reductions of different gases. According to the IPCC, GWPs typically have an uncertainty of ±40 percent.

All estimates are provided throughout the report in both MMT CO_2 equivalents and unweighted units. Recent decisions under the UNFCCC require Parties to use 100-year GWP values from the IPCC *Fifth Assessment Report* (AR5) for calculating CO_2-equivalent emissions in their national reporting by the end of 2024.

> *…Decides that, until it adopts a further decision on the matter, the global warming potential values used by Parties in their reporting under the Convention to calculate the carbon dioxide equivalence of anthropogenic greenhouse gas emissions by sources and removals by sinks shall be based on the effects of greenhouse gases over a 100-year time horizon as listed in table 8.A.1 in appendix 8.A to the contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change,[50] excluding the value for fossil methane.*[51]

This reflects updated science and ensures that national greenhouse gas inventories reported by all nations are comparable. In preparation for upcoming UNFCCC requirement,[52] this report reflects CO_2-equivalent greenhouse gas totals using 100-year AR5 GWP values. A comparison of emission values with the previously used 100-year GWP values from IPCC *Fourth Assessment Report* (AR4) (IPCC 2007), and the IPCC *Sixth Assessment Report* (AR6) (IPCC 2021) values can be found in Annex 6.1 of this report. The 100-year GWP values used in this report are listed below in Table 1-2.

Greenhouse gases with relatively long atmospheric lifetimes (e.g., CO_2, CH_4, N_2O, HFCs, PFCs, SF_6, NF_3) tend to be evenly distributed throughout the atmosphere, and consequently global average concentrations can be determined. The short-lived gases such as water vapor, carbon monoxide, tropospheric ozone, ozone precursors (e.g., NO_x, and NMVOCs), and tropospheric aerosols (e.g., SO_2 products and carbonaceous particles), however, vary regionally, and consequently it is difficult to quantify their global radiative forcing impacts. Parties to the UNFCCC have not agreed upon GWP values for these gases that are short-lived and spatially inhomogeneous in the atmosphere.

Table 1-2: Global Warming Potentials and Atmospheric Lifetimes (Years) Used in this Report

Gas	Atmospheric Lifetime	GWP[a]
CO_2	See footnote[b]	1
CH_4[c]	12.4	28
N_2O	121	265

[50] Intergovernmental Panel on Climate Change. 2013. *Climate Change 2013: The Physical Science Basis*. Contribution of Working Group I to the *Fifth Assessment Report* of the Intergovernmental Panel on Climate Change. TF Stocker, D Qin, G-K Plattner, et al. (eds.). Cambridge and New York: Cambridge University Press. Available at http://www.ipcc.ch/report/ar5/wg1.

[51] See paragraphs 1 and 2 of the decision on common metrics adopted at the 27th UNFCCC Conference of Parties (COP27), available online at https://unfccc.int/sites/default/files/resource/cp2022_10a01_E.pdf.

[52] See Annex to decision 18/CMA.1, available online at https://unfccc.int/sites/default/files/resource/CMA2018_03a02E.pdf The Paris Agreement reporting guidelines also clarified use of the 100-year GWPs listed in table 8.A.1 in Annex 8.A of Chapter 8 of the *Fifth Assessment Report* (AR5) of the Intergovernmental Panel on Climate Change, excluding the value for fossil methane. United Nations Framework Convention on Climate Change, see paragraph 25 of Decision 5/CMA.3 available online at https://unfccc.int/sites/default/files/resource/CMA2021_L10a2E.pdf.

HFC-23	222	12,400
HFC-32	5.2	677
HFC-41[d]	2.8	116
HFC-125	28.2	3,170
HFC-134a	13.4	1,300
HFC-143a	47.1	4,800
HFC-152a	1.5	138
HFC-227ea	38.9	3,350
HFC-236fa	242	8,060
CF_4	50,000	6,630
C_2F_6	10,000	11,100
C_3F_8	2,600	8,900
c-C_4F_8	3,200	9,540
SF_6	3,200	23,500
NF_3	500	16,100
Other Fluorinated Gases		See Annex 6

[a] 100-year time horizon.
[b] For a given amount of CO_2 emitted, some fraction of the atmospheric increase in concentration is quickly absorbed by the oceans and terrestrial vegetation, some fraction of the atmospheric increase will only slowly decrease over a number of years, and a small portion of the increase will remain for many centuries or more.
[c] The GWP of CH_4 includes the direct effects and those indirect effects due to the production of tropospheric ozone and stratospheric water vapor. The indirect effect due to the production of CO_2 is not included.
[d] See Table A-1 of 40 CFR Part 98
Source: IPCC (2013).

Box 1-2: The IPCC Sixth Assessment Report and Global Warming Potentials

In 2021, the IPCC published its *Sixth Assessment Report* (AR6), which updated its comprehensive scientific assessment of climate change. Within the AR6 report, the GWP values of gases were revised relative to previous IPCC assessment reports, e.g., the IPCC *Fifth Assessment Report* (AR5) (IPCC 2014). Although the AR5 GWP values are used throughout this report, consistent with UNFCCC reporting requirements, it is straight-forward to review the changes to the GWP values and their impact on estimates of the total GWP-weighted emissions of the United States. In the AR6, the IPCC used more recent estimates of the atmospheric lifetimes and radiative efficiencies of some gases and updated background concentrations. The AR6 now includes climate-carbon feedback effects for non-CO_2 gases, improving the consistency between treatment of CO_2 and non-CO_2 gases. Indirect effects of gases on other atmospheric constituents (such as the effect of methane on ozone) have also been updated to match more recent science.

Table 1-3 presents the new GWP values, relative to those presented in the AR5, using the 100-year time horizon common to Paris Agreement and UNFCCC reporting.[53] Updated reporting guidelines under the Paris Agreement require the United States and other countries to shift to use of the IPCC *Fifth Assessment Report* (AR5) (IPCC 2013) 100-year GWP values (without feedbacks) for national inventory reporting.[54] All estimates provided throughout this report are also presented in unweighted units. For informational purposes, emission estimates that use 100-year GWPs from other recent IPCC Assessment Reports are presented in detail in Annex 6.1 of this report.

[53] See Decision 7/CP.27 included in https://unfccc.int/sites/default/files/resource/cp2022_10a01_E.pdf.

[54] See https://unfccc.int/process-and-meetings/transparency-and-reporting/reporting-and-review-under-the-paris-agreement.

Table 1-3: Comparison of 100-Year GWP values

100-Year GWP Values				Comparisons to AR5	
Gas	AR5[a]	AR5 with feedbacks[b]	AR6[c]	AR5 with feedbacks[b]	AR6[c]
CO_2	1	1	1	NC	NC
CH_4[d]	28	34	27	6	(1)
N_2O	265	298	273	33	8
HFC-23	12,400	13,856	14,600	1,456	2,200
HFC-32	677	817	771	140	94
HFC-41	116	141	135	25	19
HFC-125	3,170	3,691	3,740	521	570
HFC-134a	1,300	1,549	1,530	249	230
HFC-143a	4,800	5,508	5,810	708	1,010
HFC-152a	138	167	164	29	26
HFC-227ea	3,350	3,860	3,600	510	250
HFC-236fa	8,060	8,998	8,690	938	630
CF_4	6,630	7,349	7,380	719	750
C_2F_6	11,100	12,340	12,400	1,240	1,300
C_3F_8	8,900	9,878	9,290	978	390
c-C_4F_8	9,540	10,592	10,200	1,052	660
SF_6	23,500	26,087	24,300	2,587	800
NF_3	16,100	17,885	17,400	1,785	1,300

NC (No Change)

[a] The GWP values in this column reflect values used in this report from AR5 excluding climate-carbon feedbacks and the value for fossil methane.

[b] The GWP values in this column are from the AR5 report but include climate-carbon feedbacks for the non-CO_2 gases in order to be consistent with the approach used in calculating the CO_2 lifetime.

[c] The GWP values in this column are from the AR6 report.

[d] The GWP of CH_4 includes the direct effects and those indirect effects due to the production of tropospheric ozone and stratospheric water vapor. Including the indirect effect due to the production of CO_2 resulting from methane oxidation would lead to an increase in AR5 methane GWP values by 2 for fossil methane and is not shown in this table.

Note: Parentheses indicate negative values.

Sources: IPCC (2021), IPCC (2013), IPCC (2007), IPCC (2001), IPCC (1996).

1.2 National Inventory Arrangements

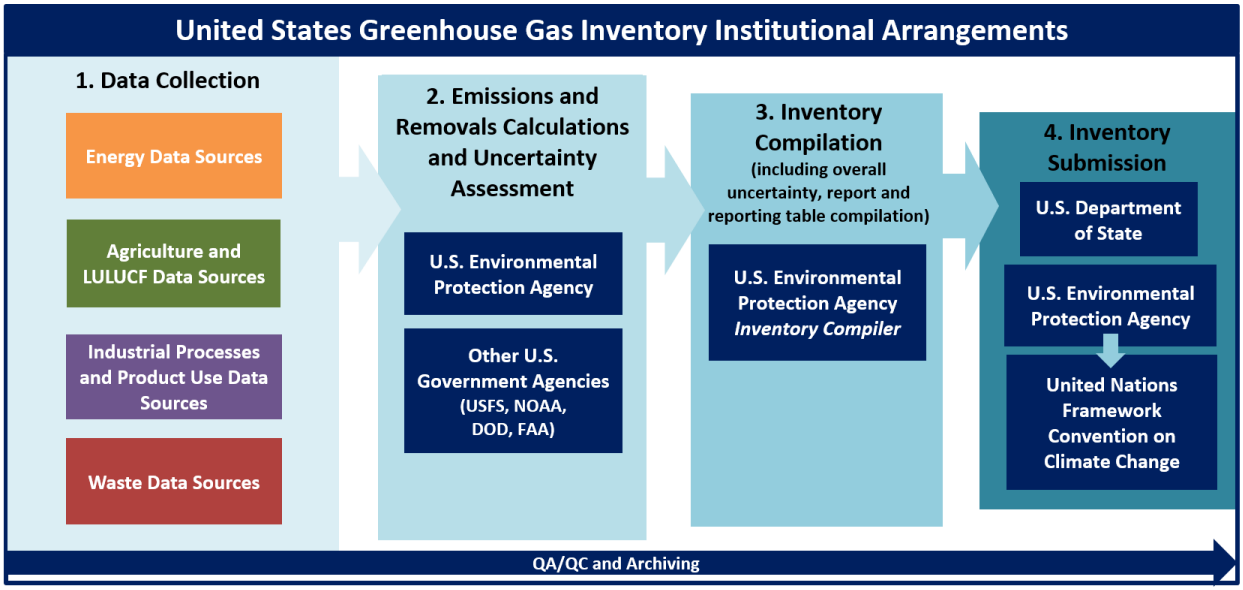
The U.S. Environmental Protection Agency (EPA), in cooperation with other U.S. government agencies, prepares the *Inventory of U.S. Greenhouse Gas Emissions and Sinks*. A wide range of agencies and individuals are involved in supplying data to, planning methodological approaches and improvements, reviewing, or preparing portions of the Inventory—including federal and state government authorities, research and academic institutions, industry associations, and private consultants.

Within EPA, the Office of Atmospheric Protection (OAP) is the lead office responsible for the emission and removal calculations provided in the Inventory, as well as the completion of the National Inventory Report including the Common Reporting Tables (CRTs). EPA's Office of Transportation and Air Quality (OTAQ) and Office of Research and Development (ORD) are also involved in calculating emissions and removals for the Inventory. The U.S. Department of State (DOS) serves as the overall national focal point to the Paris Agreement and the UNFCCC, and EPA's OAP serves as the National Inventory Focal Point for this report, including responding to technical questions and comments on the U.S. Inventory. EPA staff coordinate the annual methodological choice, activity data collection, emission and removal calculations, uncertainty assessment, QA/QC processes, and improvement

planning at the individual source and sink category level. EPA's inventory coordinator manages overall compilation of the entire *Inventory* into the proper reporting format for submission under the Paris Agreement and the UNFCCC and is responsible for the synthesis of information along with the consistent application of cross-cutting IPCC good practice across the *Inventory*.

Several other government agencies contribute to the collection and analysis of the necessary underlying activity data used in the Inventory calculations via formal (e.g., interagency agreements) and informal relationships, in addition to the calculation of estimates integrated in the report (e.g., U.S. Department of Agriculture's U.S. Forest Service and Agricultural Service, National Oceanic and Atmospheric Administration, Federal Aviation Administration, and Department of Defense). Other U.S. agencies provide official data for use in the *Inventory*. The U.S. Department of Energy's Energy Information Administration provides national fuel consumption data and the U.S. Department of Defense provides data on military fuel consumption and use of bunker fuels. Other U.S. agencies providing activity data for use in EPA's emission calculations include: the U.S. Department of Agriculture, National Oceanic and Atmospheric Administration, the U.S. Geological Survey, the Federal Highway Administration, the Department of Transportation, the Bureau of Transportation Statistics, the Department of Commerce, and the Federal Aviation Administration. Academic and research centers also provide activity data and calculations to EPA, as well as individual companies participating in voluntary outreach efforts with EPA. EPA engages with agencies regularly on data needs and improvements to ensure sufficient activity collection for annual compilation of estimates. Finally, EPA as the National Inventory Focal Point, in coordination with the U.S. Department of State, officially submits the *Inventory* under the Paris Agreement and the UNFCCC each April by the reporting deadline.

Figure 1-1: National Inventory Arrangements and Process Diagram



Overview of Inventory Data Sources by Source and Sink Category

Energy	Agriculture and LULUCF	IPPU	Waste
U.S. Energy Information Administration	USDA U.S. Forest Service Forest Inventory and Analysis Program (FIA)	EPA Greenhouse Gas Reporting Program (GHGRP)	EPA Greenhouse Gas Reporting Program (GHGRP)
U.S. Department of Commerce – Bureau of the Census	USDA Natural Resource Conservation Service (NRCS)	U.S. Geological Survey (USGS) National Minerals Information Center	EPA Office of Land and Emergency Management (OLEM)
U.S. Department of Defense – Defense Logistics Agency	USDA National Agricultural Statistics Service (NASS) and Agricultural Research Service (ARS)	American Chemistry Council (ACC)	EPA Clean Watershed Needs Survey (CWNS)
U.S. Department of Homeland Security	EPA Office of Research and Development (ORD)	American Iron and Steel Institute (AISI)	American Housing Survey
U.S. Department of Transportation - Federal Highway Administration	U.S. Fish and Wildlife Service	U.S. International Trade Commission (USITC)	Data from research studies, trade publications, and industry associations
U.S. Department of Transportation - Federal Aviation Administration	U.S. Department of Agriculture (USDA) Animal and Plant Health Inspection Service (APHIS)	Air-Conditioning, Heating, and Refrigeration Institute	
U.S. Department of Transportation & Bureau of Transportation Statistics	Association of American Plant Food Control Officials (AAPFCO)	Data from other U.S. government agencies, research studies, trade publications, and industry association	
U.S. Department of Labor – Mine Safety and Health Administration	National Oceanic and Atmospheric Administration (NOAA)	UNEP Technology and Economic Assessment Panel (TEAP)	
U.S. Department of Energy and its National Laboratories	EPA Office of Land and Emergency Management (OLEM)		
EPA Acid Rain Program	USDA Farm Service Agency		
EPA MOVES Model	U.S. Geological Survey (USGS)		
EPA Greenhouse Gas Reporting Program (GHGRP)	U.S. Department of the Interior (DOI) - Bureau of Land Management (BLM)		
U.S. Department of Labor – Mine Safety and Health Administration	EPA Office of Land and Emergency Management (OLEM)		
American Association of Railroads	Alaska Department of Natural Resources		
American Public Transportation Association	U.S. Department of Commerce – Bureau of the Census		
U.S. Department of Interior - Bureau of Ocean Energy Management	Data from research studies, trade publications, and industry associations		
Federal Energy Regulatory Commission			
Data from research studies, trade publications, and industry associations			

Note: This table is not an exhaustive list of all data sources.

1.3 Inventory Preparation Process

This section describes EPA's approach to preparing the annual U.S. *Inventory*, which includes both the National Inventory Document (NID) and Common Reporting Tables (CRTs). The inventory coordinator at EPA, with support from the cross-cutting compilation staff, is responsible for coordinating aggregation of all emission and removal estimates, conducting the overall uncertainty analysis of *Inventory* emissions and trends over time, and ensuring consistency and quality throughout the NID and CRTs. Emission and removal calculations, including associated uncertainty analysis for individual sources and/or sink categories are the responsibility of individual source and sink category leads, who are most familiar with each category, underlying data, and the unique national circumstances relevant to its emissions or removals profile. Using IPCC methodological decision trees and suggested good practice guidance, the individual leads determine the most appropriate methodology and collect the relevant activity data to use in the emission and removal calculations, based upon their expertise in the source or sink category, as well as coordinating with researchers and expert consultants familiar with the sources and sinks. Each year, the coordinator oversees a multi-stage process for collecting information from each individual source and sink category lead to compile all information and data for the *Inventory*.

Methodology Development, Data Collection, and Emissions and Sinks Estimation

Source and sink category leads at EPA coordinate the collection of input data (e.g., activity data and other information) and, as necessary, evaluate or develop the estimation methodology for the individual source and/or sink categories. Because EPA has been leading preparation of the *Inventory* for many years, for most source and sink categories, the methodology for the previous year is applied to the new "current" year of the *Inventory*, and inventory analysts collect any new data or update data that have changed from the previous year. If estimates for a new source or sink category are being developed for the first time, or if the methodology is changing for an existing category (e.g., the United States is implementing improvement efforts to apply a higher tiered approach for that category), then the source and/or sink category lead will develop and implement the new or refined methodology, gather the appropriate activity data and other information (e.g., emission factors or in some cases direct emission measurements) for the entire time series, and conduct any further category-specific review with involvement of relevant experts from industry, government, and universities (see Chapter 9 and Box ES-3 on EPA's approach to recalculations).

Once the methodology is in place and the data are collected, the individual source and sink category leads calculate emission and removal estimates. The individual leads then update or create the relevant national inventory document text and accompanying annexes for the *Inventory*. Source and sink category leads are also responsible for completing the relevant sectoral background tables of the CRTs, conducting quality control (QC) checks, preparing relevant category materials for QA, or expert reviews, category-level uncertainty assessments, and reviewing data for publication in EPA's GHG Data Explorer.[55]

The treatment of confidential business information (CBI) in the *Inventory* is based on EPA internal guidelines, as well as regulations[56] applicable to the data used. EPA has specific procedures in place to safeguard CBI during the inventory compilation process. When information derived from CBI data is used for development of inventory calculations, EPA procedures ensure that these confidential data are sufficiently aggregated to protect confidentiality while still providing useful information for analysis. For example, within the Energy and Industrial

[55] See https://cfpub.epa.gov/ghgdata/inventoryexplorer/.

[56] 40 CFR Part 2, Subpart B titled "Confidentiality of Business Information" which is the regulation establishing rules governing handling of data entitled to confidentiality treatment. See https://www.ecfr.gov/cgi-bin/text-idx?SID=a764235c9eadf9afe05fe04c07a28939&mc=true&node=sp40.1.2.b&rgn=div6.

Processes and Product Use (IPPU) sectors, EPA has used aggregated facility-level data from the Greenhouse Gas Reporting Program (GHGRP) to develop, inform, and/or quality-assure U.S. emission estimates. In 2014, EPA's GHGRP, with industry engagement, compiled criteria that would be used for aggregating its confidential data to shield the underlying CBI from public disclosure.[57] In the *Inventory*, EPA is publishing only data values that meet the GHGRP aggregation criteria.[58] Specific uses of aggregated facility-level data are described in the respective methodological sections within those chapters. In addition, EPA uses historical data reported voluntarily to EPA via various voluntary initiatives with U.S. industry (e.g., EPA Voluntary Aluminum Industrial Partnership (VAIP)) and follows guidelines established under the voluntary programs for managing CBI.

Data Compilation and Archiving

The inventory coordinator at EPA with support from the data/document manager collects the source and sink categories' descriptive text and annexes, and also aggregates the emission and removal estimates into a summary data file that links the individual source and sink category data files together. This summary data file contains all of the essential data in one central location, in formats commonly used in the *Inventory* document. In addition to the data from each source and sink category, other national trend and related data are also gathered in the summary sheet for use in the Executive Summary, Introduction, and Trends chapters of the *Inventory* report (e.g., GDP, population, energy use). Similarly, the recalculation analysis and key category analysis are completed in a separate data file based on output from the summary data file. The uncertainty estimates for each source and sink category are also aggregated into uncertainty summary data files that are used to conduct the overall *Inventory* uncertainty analysis (see Section 1.7). A Microsoft SharePoint work site, maintained within EPA's IT infrastructure by the inventory coordinator, provides a platform for facilitating collaboration on the national inventory report preparation during each compilation phase, but also the efficient storage and archiving of electronic document and data files each annual cycle. Previous final published inventories are also maintained on a report archive page on EPA's Greenhouse Gas Emissions website.[59]

National Inventory Document (NID) Preparation

The NID is compiled from the sections developed by each individual source or sink category lead. In addition, the inventory coordinator prepares a brief overview of each chapter that summarizes the emissions and removals from all sources and sinks discussed in the chapters. Also at this time, the Executive Summary, Introduction, Trends in Greenhouse Gas Emissions and Removals, and Recalculations and Improvements chapters are drafted, to reflect the trends and impact from improvements for the time series of the current *Inventory*. The analysis of trends necessitates gathering supplemental data, including annual climate, economic activity and gross domestic product, population, atmospheric conditions, and the annual use of electricity, energy, fossil and non-fossil fuels. Changes in these data are used to explain the trends observed in greenhouse gas emissions in the United States. Furthermore, specific factors that affect individual sectors are researched and discussed. Many of the factors that affect emissions are included in the *Inventory* document as separate analyses or side discussions in boxes within the text. Finally, the uncertainty analysis and key category analysis are compiled and updated in the report as part of final analysis steps. Throughout the report text boxes are also created to provide additional documentation (e.g., definitions) and/or examine the data aggregated in different ways than in the remainder of the document, such as a focus on transportation activities or emissions from electricity generation. The document is prepared to align with the Paris Agreement and UNFCCC reporting guidelines for National Inventory Reports while also reflecting national circumstances.

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[57] Federal Register Notice on "Greenhouse Gas Reporting Program: Publication of Aggregated Greenhouse Gas Data." See pp. 79 and 110 of notice at https://www.gpo.gov/fdsys/pkg/FR-2014-06-09/pdf/2014-13425.pdf.

[58] U.S. EPA Greenhouse Gas Reporting Program. Developments on Publication of Aggregated Greenhouse Gas Data, November 25, 2014. See http://www.epa.gov/ghgreporting/confidential-business-information-ghg-reporting.

[59] See https://www.epa.gov/ghgemissions/us-greenhouse-gas-inventory-report-archive.

Common Reporting Tables (CRTs) Compilation

The CRTs are compiled from individual time series input data sheets completed by each individual source or sink category lead, which contain emissions and/or removals and activity data, estimates, methodological and completeness notations and associated explanations. The inventory coordinator and cross-cutting compilation staff import the U.S. category and subcategory background data into the UNFCCC's Enhanced Transparency Framework Reporting Tools to export CRTs, assuring consistency and completeness across all sectoral tables. The summary reports for emissions and removals, methods, and emission factors used, the summary tables indicating completeness of estimates (i.e., notation key NE/IE tables), the recalculation tables, and the emission and removal trends tables are automatically compiled by the online reporting software and reviewed by the inventory coordinator with support from the cross-cutting compilation staff. Internal automated quality checks within the software, as well as checks by the cross-cutting and category leads, are completed for the entire time series of CRTs before submission.

QA/QC and Uncertainty

Quality assurance and quality control (QA/QC) and uncertainty analyses are guided by the QA/QC and inventory coordinators, who help maintain the QA/QC plan and the overall uncertainty analysis procedures (see sections on QA/QC and Uncertainty, below) in collaboration with the broader inventory compilation team. The QA/QC coordinator works closely with the Inventory coordinator and source and sink category leads to ensure that a consistent QA/QC plan is implemented across all inventory categories. Similarly, the inventory coordinator ensures the uncertainty analysis is implemented consistently across all categories. The inventory QA/QC plan, outlined in Section 1.6 and Annex 8, is consistent with the quality assurance procedures outlined by EPA and IPCC good practices. The QA/QC and uncertainty findings also inform overall improvement planning, and specific improvements are noted in the Planned Improvements sections of respective categories. QA processes are outlined below.

Expert, Public, and UNFCCC/Paris Reviews

The compilation of the *Inventory* includes a two-stage review or QA process, in addition to international technical expert review following submission of the report under the UNFCCC and Paris Agreement. EPA publishes responses to comments received during both expert and public reviews with the publication of the final report on its website.[60] Responses to UNFCCC and Paris reviews are included in Annex 8 of this document.

During the first stage of review, i.e., the 30-day expert review period, a first draft of updated sectoral chapters are sent to technical experts who are not directly involved in preparing estimates. The purpose of the expert review is to provide an objective review of the methodological approaches and data sources used in the current *Inventory*, especially for sources and sinks which have experienced any changes since the previous *Inventory*. Expert review follows good practices from EPA's Peer Review handbook, i.e., the review is organized by sector, and reviewers are provided a guidance memo and charge questions to facilitate their review.[61] Expert reviewers include other federal agency staff, researchers, industry experts, and others who have technical knowledge of the data, industry, and methods. EPA reviews and updates expert participation and outreach on an annual basis prior to each expert review cycle. Experts are identified in various ways; for example, many reach out to EPA with technical feedback and are added to the expert reviewer list. Reviewers are also identified through direct outreach by inventory staff based on expertise. Currently, EPA's expert list includes nearly 300 experts across all sectors. Once comments are received, they are reviewed by the source or sink lead and addressed in several ways. For example, comments suggesting methodological clarifications may be incorporated into methodological discussions prior to the next

[60] See https://www.epa.gov/ghgemissions/draft-inventory-us-greenhouse-gas-emissions-and-sinks-1990-2022.

[61] See https://www.epa.gov/osa/peer-review-handbook-4th-edition-2015.

review phase, while comments citing new literature or data will be noted for review as part of planned improvements.

Following expert review, a second draft of the document, including cross-cutting synthesis chapters, is released for a 30-day public review through a notice in the U.S. Federal Register. The entire draft *Inventory* document is published on the EPA website. The public review period is open to the entire U.S. public. Comments are submitted and tracked using an online electronic docket that is accessible to the general public as well. Similar to expert review, some comments received may require further discussion with commenters, other experts and/or additional research. Specific *Inventory* improvements requiring further analysis as a result of comments are noted in the relevant category's Planned Improvement section.

As mentioned above, following completion and submission of the report under the UNFCCC and the Paris Agreement, the report also undergoes review by an international team of independent experts for adherence to UNFCCC/Paris reporting guidelines and consistency with IPCC methodological guidance.[62] Feedback from all review processes that contribute to improving inventory quality over time are described within each planned improvement section and further in Annex 8. See also the Improvement Planning process discussed below.

Final Submittal and Publication under the Paris Agreement and the UNFCCC

After the final revisions to incorporate any comments from the Expert Review and Public Review periods, EPA prepares the final NIR, which includes the NID and the accompanying CRTs for electronic reporting. Prior to submission, EPA's Office of Atmospheric Protection briefs senior leadership on reporting findings and improvements since the previous report, along with an overview of feedback from the expert and public review processes.

EPA, as the National Inventory Focal Point, sends the official submission of the U.S. *Inventory* under the Paris Agreement and the UNFCCC using the UN's reporting software, coordinating with the U.S. Department of State, the overall UNFCCC focal point. Concurrently, the report is also published on EPA's website.[63] On EPA's website, users can also visualize and download the current time-series estimates from the GHG Inventory Data Explorer Tool,[64] and also download more detailed data presented in tables within the report and report annex in CSV format.

Improvement Planning

Each year, several emission and sink estimates in the *Inventory of U.S. Greenhouse Gas Emissions and Sinks* are recalculated and revised, through the use of better methods and/or data with the goal of improving inventory quality and reducing uncertainties, including the transparency, completeness, consistency, and overall usefulness of the report. In this effort, the United States follows the *2006 IPCC Guidelines* (IPCC 2006) and its *2019 Refinement*, which state, "Both methodological changes and refinements over time are an essential part of improving inventory quality. It is *good practice* to change or refine methods when available data have changed; the previously used method is not consistent with the IPCC guidelines for that category; a category has become key; the previously used method is insufficient to reflect mitigation activities in a transparent manner; the capacity for inventory preparation has increased; improved inventory methods become available; and/or for correction of errors." The EPA's OAP coordinates improvement planning across all sectors and also cross-cutting analyses based on annual review and input from the technical teams leading compilation of each sector's estimates, including

[62] See https://unfccc.int/process-and-meetings/transparency-and-reporting/reporting-and-review-under-the-convention/greenhouse-gas-inventories-annex-i-parties/review-process.

[63] See https://www.epa.gov/ghgemissions/inventory-us-greenhouse-gas-emissions-and-sinks.

[64] See https://cfpub.epa.gov/ghgdata/inventoryexplorer/.

continuous improvements to the overall data and document compilation and QA/QC processes. Planned improvements are identified through QA/QC processes (including completeness checks), the key category analysis, and the uncertainty analysis. The inventory coordinator, with input from EPA source and sink category leads, maintains a log of all planned improvements, by sector and cross-cutting, tracking the category significance, specific category improvement, prioritization, anticipated time frame for implementation of each proposed improvement, and status of progress in implementing improvement. Improvements for significant or key categories are usually prioritized across all improvements unless effort would require disproportionate levels of effort and resources relative to improvements for other key categories to address.

1.4 Methodology and Data Sources

Emissions and removals of greenhouse gases from various source and sink categories have been estimated using methodologies that are consistent with the *2006 IPCC Guidelines for National Greenhouse Gas Inventories* (IPCC 2006) and its supplements and refinements. To a great extent, this report makes use of published official economic and physical statistics for activity data, emission factors and other key parameters as inputs to the methods applied. Depending on the category, activity data can include fuel consumption or deliveries, vehicle-miles traveled, raw material processed, or commodity produced, etc. Emission factors are factors that relate quantities of emissions to an activity. For more information on data sources see Section 1.2 above, Box 1-1 on use of GHGRP data, and categories' methodology sections for more information on other data sources. In addition to official statistics, the report utilizes findings from academic studies, trade association surveys and statistical reports, along with expert judgment, consistent with the *2006 IPCC Guidelines*.

The methodologies provided in the *2006 IPCC Guidelines* represent foundational methodologies for a variety of source and sink categories, and many of these methodologies continue to be improved and refined as new research and data become available. This report uses those IPCC methodologies when applicable, and supplements them with refined guidance, other available country-specific methodologies and data where possible (e.g., EPA's GHGRP). For example, as noted earlier in this chapter, this report does apply recent supplements and refinements to *2006 IPCC Guidelines* in estimating emissions and removals from coal mining, wastewater treatment and discharge, low voltage anode effects (LVAE) during aluminum production, drained organic soils, and management of wetlands, including flooded lands. Choices made regarding the methodologies and data sources used are provided in the Methodology and Time-Series Consistency discussion of each category within each sectoral chapter of the report, applying higher tiered methods when feasible, especially for key categories consistent with methodological decision trees. Where additional detail is helpful and necessary to explain methodologies and data sources used to estimate emissions, complete documentation is provided in the annexes as indicated in the methodology sections of those respective source categories (e.g., Annex 3.13 for forest land remaining forest land and land converted to forest land). Methods used for key categories (discussed below) are summarized in Annex 1.

1.5 Key Categories

The *2006 IPCC Guidelines* (IPCC 2006) and *2019 Refinement to the 2006 IPCC Guidelines* (IPCC 2019) define key categories as "inventory categories which individually, or as a group of categories (for which a common method, emission factor and activity data are applied) are prioritized within the national inventory system because their estimates have a significant influence on a country's total inventory of greenhouse gases in terms of the absolute level, the trend, or the level of uncertainty in emissions or removals. Whenever the term *key category* is used, it

includes both source and sink categories."[65] A key category analysis identifies source or sink categories for focusing efforts to improve overall Inventory quality, including additional review when feasible.

The *2006 IPCC Guidelines* (IPCC 2006) and its *2019 Refinement* (2019) define several approaches, both quantitative and qualitative, to conduct a key category analysis and identify key categories both in terms of absolute level and trend, along with consideration of uncertainty. This report employs all approaches to identify key categories for the United States. The first approach, Approach 1, identifies significant or key categories without considering uncertainty in its calculations. An Approach 1 level assessment identifies all source and sink categories that cumulatively account for 95 percent of total level, i.e., total emissions (gross) in a given year when assessed in descending order of absolute magnitude. The level analysis was performed twice, including and excluding sources and sinks from the land use, land-use change, and forestry (LULUCF) sector categories. Similarly, an Approach 1 trend analysis can identify categories with trends that significantly influence overall trends by identifying all source and sink categories that cumulatively account for 95 percent of the sum all the trend assessments (e.g., percent change relative to national trend) when sorted in descending order of absolute magnitude.

The next method, Approach 2, was then implemented to identify any additional key categories not already identified from the Approach 1 level and trend assessments by considering uncertainty. The Approach 2 analysis differs from Approach 1 by incorporating each category's uncertainty assessments in its calculations and was also performed twice, including and excluding LULUCF categories. An Approach 2 level assessment identifies all sources and sink categories that cumulatively account for 90 percent of the sum of all level assessments when sorted in descending order of magnitude. Similarly, an Approach 2 trend analysis can identify categories whose trends contribute significantly to overall trends weighing the relative trend difference with the category's relative uncertainty assessment for 2022.

For 2022, based on the key category analysis, excluding the LULUCF sector and uncertainty, 34 categories accounted for 95 percent of emissions. Four categories account for 55 percent of emissions: CO_2 from road transport-related fuel combustion, CO_2 from coal-fired electricity generation, CO_2 from gas fired electricity generation, and CO_2 from gas-fired industrial processes. When considering uncertainties, additional categories such as emissions from substitutes for ozone depleting substances in aerosols were also identified as a key category. In the trend analysis, 32 categories were identified as key categories, and when considering uncertainties, 7 additional categories were identified as key. The trend analysis shows that CO_2 emissions from coal-fired electricity generation, in addition to CO_2 from gas fired electricity generation, CO_2 from road transport related combustion, and HFC and PFC emissions from substitutes for ozone depleting substances in the refrigeration and air conditioning sector are also significant with respect to trends over the time series.

When considering the contribution of the LULUCF sector to 2022 emissions and removals, 42 categories accounted for 95 percent of emissions and sinks, with the most significant category from LULUCF being net CO_2 emission from forest land remaining forest land. When considering uncertainties and the contribution of the LULUCF sector, additional categories such as net CO_2 emissions from grassland remaining grassland were also identified as a key category. In the trend analysis, 40 categories were identified as key, and when considering uncertainties, 2 additional categories were identified as key.

Finally, in addition to conducting Approach 1 and 2 level and trend assessments as described above, a qualitative assessment of the source and sinks categories was conducted to capture any additional key categories that were not identified using the previously described quantitative approaches. For this *Inventory*, no additional categories were identified using qualitative criteria recommend by IPCC, but EPA continues to review its qualitative assessment on an annual basis. Find more information on the key category analysis, including the approach to disaggregation of inventory estimates, see Annex 1 to this report.

[65] See Chapter 4 Volume 1, "Methodological Choice and Identification of Key Categories" in IPCC (2006) and IPCC (2019). See http://www.ipcc-nggip.iges.or.jp/public/2006gl/index.html.

Table 1-4: Summary of Key Categories for the United States (1990 and 2022) by Sector

CRT Code and Source/Sink Category	Greenhouse Gas	Approach 1[a]				Approach 2 (includes uncertainty)[a]				2022 Emissions (MMT CO_2 Eq.)
		Level Without LULUCF	Trend Without LULUCF	Level With LULUCF	Trend With LULUCF	Level Without LULUCF	Trend Without LULUCF	Level With LULUCF	Trend With LULUCF	
Energy										
1.A.3.b Transportation: Road	CO_2	◉	•	◉	•	◉	•	◉	•	1,438.1
1.A.1 Stationary Combustion - Coal - Electricity Generation	CO_2	◉	•	◉	•	◉	•	◉	•	851.5
1.A.1 Stationary Combustion - Natural Gas - Electricity Generation	CO_2	◉	•	◉	•	◉	•		•	659.3
1.A.2 Stationary Combustion - Natural Gas - Industrial	CO_2	◉	•	◉	•	◉	•	◉	•	510.4
1.A.4.b Stationary Combustion - Natural Gas - Residential	CO_2	◉	•	◉	•	◉	•	◉		272.0
1.A.2 Stationary Combustion - Oil - Industrial	CO_2	◉	•	◉	•	◉	•	◉	•	247.6
1.A.4.a Stationary Combustion - Natural Gas - Commercial	CO_2	◉	•	◉	•	◉	•	•	•	192.3
1.A.3.a Transportation: Aviation	CO_2	◉	•	◉	•	◉		◉		165.6
1.A.5 Non-Energy Use of Fuels	CO_2	◉		◉		◉	•	◉		102.8
1.A.3.e Transportation: Other	CO_2	◉	•	◉	•		•			69.3
1.A.4.a Stationary Combustion - Oil - Commercial	CO_2	◉	•	◉	•					65.1
1.A.4.b Stationary Combustion - Oil - Residential	CO_2	◉	•	◉	•					62.1

CRT Code and Source/Sink Category	Greenhouse Gas	Approach 1[a]				Approach 2 (includes uncertainty)[a]				2022 Emissions (MMT CO_2 Eq.)
		Level Without LULUCF	Trend Without LULUCF	Level With LULUCF	Trend With LULUCF	Level Without LULUCF	Trend Without LULUCF	Level With LULUCF	Trend With LULUCF	
1.A.2 Stationary Combustion - Coal - Industrial	CO_2	◉	•	◉	•	◉	•	○	•	43.0
1.A.3.d Transportation: Domestic Navigation	CO_2	◉		◉						40.9
1.B.2 Natural Gas Systems	CO_2	◉		◉						36.5
1.A.3.c Transportation: Railways	CO_2	◉		◉						32.5
1.B.2 Petroleum Systems	CO_2	•	•	•	•		•		•	22.0
1.A.1 Stationary Combustion - Oil - Electricity Generation	CO_2	◉	•	◉	•	○	•		•	20.5
1.A.5 Stationary Combustion - Oil - U.S. Territories	CO_2	○		○						17.0
1.A.5.b Transportation: Military	CO_2		•		•					4.8
1.A.4.a Stationary Combustion - Coal - Commercial	CO_2		•		•					1.4
1.A.4.b Stationary Combustion - Coal - Residential	CO_2						•			NO
1.B.2 Natural Gas Systems	CH_4	◉	•	◉	•	◉	•	◉	•	173.1
1.B.1 Fugitive Emissions from Coal Mining	CH_4	◉	•	◉	•	◉	•	◉	•	43.6
1.B.2 Petroleum Systems	CH_4	◉	•	◉	•	◉	•	◉		39.6
1.B.2 Abandoned Oil and Natural Gas Wells	CH_4					◉		◉		8.5
1.A.4.b Stationary Combustion - Residential	CH_4					◉	•	◉	•	4.3
1.A.1 Stationary Combustion - Coal - Electricity Generation	N_2O					◉		•		18.2
1.A.3.b Transportation: Road	N_2O	○	•	○	•					8.9

CRT Code and Source/Sink Category	Greenhouse Gas	Approach 1[a]				Approach 2 (includes uncertainty)[a]				2022 Emissions (MMT CO_2 Eq.)
		Level Without LULUCF	Trend Without LULUCF	Level With LULUCF	Trend With LULUCF	Level Without LULUCF	Trend Without LULUCF	Level With LULUCF	Trend With LULUCF	
1.A.1 Stationary Combustion - Natural Gas - Electricity Generation	N_2O						•			3.4
Industrial Processes and Product Use										
2.A.1 Cement Production	CO_2	◉		◉	•					41.9
2.C.1 Iron and Steel Production & Metallurgical Coke Production	CO_2	◉	•	◉	•	◉	•	○	•	40.7
2.B.8 Petrochemical Production	CO_2	◉	•	◉	•					28.8
2.B.3 Adipic Acid Production	N_2O		•		•					2.1
2.F.1 Substitutes for Ozone Depleting Substances: Refrigeration and Air Conditioning	HFCs, PFCs	•	•	•	•	•	•	•	•	144.6
2.F.4 Substitutes for Ozone Depleting Substances: Aerosols	HFCs, PFCs		•		•	•	•	•	•	17.0
2.F.2 Substitutes for Ozone Depleting Substances: Foam Blowing Agents	HFCs, PFCs		•		•					11.7
2.B.9 Fluorochemical Production	PFCs, HFCs, SF_6, NF_3	○	•	○	•	○	•	○	•	7.8
2.G Electrical Equipment	PFCs, SF_6	○	•	○	•		•		•	5.1
2.C.3 Aluminum Production	PFCs	○	•	○	•					0.8
Agriculture										
3.A.1 Enteric Fermentation: Cattle	CH_4	◉	•	◉	•	◉	•	◉	•	185.9
3.B.1 Manure Management: Cattle	CH_4	•	•	•	•	•	•		•	37.7
3.B.4 Manure Management: Other Livestock	CH_4	◉		◉		•				27.0
3.C Rice Cultivation	CH_4	◉		•		◉		◉		18.9

CRT Code and Source/Sink Category	Greenhouse Gas	Approach 1[a]				Approach 2 (includes uncertainty)[a]				2022 Emissions (MMT CO_2 Eq.)
		Level Without LULUCF	Trend Without LULUCF	Level With LULUCF	Trend With LULUCF	Level Without LULUCF	Trend Without LULUCF	Level With LULUCF	Trend With LULUCF	
3.D.1 Direct Emissions from Agricultural Soil Management	N_2O	◉		◉		◉		◉		262.5
3.D.2 Indirect Emissions from Applied Nitrogen	N_2O	◉		◉		◉	•	◉		28.3
Waste										
5.A Commercial Landfills	CH_4	◉	•	◉	•	◉	•	◉	•	100.9
5.A Industrial Landfills	CH_4	•		•		•	•			18.9
5.D Domestic Wastewater Treatment	CH_4					○				13.6
5.D Domestic Wastewater Treatment	N_2O	•		•		◉	•	◉	•	21.4
Land Use, Land-Use Change, and Forestry										
4.E.2 Net Emissions from Land Converted to Settlements	CO_2			◉	•			◉	•	68.2
4.B.2 Net Emissions from Land Converted to Cropland	CO_2			◉	•			◉	•	35.1
4.C.2 Net Emissions from Land Converted to Grassland	CO_2			◉	•			◉	•	25.6
4.C.1 Net Emissions from Grassland Remaining Grassland	CO_2			○	•			◉	•	13.4
4.B.1 Net Removals from Cropland Remaining Cropland	CO_2			•	•			◉	•	(31.7)
4.A.2 Net Removals from Land Converted to Forest Land	CO_2			◉				◉		(100.3)
4.E.1 Net Removals from Settlements Remaining Settlements	CO_2			◉	•			◉	•	(134.8)

CRT Code and Source/Sink Category	Greenhouse Gas	Approach 1[a]				Approach 2 (includes uncertainty)[a]				2022 Emissions (MMT CO_2 Eq.)
		Level Without LULUCF	Trend Without LULUCF	Level With LULUCF	Trend With LULUCF	Level Without LULUCF	Trend Without LULUCF	Level With LULUCF	Trend With LULUCF	
4.A.1 Net Removals from Forest Land Remaining Forest Land	CO_2			◉	•			◉	•	(787.0)
4.D.1 Flooded Lands Remaining Flooded Lands	CH_4			◉						44.2
Subtotal of Key Categories Without LULUCF[b]										**6,169.7**
Total Gross Emissions Without LULUCF										**6,343.2**
Percent of Gross Total Without LULUCF										**97%**
Subtotal of Key Categories With LULUCF[c]										**5,285.4**
Total Net Emissions With LULUCF										**5,488.9**
Percent of Net Total With LULUCF										**96%**

NO (Not Occurring)

[a] Symbols correspond to the year(s) in which a category is key: 1990 = ○; 2022 = •; 1990 and 2022 = ◉.

[b] Subtotal includes key categories from Level Approach 1 Without LULUCF, Level Approach 2 Without LULUCF, Trend Approach 1 Without LULUCF, and Trend Approach 2 Without LULUCF.

[c] Subtotal includes key categories from Level Approach 1 With LULUCF, Level Approach 2 With LULUCF, Trend Approach 1 With LULUCF, and Trend Approach 2 With LULUCF.

Note: Parentheses indicate negative values (or sequestration).

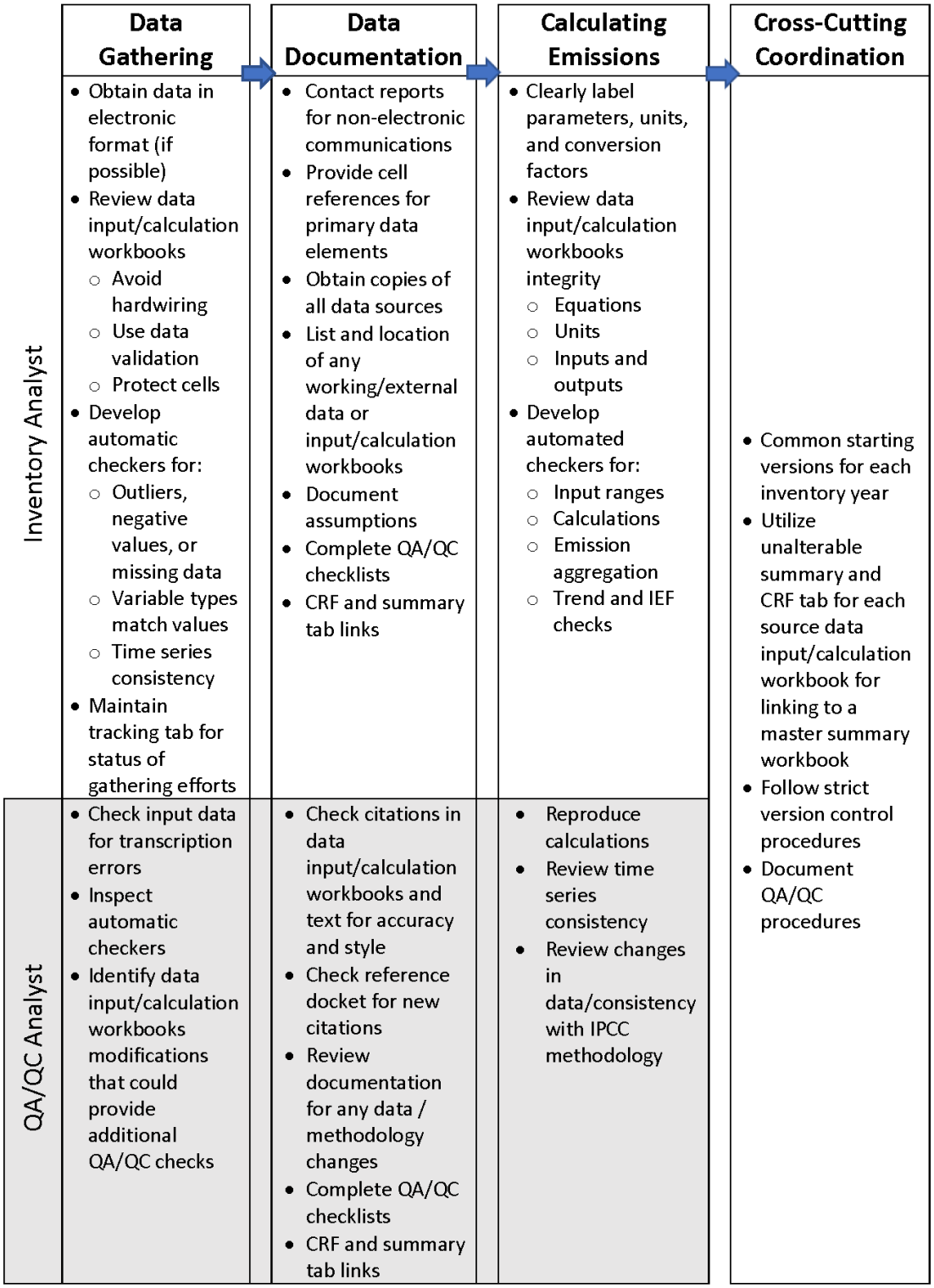
1.6 Quality Assurance and Quality Control (QA/QC)

As part of efforts to achieve its stated goals for inventory quality, transparency, and credibility, the United States has developed a quality assurance and quality control plan designed to check, document, and improve the quality of its inventory over time. QA/QC activities on the *Inventory* are undertaken within the framework of the U.S. *Quality Assurance/Quality Control and Uncertainty Management Plan* (QA/QC plan) *for the U.S. Greenhouse Gas Inventory: Procedures Manual for QA/QC and Uncertainty Analysis*.

Key attributes of the QA/QC plan are summarized in Figure 1-2. These attributes include:

- *Procedures and Forms:* detailed and specific systems that serve to standardize the process of documenting and archiving QA/QC implementation and related information, as well as to guide the implementation of QA/QC and the analysis of uncertainty
- *Implementation of Procedures:* guidance on application of QA/QC procedures throughout the whole Inventory development process from initial data collection, through preparation of the emission and removal estimates, to publication of the *Inventory,* consistent with the *2006 IPCC Guidelines*.
- *Quality Assurance (QA):* process for implementing expert and public reviews for both the inventory estimates and the Inventory report (which is the primary vehicle for disseminating the results of the inventory development process). The expert technical review conducted by the UNFCCC supplements these QA processes, consistent with the QA good practice and the *2006 IPCC Guidelines* (IPCC 2006). See Section 1.3 for more details on these QA processes.
- *Quality Control (QC)*: application of *General (Tier 1) and Category-specific (Tier 2)* quality controls and checks, as recommended by *2006 IPCC Guidelines* (IPCC 2006), along with consideration of secondary data and category-specific checks (additional Tier 2 QC) in parallel and coordination with the uncertainty assessment; the development of protocols and templates, which provides for more structured communication and integration with the suppliers of secondary information
- *General (Tier 1) and Category-specific (Tier 2) Checks:* quality controls and checks, as recommended by *IPCC Good Practice Guidance* and *2006 IPCC Guidelines* (IPCC 2006)
- *Record Keeping:* provisions to track which procedures have been followed, the results of the QA/QC, uncertainty analysis, and feedback mechanisms for corrective action based on the results of the investigations which provide for continual data quality improvement and guided research efforts moving forward.
- *Multi-Year Implementation*: tracking the application of more involved QA/QC procedures which may take more than one cycle to fully implement, especially for category-specific QC, prioritizing key categories in conjunction with improvement planning (see Section 1.3).
- *Interaction and Coordination:* promoting communication within the EPA, across federal agencies and departments, state government programs, and research institutions and consulting firms involved in supplying data or preparing estimates for the *Inventory*. The QA/QC Management Plan itself is intended to be revised and reflect new information that becomes available as the program develops, methods are improved, or additional supporting documents become necessary.

Figure 1-2: Summary of Key QC Processes from U.S. QA/QC Plan



Box 1-3: Examples of Verification Activities

Consistent with IPCC guidance for national greenhouse gas inventories, verification activities include comparisons with emission or removal estimates prepared by other bodies and comparisons with estimates derived from fully independent assessments, e.g., atmospheric concentration measurements. Verification activities provide information to improve inventories and are part of the overall QA/QC system.

Use of Lower Tier Methods. The Paris Agreement/UNFCCC reporting guidelines require countries to complete a "top-down" reference approach for estimating CO_2 emissions from fossil fuel combustion in addition to their "bottom-up" sectoral methodology for purposes of verification. This estimation method uses alternative methodologies and different data sources than those contained in that section of the Energy chapter. The reference approach estimates fossil fuel consumption by adjusting national aggregate fuel production data for imports, exports, and stock changes rather than relying on end-user consumption surveys (see Annex 4 of this report). The reference approach assumes that once carbon-based fuels are brought into a national economy, they are either saved in some way (e.g., stored in products, kept in fuel stocks, or left unoxidized in ash) or combusted, and therefore the carbon in them is oxidized and released into the atmosphere. Accounting for actual consumption of fuels at the sectoral or sub-national level is not required.

Use of Ambient Measurements Systems for Validation of Emission Inventories. In following the Paris Agreement and UNFCCC reporting requirements to develop and submit national greenhouse gas emission inventories, the emissions and sinks presented in this report are organized by source and sink categories and calculated using internationally accepted methods provided by the IPCC.[66] Several recent studies have estimated emissions at the national or regional level with estimated results that sometimes differ from EPA's estimate of emissions. EPA has engaged with researchers on how remote sensing, ambient measurement, and inverse modeling techniques for estimating greenhouse gas emissions could assist in improving the understanding of inventory estimates. In working with the research community to improve national greenhouse gas inventories, EPA follows guidance from the IPCC on the use of measurements and modeling to validate emission inventories.[67] An area of particular interest in EPA's outreach efforts is how ambient measurement data can be used to assess estimates or potentially be incorporated into the *Inventory* in a manner consistent with this *Inventory* report's transparency of its calculation methodologies, and the ability of inverse modeling to attribute emissions and removals from remote sensing to anthropogenic sources, as defined by the IPCC for this report, versus natural sources and sinks.

The *2019 Refinement to the IPCC 2006 Guidelines for National Greenhouse Gas Inventories* (IPCC 2019) Volume 1 General Guidance and Reporting, Chapter 6: Quality Assurance, Quality Control and Verification notes that emission estimates derived from atmospheric concentration measurements can provide independent data sets as a basis for comparison with inventory estimates. The *2019 Refinement* provides guidance on conducting such comparisons (as summarized in Table 6.2 of IPCC [2019] Volume 1, Chapter 6) and provides guidance on using such comparisons to identify areas of improvement in national inventories (as summarized in Box 6.5 of IPCC [2019] Volume 1, Chapter 6). Further, it identified fluorinated gases as particularly suitable for such comparisons due their limited natural sources, their generally long atmospheric lifetimes, and well-understood loss mechanisms, which makes it relatively more straightforward to model their emission fluxes from observed mass quantities. Unlike emissions of CO_2, CH_4, and N_2O, emissions of fluorinated greenhouse gases are almost exclusively anthropogenic, meaning that the fluorinated greenhouse gas emission sources included in this Inventory account for the majority of the total U.S. emissions of these gases detectable in the atmosphere. This evaluation approach is also useful for gases and sources with larger uncertainties in available bottom-up inventory methods and data, such as emissions of CH_4, which are primarily from uncertain biological (e.g., enteric fermentation) and fugitive (e.g., natural gas production) activities.

In this *Inventory*, EPA includes the results from current and previous comparisons between fluorinated gas

[66] See http://www.ipcc-nggip.iges.or.jp/public/index.html.

[67] See http://www.ipcc-nggip.iges.or.jp/meeting/pdfiles/1003_Uncertainty%20meeting_report.pdf.

emissions inferred from atmospheric measurements and fluorinated gas emissions estimated based on bottom-up measurements and modeling. These comparisons, performed for HFCs and SF_6 respectively, are described under the QA/QC and Verification discussions in Chapter 4, Sections 4.25 Substitution of Ozone Depleting Substances and 4.26 Electrical Equipment in the IPPU chapter of this report.

Consistent with the *2019 Refinement*, a key element to facilitate such comparisons is a spatially-explicit (or gridded) emissions inventory as an input to inverse modeling. To improve the ability to compare methane emissions from the national-level greenhouse gas inventory with observation-based emission estimates, a team of researchers from U.S. EPA, SRON Netherlands Institute for Space Research, Harvard University, and Lawrence Berkely National Laboratory developed a time series of annual anthropogenic methane emissions maps with 0.1° x 0.1° (~10km x 10km) spatial resolution and monthly temporal resolution for the contiguous United States.[68] The gridded methane inventory is designed to be consistent with the *U.S. EPA Inventory of U.S. Greenhouse Gas Emissions and Sinks* estimates, which presents national totals for different source types.[69] The development of this gridded inventory is consistent with the recommendations contained in two National Academies of Science reports examining greenhouse gas emissions data (National Research Council 2010; National Academies of Sciences, Engineering, and Medicine 2018).

Finally, in addition to use of atmospheric concentration measurement data for comparison with Inventory data, information from top-down studies is directly incorporated in the Natural Gas Systems calculations to quantify emissions from certain well blowout events.

In addition, based on the national QA/QC plan for the *Inventory*, some sector, subsector and category-specific QA/QC and verification checks have been applied. These checks follow the procedures outlined in the national QA/QC plan, tailoring the procedures to the specific documentation and data files associated with individual sources. For each greenhouse gas emissions source or sink category included in this *Inventory*, a minimum of general or Tier 1 QC analysis has been undertaken. Where QC activities for a particular category go beyond the minimum general checks and include category-specific checks (Tier 2) or include verification, further explanation is provided within the respective source or sink category text. Similarly, responses or updates based on comments from the expert, public and the international technical expert reviews (e.g., UNFCCC) are also addressed within the respective source or sink category sections in each sectoral chapter and Annex 8.

The quality control activities described in the U.S. QA/QC plan occur throughout the inventory process; QA/QC is not separate from, but is an integral part of, preparing the *Inventory*. Quality control—in the form of both good practices (such as documentation procedures) and checks on whether good practices and procedures are being followed—is applied at every stage of inventory development and document preparation. In addition, quality assurance occurs during the expert review and the public review, in addition to the UNFCCC expert technical review. While all phases significantly contribute to improving inventory quality, the public review phase is also essential for promoting the openness of the inventory development process and the transparency of the inventory methods and underlying input data sources.

The QA/QC plan guides the process of ensuring inventory quality by describing data and methodology checks, developing processes governing peer review and public comments, and developing guidance on conducting an analysis of the uncertainty surrounding the emission and removal estimates. The QA/QC procedures also include feedback loops and provide for corrective actions that are designed to improve the inventory estimates over time.

[68] See https://www.epa.gov/ghgemissions/us-gridded-methane-emissions.

[69] See https://www.epa.gov/ghgemissions/inventory-us-greenhouse-gas-emissions-and-sinks.

1.7 Uncertainty Analysis

Emissions and removals calculated for the U.S. Inventory reflect best estimates for greenhouse gas source and sink categories in the United States and are continuously revised and improved as new information becomes available. Uncertainty assessment is an essential element of a complete and transparent emissions inventory because it helps inform and prioritize Inventory improvements. For the U.S. Inventory, uncertainty analyses are conducted for each source and sink category as well as for the uncertainties associated with the overall emission (current and base year) and trends estimates. These analyses reflect the quantitative uncertainty in the emission (and removal) estimates associated with uncertainties in their input parameters (e.g., activity data and EFs) and serve to evaluate the relative contribution of individual input parameter uncertainties to the overall Inventory, its trends, and each source and sink category.

The overall level and trend uncertainty estimates for total U.S. greenhouse gas emissions was developed using the IPCC Approach 2 uncertainty estimation methodology (assuming a Normal distribution for Approach 1 estimates), which employs a Monte Carlo stochastic simulation technique. The IPCC provides good practice guidance on two approaches—Approach 1 and Approach 2—to estimating uncertainty for both individual and combined source categories. Approach 2 quantifies uncertainties based on a distribution of emissions (or removals), built-up from repeated calculations of emission estimation models and the underlying input parameters, randomly selected according to their known distributions. Approach 2 methodology is applied to each individual source and sink category wherever data and resources are permitted and is also used to quantify the uncertainty in the overall Inventory and its Trends. Source and sink chapters in this report provide additional details on the uncertainty analysis conducted for each source and sink category. See Annex 7 of this report for further details on the U.S. process for estimating uncertainty associated with the overall emission (base and current year) and trends estimates. Consistent with IPCC (IPCC 2006), the United States has ongoing efforts to continue to improve the overall Inventory uncertainty estimates presented in this report.

The United States has also implemented many improvements over the last several years to reduce uncertainties across the source and sink categories and improve Inventory estimates. These improvements largely result from new data sources that provide more accurate data and/or increased data coverage, as well as methodological improvements. Following IPCC good practice, additional efforts to reduce Inventory uncertainties can occur through efforts to incorporate excluded emission and sink categories (see Annex 5), improve estimation methods, and collect more detailed, measured, and representative data. Individual category chapters and Annex 7 both describe current ongoing and planned Inventory and uncertainty analysis improvements. Consistent with IPCC (2006), the United States has ongoing efforts to continue to improve the category-specific uncertainty estimates presented in this report, largely prioritized by considering improvements categories identified as significant by the Key Category Analysis.

Estimates of quantitative uncertainty for the total U.S. greenhouse gas emissions in 1990 (base year) and 2022 are shown below in Table 1-5 and Table 1-6, respectively. The overall uncertainty surrounding the Total Net Emissions is estimated to be -6 to +6 percent in 1990 and -5 to +6 percent in 2022. When the LULUCF sector is excluded from the analysis the uncertainty is estimated to be -3 to +4 percent in 1990 and -2 to +4 percent in 2022.

Table 1-5: Estimated Overall Inventory Quantitative Uncertainty for 1990 (MMT CO_2 Eq. and Percent)

Gas	1990 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Greenhouse Gas Estimate[a] (MMT CO_2 Eq.)		Uncertainty Range Relative to Greenhouse Gas Estimate[a] (%)		Mean[b] (MMT CO_2 Eq.)	Standard Deviation[b] (MMT CO_2 Eq.)
		Lower Bound[c]	Upper Bound[c]	Lower Bound	Upper Bound		
CO_2	5,131.6	5,008.2	5,348.2	-2%	4%	5,098.2	88.0
CH_4[d]	871.7	731.3	948.4	-16%	9%	701.5	56.3
N_2O[d]	408.2	349.7	513.0	-14%	26%	434.8	41.6
PFC, HFC, SF_6, and NF_3[d]	125.5	108.6	152.9	-13%	22%	207.3	11.6
Total Gross Emissions	**6,536.9**	**6,354.3**	**6,792.8**	**-3%**	**4%**	**6,441.8**	**113.3**
LULUCF Emissions[e]	57.9	55.2	61.9	-5%	7%	68.7	1.7
LULUCF Carbon Stock Change Flux[f]	(1,034.7)	(1,296.1)	(845.3)	25%	-18%	(957.3)	116.7
LULUCF Sector Net Total[g]	**(976.7)**	**(1,237.7)**	**(787.8)**	**27%**	**-19%**	**(888.6)**	**116.7**
Net Emissions (Sources and Sinks)	**5,560.2**	**5,247.0**	**5,882.2**	**-6%**	**6%**	**5,553.3**	**161.4**

[a] The lower and upper bounds for emission estimates correspond to a 95 percent confidence interval, with the lower bound corresponding to 2.5th percentile and the upper bound corresponding to 97.5th percentile.

[b] Mean value indicates the arithmetic average of the simulated emission estimates; standard deviation indicates the extent of deviation of the simulated values from the mean.

[c] The lower and upper bound emission estimates for the sub-source categories do not sum to total emissions because the low and high estimates for total emissions were calculated separately through simulations.

[d] The overall uncertainty estimates did not take into account the uncertainty in the GWP values for CH_4, N_2O and high GWP gases used in the Inventory emission calculations for 1990.

[e] LULUCF emissions include the CH_4 and N_2O emissions reported for peatlands remaining peatlands, forest fires, drained organic soils, grassland fires, and coastal wetlands remaining coastal wetlands; CH_4 emissions from land converted to coastal wetlands, land converted to flooded land, and flooded land remaining flooded land; and N_2O emissions from forest soils and settlement soils.

[f] LULUCF carbon stock change is the net C stock change from the following categories: forest land remaining forest land, land converted to forest land, cropland remaining cropland, land converted to cropland, grassland remaining grassland, land converted to grassland, wetlands remaining wetlands, land converted to wetlands, settlements remaining settlements, and land converted to settlements. Since the resulting flux is negative the signs of the resulting lower and upper bounds are reversed.

[g] The LULUCF sector net total is the net sum of all CH_4 and N_2O emissions to the atmosphere plus net carbon stock changes.

Notes: Total emissions (excluding emissions for which uncertainty was not quantified) are presented without LULUCF. Net emissions are presented with LULUCF. Totals may not sum due to independent rounding. Parentheses indicate net sequestration.

Table 1-6: Estimated Overall Inventory Quantitative Uncertainty for 2022 (MMT CO_2 Eq. and Percent)

Gas	2022 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Greenhouse Gas Estimate[a] (MMT CO_2 Eq.)		Uncertainty Range Relative to Greenhouse Gas Estimate[a] (%)		Mean[b] (MMT CO_2 Eq.)	Standard Deviation[b] (MMT CO_2 Eq.)
		Lower Bound[c]	Upper Bound[c]	Lower Bound	Upper Bound		
CO_2	5,053.0	4,937.3	5,257.7	-2%	4%	5,095.2	81.9
CH_4[d]	702.4	604.3	803.1	-14%	14%	703.8	52.0
N_2O[d]	389.7	324.6	490.2	-17%	26%	399.5	42.3
PFC, HFC, SF_6, and NF_3[d]	198.1	182.8	217.5	-8%	10%	199.5	9.0

Total Gross Emissions	**6,343.2**	**6,190.3**	**6,604.8**	**-2%**	**4%**	**6,397.9**	**106.3**
LULUCF Emissions[e]	67.5	64.3	73.2	-5%	8%	68.6	2.3
LULUCF Carbon Stock Change Flux[f]	(921.8)	(1,158.6)	(748.7)	26%	-19%	(957.5)	105.3
LULUCF Sector Net Total[g]	**(854.3)**	**(1,090.3)**	**(680.5)**	**28%**	**-20%**	**(888.8)**	**105.3**
Net Emissions (Sources and Sinks)	**5,488.9**	**5,216.2**	**5,801.9**	**-5%**	**6%**	**5,509.0**	**150.6**

[a] The lower and upper bounds for emission estimates correspond to a 95 percent confidence interval, with the lower bound corresponding to 2.5th percentile and the upper bound corresponding to 97.5th percentile.

[b] Mean value indicates the arithmetic average of the simulated emission estimates; standard deviation indicates the extent of deviation of the simulated values from the mean.

[c] The lower and upper bound emission estimates for the sub-source categories do not sum to total emissions because the low and high estimates for total emissions were calculated separately through simulations.

[d] The overall uncertainty estimates did not take into account the uncertainty in the GWP values for CH_4, N_2O and high GWP gases used in the Inventory emission calculations for 2022.

[e] LULUCF emissions include the CH_4 and N_2O emissions reported for peatlands remaining peatlands, forest fires, drained organic soils, grassland fires, and coastal wetlands remaining coastal wetlands; CH_4 emissions from land converted to coastal wetlands, land converted to flooded land, and flooded land remaining flooded land; and N_2O emissions from forest soils and settlement soils.

[f] LULUCF carbon stock change is the net C stock change from the following categories: forest land remaining forest land, land converted to forest land, cropland remaining cropland, land converted to cropland, grassland remaining grassland, land converted to grassland, wetlands remaining wetlands, land converted to wetlands, settlements remaining settlements, and land converted to settlements. Since the resulting flux is negative the signs of the resulting lower and upper bounds are reversed.

[g] The LULUCF sector net total is the net sum of all CH_4 and N_2O emissions to the atmosphere plus net carbon stock changes.

Notes: Total emissions (excluding emissions for which uncertainty was not quantified) are presented without LULUCF. Net emissions are presented with LULUCF. Totals may not sum due to independent rounding. Parentheses indicate net sequestration.

The uncertainty for 2022 is similar to the uncertainty for 1990, though slightly lower. There have been some improvements in significant categories which do not necessarily reduce uncertainties as also acknowledged in the IPCC 2006 IPCC GL, p. 3.13 (e.g., improvements to estimates for Agricultural Soil Management over time, implications of methodological choice). For example, the 95 percent uncertainty bounds for nitrous oxide emissions from Agricultural Soil Management were increased from –25 percent to 29 percent in 1990 to –30 percent to 72 percent in 2022. Methodological and data quality improvements were also made for HFCs, PFCs, SF_6 and NF_3 this year but the uncertainties for these sources also slightly increased, better representing the limitations of existing emissions estimates. The methods and data for fossil fuel combustion categories, the most significant source, has not changed significantly and neither have uncertainties. It is also worth noting that some of the improvements to shift to use of GHGRP have been in less significant categories within the inventory (e.g., for IPPU). So, the overall uncertainty for latest year reflects these offsetting effects and trends within the uncertainty assessment.

In addition to the estimates of uncertainty associated with the current and base year estimates, Table 1-7 presents the estimates of inventory trend uncertainty. The *2006 IPCC Guidelines* defines trend as the difference in emissions between the base year (i.e., 1990) and the current year (i.e., 2022) *Inventory* estimates. However, for purposes of understanding the concept of trend uncertainty, the trend is defined in this Inventory as the percentage change in the gross emissions (or net emissions) estimated for the current year, relative to the gross emission (or net emissions) estimated for the base year. The uncertainty associated with this trend is referred to as trend uncertainty and is reported as between -8 and 8 percent at the 95 percent confidence level between 1990 and 2022. This indicates a range of approximately -8 percent below and 8 percent above the trend estimate of -1.3 percent. See Annex 7 for trend uncertainty estimates for individual source and sink categories by gas.

Table 1-7: Quantitative Assessment of Trend Uncertainty (MMT CO_2 Eq. and Percent)

Gas	Base Year Emissions[a]	2022 Emissions	Emissions Trend	Trend Range[b]	
	(MMT CO_2 Eq.)		(%)	(%)	
				Lower Bound	Upper Bound
CO_2	5,131.6	5,053.0	-2%	-6%	3%
CH_4	871.7	702.4	-19%	-32%	2%
N_2O	408.2	389.7	-5%	-30%	51%
HFCs, PFCs, SF_6, and NF_3	125.5	198.1	58%	32%	95%
Total Gross Emissions[c]	**6,536.9**	**6,343.2**	**-3%**	**-7%**	**3%**
LULUCF Emissions[d]	57.9	67.5	17%	6%	30%
LULUCF Carbon Stock Change Flux[e]	(1,034.7)	(921.8)	-11%	-35%	21%
LULUCF Sector Net Total[f]	**(976.7)**	**(854.3)**	**-13%**	**-37%**	**21%**
Net Emissions (Sources and Sinks)[c]	**5,560.2**	**5,488.9**	**-1.3%**	**-8%**	**8%**

[a] Base Year is 1990 for all sources.

[b] The trend range represents a 95 percent confidence interval for the emission trend, with the lower bound corresponding to 2.5th percentile value and the upper bound corresponding to 97.5th percentile value.

[c] Totals exclude emissions for which uncertainty was not quantified.

[d] LULUCF emissions include the CH_4 and N_2O emissions reported for peatlands remaining peatlands, forest fires, drained organic soils, grassland fires, and coastal wetlands remaining coastal wetlands; CH_4 emissions from land converted to coastal wetlands, land converted to flooded land, and flooded land remaining flooded land; and N_2O emissions from forest soils and settlement soils.

[e] LULUCF carbon stock change is the net C stock change from the following categories: forest land remaining forest land, land converted to forest land, cropland remaining cropland, land converted to cropland, grassland remaining grassland, land converted to grassland, wetlands remaining wetlands, land converted to wetlands, settlements remaining settlements, and land converted to settlements.

[f] The LULUCF sector net total is the net sum of all CH_4 and N_2O emissions to the atmosphere plus net carbon stock changes.

Notes: Totals may not sum due to independent rounding. Parentheses indicate net sequestration. Total emissions (excluding emissions for which uncertainty was not quantified) are presented without LULUCF. Net emissions are presented with LULUCF.

1.8 Completeness

This report, along with its accompanying CRTs, serves as a thorough assessment of the anthropogenic sources and sinks of greenhouse gas emissions for the United States for the time series 1990 through 2022. This report is intended to be comprehensive and includes the vast majority of emissions and removals identified as anthropogenic, consistent with IPCC methods and the Paris Agreement and UNFCCC reporting guidelines. In general, sources or sink categories not accounted for in this *Inventory* are excluded because they are not occurring in the United States and its territories, or because data are unavailable to develop an estimate and/or the categories were determined to be insignificant[70] in terms of overall national emissions per the Paris Agreement and UNFCCC reporting guidelines.

The United States is continually working to improve upon the understanding of such sources and sinks currently not included and seeking to find the data required to estimate related emissions and removals, focusing on categories that are anticipated to be significant. See Chapter 9 on Improvements and Recalculations for more

[70] See paragraph 32 in the Annex to Decision18/CMA.1 of the Paris Agreement reporting guidelines on national inventories that state "…emissions from a category should only be considered insignificant if the likely level of emissions is below 0.05 per cent of the national total GHG emissions, excluding LULUCF, or 500 kilotonnes of carbon dioxide equivalent (kt CO_2 eq), whichever is lower. The total national aggregate of estimated emissions for all gases from categories considered insignificant shall remain below 0.1 per cent of the national total GHG emissions, excluding LULUCF. Parties should use approximated activity data and default IPCC emission factors to derive a likely level of emissions for the respective category."

information on completeness and improvements implemented this cycle. As such improvements are implemented, new emission and removal estimates are quantified and included in the *Inventory*, improving completeness of national estimates. For a list of sources and sink categories not included and more information on significance of these categories, see Annex 5 and the respective category sections in each sectoral chapter of this report.

1.9 Organization of Report

In accordance with the Paris Agreement and UNFCCC reporting guidelines, this *Inventory* is grouped into five sector-specific chapters consistent with the Paris Agreement Common Reporting Tables (CRT),[71] listed below in Table 1-8. In addition, the U.S. *Inventory* submission includes chapters on Trends in Greenhouse Gas Emissions, Other information, and Recalculations and Improvements to be considered consistent with the suggested outline or national inventory documents submitted under the Paris Agreement and UNFCCC.

Table 1-8: CRT/IPCC Sector Descriptions

Chapter (CRT and UNFCCC/IPCC Sector)	Activities Included
Energy	Emissions of all greenhouse gases resulting from stationary and mobile energy activities including fuel combustion and fugitive fuel emissions, and non-energy use of fossil fuels.
Industrial Processes and Product Use	Emissions resulting from industrial processes and product use of greenhouse gases.
Agriculture	Emissions from agricultural activities except fuel combustion, which is addressed under Energy.
Land Use, Land-Use Change, and Forestry	Emissions and removals of CO_2, and emissions of CH_4, and N_2O from land use, land-use change, and forestry.
Waste	Emissions from waste management activities.

Within each chapter, emissions are identified by the anthropogenic activity that is the source or sink of the greenhouse gas emissions being estimated (e.g., coal mining). Overall, the following organizational structure is consistently applied throughout this report:

Chapter/CRT/IPCC Sector: Overview of emissions and trends for each CRT/IPCC defined sector.

CRT Source or Sink Category: Description of category pathway and emission/removal trends based on IPCC methodologies, consistent with the Paris Agreement and UNFCCC reporting guidelines.

Methodology and Time-Series Consistency: Description of analytical methods (e.g., from *2006 IPCC Guidelines,* or country-specific methods) employed to produce emission estimates and identification of data references, primarily for activity data and emission factors, and a discussion of time-series consistency.

Uncertainty: A discussion and quantification of the uncertainty in emission estimates.

QA/QC and Verification: A discussion on steps taken to QA/QC and verify the emission estimates, consistent with the U.S. QA/QC plan, and any key QC findings.

Recalculations Discussion: A discussion of any data or methodological changes that necessitate a recalculation of previous years' emission estimates, and the impact of the recalculation on the emission estimates, if applicable.

Planned Improvements: A discussion on any category-specific planned improvements, if applicable.

[71] See paragraph 50 in the Annex to Decision 18/CMA.1

Special attention is given to CO_2 from fossil fuel combustion relative to other sources because of its share of emissions and its dominant influence on emission trends. For example, each energy consuming end-use sector (i.e., residential, commercial, industrial, and transportation), as well as the electricity generation sector, is described individually. Additional information for certain source categories and other topics is also provided in several Annexes listed in Table 1-9.

Table 1-9: List of Annexes

ANNEX 1 Key Category Analysis	
ANNEX 2 Methodology and Data for Estimating CO_2 Emissions from Fossil Fuel Combustion	
2.1.	Methodology for Estimating Emissions of CO_2 from Fossil Fuel Combustion
2.2.	Methodology for Estimating the Carbon Content of Fossil Fuels
2.3.	Methodology for Estimating Carbon Emitted from Non-Energy Uses of Fossil Fuels
ANNEX 3 Methodological Descriptions for Additional Source or Sink Categories	
3.1.	Methodology for Estimating Emissions of CH_4, N_2O, and Indirect Greenhouse Gases from Stationary Combustion
3.2.	Methodology for Estimating Emissions of CH_4, N_2O, and Indirect Greenhouse Gases from Mobile Combustion and Methodology for and Supplemental Information on Transportation-Related Greenhouse Gas Emissions
3.3.	Methodology for Estimating Emissions from Commercial Aircraft Jet Fuel Consumption
3.4.	Methodology for Estimating CH_4 Emissions from Coal Mining
3.5.	Methodology for Estimating CH_4 and CO_2 Emissions from Petroleum Systems
3.6.	Methodology for Estimating CH_4 Emissions from Natural Gas Systems
3.7.	Methodology for Estimating CO_2 and N_2O Emissions from Incineration of Waste
3.8.	Methodology for Estimating Emissions from International Bunker Fuels used by the U.S. Military
3.9.	Methodology for Estimating HFC and PFC Emissions from Substitution of Ozone Depleting Substances
3.10.	Methodology for Estimating CH_4 Emissions from Enteric Fermentation
3.11.	Methodology for Estimating CH_4 and N_2O Emissions from Manure Management
3.12.	Methodology for Estimating N_2O Emissions, CH_4 Emissions and Soil Organic C Stock Changes from Agricultural Lands (Cropland and Grassland)
3.13.	Methodology for Estimating Net Carbon Stock Changes in Forest Land Remaining Forest Land and Land Converted to Forest Land
3.14.	Methodology for Estimating CH_4 Emissions from Landfills
ANNEX 4 IPCC Reference Approach for Estimating CO_2 Emissions from Fossil Fuel Combustion	
ANNEX 5 Assessment of the Sources and Sinks of Greenhouse Gas Emissions Not Included	
ANNEX 6 Additional Information	
6.1.	Global Warming Potential Values
6.2.	Ozone Depleting Substance Emissions
6.3.	Greenhouse Gas Precursors: Mapping of NEI categories to the Inventory
6.4.	Constants, Units, and Conversions
6.5.	Chemical Formulas
ANNEX 7 Uncertainty	
7.1.	Overview
7.2.	Methodology and Results
7.3.	Reducing Uncertainty
7.4.	Planned Improvements
7.5.	Additional Information on Uncertainty Analyses by Source
ANNEX 8 QA/QC Procedures	
8.1.	Background
8.2.	Purpose
8.3.	Assessment Factors
8.4.	Responses During the Review Process
ANNEX 9 Use of Greenhouse Gas Reporting Program (GHGRP) in Inventory	

2. Trends in Greenhouse Gas Emissions and Removals

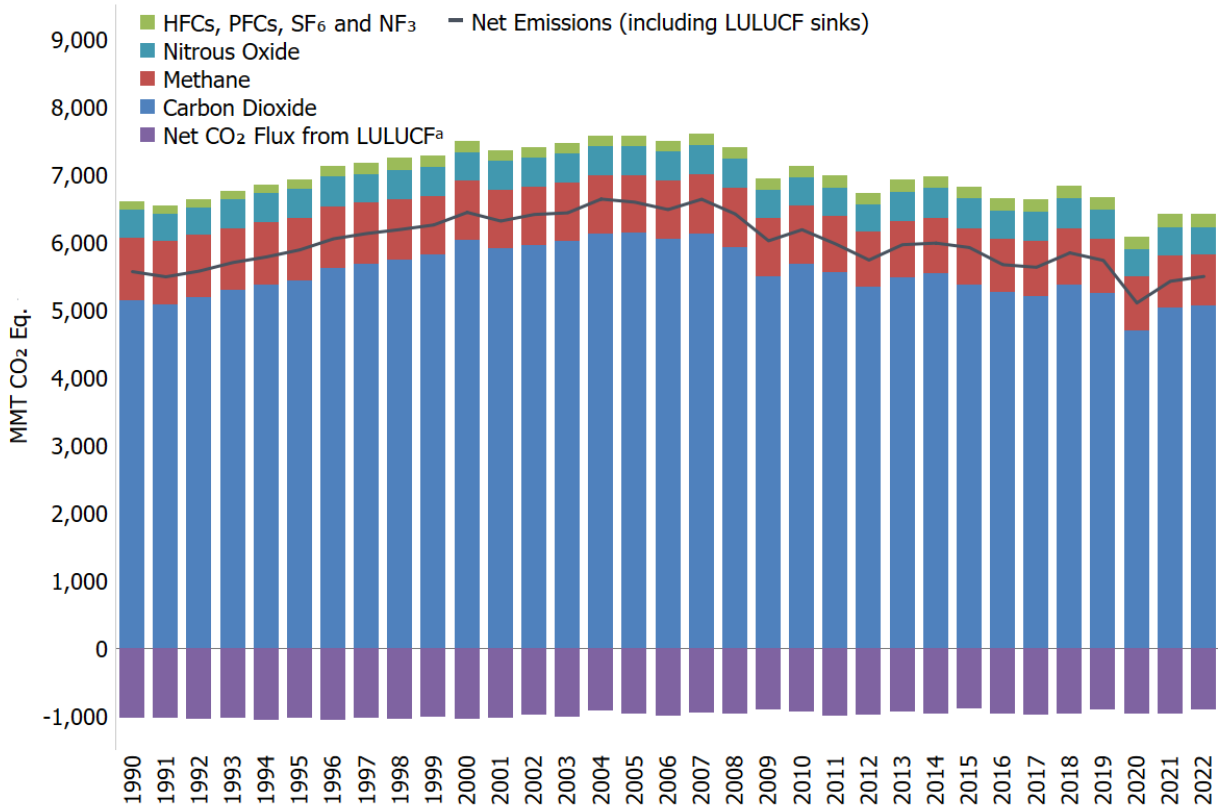
2.1 Overview of U.S. Greenhouse Gas Emissions and Sinks Trends

In 2022, total gross U.S. greenhouse gas emissions were 6,343.2 million metric tons of carbon dioxide equivalent (MMT CO_2 Eq.).[1] Total gross U.S. emissions decreased by 3.0 percent from 1990 to 2022, down from a high of 15.2 percent above 1990 levels in 2007. Gross emissions increased from 2021 to 2022 by 0.2 percent (14.4 MMT CO_2 Eq.). Net emissions (i.e., including sinks) were 5,489.0 MMT CO_2 Eq. in 2022. Overall, net emissions increased by 1.3 percent from 2021 to 2022 and decreased by 16.7 percent from 2005 levels, as shown in Table 2-1. Between 2021 and 2022, the increase in total greenhouse gas emissions was driven largely by an increase in CO_2 emissions from fossil fuel combustion across most end-use sectors due in part to increased energy use from the continued rebound of economic activity after the height of the COVID-19 pandemic. The CO_2 emissions from fossil fuel combustion increased by 1.0 percent from 2021 to 2022, including a 5.0 percent increase in residential sector emissions, 8.9 percent increase in commercial sector emissions, 0.1 percent decrease in transportation sector emissions, 2.6 percent increase in industrial emissions, and 0.6 percent decrease in electric power sector emissions. Carbon sequestration in the Land Use, Land-Use Change, and Forestry (LULUCF) sector offset 14.5 percent of total emissions in 2022.

Figure 2-1 and Figure 2-2 illustrate the overall trend in total U.S. emissions and sinks since 1990, by gas and by annual percentage changes relative to the previous year.

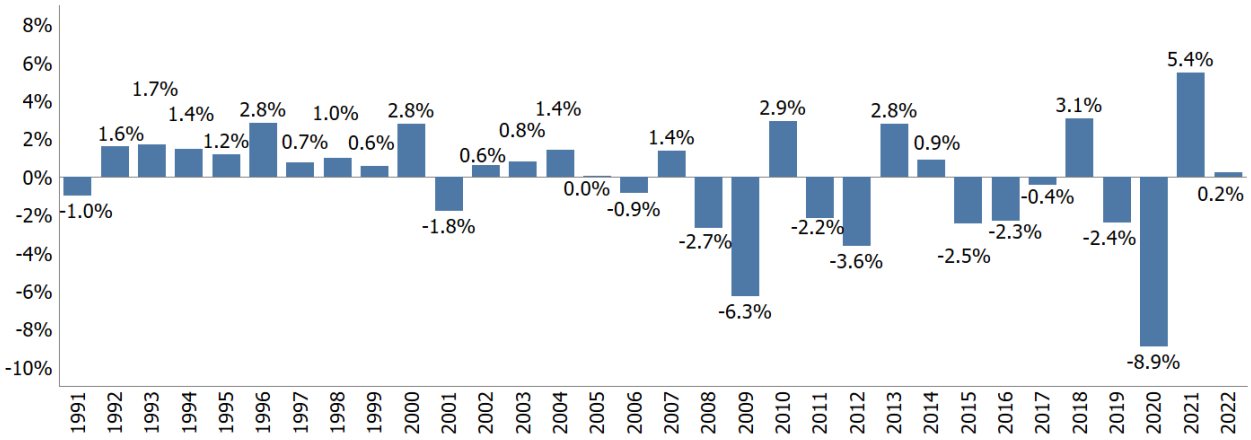
[1] The gross emissions total presented in this report for the United States excludes emissions and sinks from removals from LULUCF. The net emissions total presented in this report for the United States includes emissions and sinks from removals from LULUCF.

Figure 2-1: U.S. Greenhouse Gas Emissions and Sinks by Gas



[a] The term "flux" is used to describe the exchange of CO_2 to and from the atmosphere, with net flux being either positive or negative depending on the overall balance. Removal and long-term storage of CO_2 from the atmosphere is also referred to as "carbon sequestration."

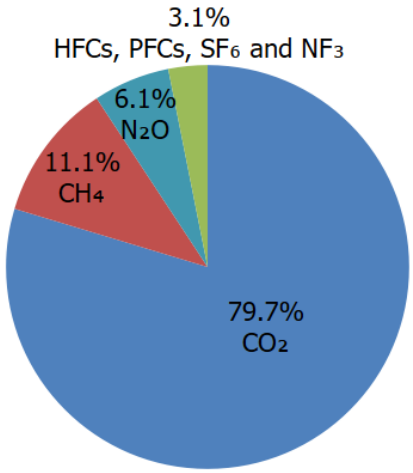
Figure 2-2: Annual Percentage Change in Gross U.S. Greenhouse Gas Emissions Relative to the Previous Year



Emissions and Sinks by Gas

Figure 2-3 illustrates the relative contribution of each gas to total gross U.S. greenhouse gas emissions in 2022, in CO_2 equivalents (i.e., weighted by global warming potential). The primary greenhouse gas emitted by human activities in the United States is CO_2, representing 79.7 percent of total greenhouse gas emissions. The largest source of CO_2—and of overall greenhouse gas emissions—is fossil fuel combustion, primarily from transportation and power generation. Methane (CH_4) emissions account for 11.1 percent of emissions. The major sources of methane include enteric fermentation associated with domestic livestock, natural gas systems, and decomposition of waste in landfills. Agricultural soil management, wastewater treatment, stationary sources of fuel combustion, and manure management are the major sources of N_2O emissions. Ozone depleting substance (ODS) substitute emissions were the primary contributor to aggregate hydrofluorocarbon (HFC) emissions. Perfluorocarbon (PFC) emissions were attributable primarily to fluorochemical production and electronics manufacturing. Electrical equipment accounted for most sulfur hexafluoride (SF_6) emissions. Nitrogen trifluoride (NF_3) emissions were approximately evenly split between electronics manufacturing and fluorochemical production.

Figure 2-3: 2022 Gross Total U.S. Greenhouse Gas Emissions by Gas (Percentages based on MMT CO_2 Eq.)



Note: Emissions and removals from LULUCF are excluded from the figure above.

From 1990 to 2022, total emissions of CO_2 decreased by 1.5 percent (78.6 MMT CO_2 Eq.), total emissions of methane (CH_4) decreased by 19.4 percent (169.3 MMT CO_2 Eq.), and total emissions of nitrous oxide (N_2O) decreased by 4.5 percent (18.4 MMT CO_2 Eq.). During the same period, emissions of fluorinated gases including HFCs, PFCs, SF_6, and NF_3 rose by 57.9 percent (72.7 MMT CO_2 Eq.). Rapidly growing emissions of HFCs drove this trend, overwhelming decreases in emissions of PFCs and SF_6. Despite being emitted in smaller quantities relative to the other principal greenhouse gases, emissions of HFCs, PFCs, SF_6, and NF_3 are significant because many of them have extremely high global warming potentials (GWPs), and, in the cases of PFCs, SF_6, and NF_3, very long atmospheric lifetimes. U.S. greenhouse gas emissions were partly offset by carbon sequestration in managed forests, trees in urban areas, agricultural soils, landfilled yard trimmings, and coastal wetlands. These were estimated to offset 14.5 percent (921.8 MMT CO_2 Eq.) of total gross emissions in 2022.

Table 2-1 provides information on trends in emissions and sinks from all U.S. anthropogenic sources and sinks in weighted units of MMT CO_2 Eq., while unweighted gas emissions and sinks in kilotons (kt) are provided in Table 2-2.

Table 2-1: Recent Trends in U.S. Greenhouse Gas Emissions and Sinks by Gas (MMT CO_2 Eq.)

Gas/Source	1990	2005	2018	2019	2020	2021	2022
CO_2	**5,131.6**	**6,126.9**	**5,362.2**	**5,234.5**	**4,689.0**	**5,017.2**	**5,053.0**
Fossil Fuel Combustion	4,752.2	5,744.1	4,988.2	4,852.6	4,341.7	4,654.3	4,699.4
Transportation	*1,468.9*	*1,858.6*	*1,813.1*	*1,816.6*	*1,572.8*	*1,753.5*	*1,751.3*
Electric Power Sector	*1,820.0*	*2,400.1*	*1,753.4*	*1,606.7*	*1,439.6*	*1,540.9*	*1,531.7*
Industrial	*876.5*	*847.6*	*810.5*	*809.8*	*762.0*	*780.5*	*801.1*
Residential	*338.6*	*358.9*	*338.9*	*342.9*	*314.8*	*318.0*	*334.1*
Commercial	*228.3*	*227.1*	*246.3*	*251.7*	*229.3*	*237.5*	*258.7*
U.S. Territories	*20.0*	*51.9*	*25.9*	*24.8*	*23.3*	*23.8*	*22.6*
Non-Energy Use of Fuels	99.1	125.0	118.4	106.5	97.8	111.6	102.8
Cement Production	33.5	46.2	39.0	40.9	40.7	41.3	41.9
Iron and Steel Production & Metallurgical Coke Production	104.7	70.1	42.9	43.1	37.7	41.9	40.7
Natural Gas Systems	32.4	26.3	32.8	38.5	36.7	35.8	36.5
Petrochemical Production	20.1	26.9	27.2	28.5	27.9	30.7	28.8
Petroleum Systems	9.6	10.2	34.8	45.5	28.9	24.1	22.0
Ammonia Production	14.4	10.2	12.7	12.4	13.0	12.2	12.6
Incineration of Waste	12.9	13.3	13.3	12.9	12.9	12.5	12.4
Lime Production	11.7	14.6	13.1	12.1	11.3	11.9	12.2
Other Process Uses of Carbonates	7.1	8.5	7.9	9.0	9.0	8.6	10.4
Urea Consumption for Non-Agricultural Purposes	3.8	3.7	6.1	6.2	5.8	6.6	7.1
Urea Fertilization	2.4	3.5	4.9	5.0	5.1	5.2	5.3
Carbon Dioxide Consumption	1.5	1.4	4.1	4.9	5.0	5.0	5.0
Liming	4.7	4.4	2.2	2.2	2.9	2.4	3.3
Coal Mining	4.6	4.2	3.1	3.0	2.2	2.5	2.5
Glass Production	2.3	2.4	2.0	1.9	1.9	2.0	2.0
Soda Ash Production	1.4	1.7	1.7	1.8	1.5	1.7	1.7
Titanium Dioxide Production	1.2	1.8	1.5	1.3	1.3	1.5	1.5
Aluminum Production	6.8	4.1	1.5	1.9	1.7	1.5	1.4
Ferroalloy Production	2.2	1.4	2.1	1.6	1.4	1.6	1.3
Zinc Production	0.6	1.0	1.0	1.0	1.0	1.0	0.9
Phosphoric Acid Production	1.5	1.3	0.9	0.9	0.9	0.9	0.8
Lead Production	0.5	0.6	0.5	0.5	0.5	0.4	0.4
Carbide Production and Consumption	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Abandoned Oil and Gas Wells	+	+	+	+	+	+	+
Substitution of Ozone Depleting Substances	+	+	+	+	+	+	+
Magnesium Production and Processing	0.1	+	+	+	+	+	+
Biomass and Biodiesel Consumption[a]	*237.9*	*245.4*	*336.0*	*333.1*	*295.7*	*303.0*	*305.4*
International Bunker Fuels[b]	*103.6*	*113.3*	*124.3*	*113.6*	*69.6*	*80.2*	*98.2*
CH_4[c]	**871.7**	**795.4**	**771.5**	**754.3**	**735.3**	**720.5**	**702.4**
Enteric Fermentation	183.1	188.2	196.8	197.3	196.3	196.5	192.6
Natural Gas Systems	218.8	210.1	190.3	188.7	180.3	174.6	173.1
Landfills	197.8	147.7	126.3	128.7	124.1	122.0	119.8
Manure Management	39.1	55.0	67.7	66.7	66.9	66.4	64.7
Coal Mining	108.1	71.5	59.1	53.0	46.2	44.7	43.6
Petroleum Systems	49.4	48.2	59.0	52.2	53.3	48.6	39.6
Wastewater Treatment	22.7	22.7	21.4	21.1	21.0	20.7	20.8
Rice Cultivation	18.9	20.6	19.9	15.6	18.6	18.3	18.9
Stationary Combustion	9.7	8.8	9.6	9.8	8.0	8.0	8.6
Abandoned Oil and Gas Wells	7.8	8.2	8.4	8.5	8.5	8.6	8.5
Abandoned Underground Coal Mines	8.1	7.4	6.9	6.6	6.5	6.3	6.3
Mobile Combustion	7.2	4.3	2.8	2.9	2.5	2.6	2.6
Composting	0.4	2.1	2.5	2.5	2.6	2.6	2.6
Field Burning of Agricultural Residues	0.5	0.6	0.6	0.7	0.6	0.6	0.6
Anaerobic Digestion at Biogas Facilities	+	+	+	+	+	+	+

Carbide Production and Consumption	+	+	+	+	+	+	+
Ferroalloy Production	+	+	+	+	+	+	+
Iron and Steel Production & Metallurgical Coke Production	+	+	+	+	+	+	+
Petrochemical Production	+	+	+	+	+	+	+
Incineration of Waste	+	+	+	+	+	+	+
International Bunker Fuels[b]	*0.2*	*0.1*	*0.1*	*0.1*	*0.1*	*0.1*	*0.1*
N_2O[c]	**408.2**	**419.2**	**439.5**	**416.4**	**391.2**	**398.2**	**389.7**
Agricultural Soil Management	288.8	294.1	333.4	315.6	292.1	298.0	290.8
Stationary Combustion	22.3	30.5	25.1	22.2	20.5	22.0	24.7
Wastewater Treatment	14.8	18.1	21.2	21.6	22.3	22.1	21.9
Manure Management	13.4	15.2	16.6	16.8	16.9	17.1	17.0
Mobile Combustion	38.4	37.0	17.7	19.1	16.1	16.8	16.7
Nitric Acid Production	10.8	10.1	8.5	8.9	8.3	7.9	8.6
N_2O from Product Uses	3.8	3.8	3.8	3.8	3.8	3.8	3.8
Adipic Acid Production	13.5	6.3	9.3	4.7	7.4	6.6	2.1
Composting	0.3	1.5	1.8	1.8	1.8	1.8	1.8
Caprolactam, Glyoxal, and Glyoxylic Acid Production	1.5	1.9	1.3	1.2	1.1	1.2	1.3
Incineration of Waste	0.4	0.3	0.4	0.4	0.3	0.4	0.3
Electronics Industry	+	0.1	0.2	0.2	0.3	0.3	0.3
Field Burning of Agricultural Residues	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Natural Gas Systems	+	+	+	+	+	+	0.2
Petroleum Systems	+	+	+	+	+	+	+
International Bunker Fuels[b]	*0.8*	*0.9*	*1.0*	*0.9*	*0.5*	*0.6*	*0.8*
HFCs	**47.7**	**121.7**	**163.9**	**168.2**	**170.3**	**177.0**	**182.8**
Substitution of Ozone Depleting Substances	0.3	99.5	157.9	162.1	166.2	172.6	178.1
Fluorochemical Production	47.3	22.1	5.7	5.7	3.8	4.0	4.3
Electronics Industry	0.2	0.2	0.3	0.3	0.3	0.4	0.3
Magnesium Production and Processing	0.0	0.0	0.1	0.1	0.1	+	+
PFCs	**39.5**	**10.2**	**7.4**	**7.3**	**6.6**	**6.3**	**6.7**
Fluorochemical Production	17.5	4.0	2.9	3.0	2.5	2.6	3.0
Electronics Industry	2.5	3.0	2.9	2.6	2.5	2.6	2.7
Aluminum Production	19.3	3.1	1.4	1.4	1.4	0.9	0.8
SF_6 and PFCs from Other Product Use	0.1	0.1	0.2	0.2	0.2	0.1	0.2
Substitution of Ozone Depleting Substances	0.0	+	+	+	+	+	+
Electrical Equipment	0.0	+	0.0	+	+	+	+
SF_6	**37.9**	**20.2**	**7.6**	**8.4**	**8.1**	**8.5**	**7.6**
Electrical Equipment	24.7	11.8	5.0	6.1	5.9	6.0	5.1
Magnesium Production and Processing	5.6	3.0	1.1	0.9	0.9	1.2	1.1
Electronics Industry	0.5	0.8	0.8	0.8	0.8	0.9	0.8
SF_6 and PFCs from Other Product Use	1.3	1.3	0.8	0.6	0.5	0.4	0.6
Fluorochemical Production	5.8	3.3	+	+	+	+	+
NF_3	**0.3**	**1.0**	**0.7**	**1.1**	**1.3**	**1.1**	**1.1**
Electronics Industry	+	0.4	0.5	0.5	0.6	0.6	0.6
Fluorochemical Production	0.3	0.6	0.1	0.6	0.7	0.5	0.5
Total Gross Emissions (Sources)	**6,536.9**	**7,494.6**	**6,752.7**	**6,590.1**	**6,001.8**	**6,328.8**	**6,343.2**
LULUCF Emissions[c]	**58.0**	**68.9**	**62.8**	**58.0**	**68.4**	**72.9**	**67.6**
CH_4	53.1	58.5	55.5	52.5	59.3	62.1	58.4
N_2O	4.8	10.3	7.3	5.5	9.1	10.7	9.1
LULUCF Carbon Stock Change[e]	**(1,034.7)**	**(976.6)**	**(978.3)**	**(921.6)**	**(972.8)**	**(983.4)**	**(921.8)**
LULUCF Sector Net Total[f]	**(976.7)**	**(907.7)**	**(915.5)**	**(863.6)**	**(904.4)**	**(910.6)**	**(854.2)**
Net Emissions (Sources and Sinks)	**5,560.2**	**6,586.9**	**5,837.3**	**5,726.6**	**5,097.4**	**5,418.2**	**5,489.0**

+ Does not exceed 0.05 MMT CO_2 Eq.

NO (Not Occurring)

[a] Emissions from biomass and biofuel consumption are not included specifically in Energy sector totals. Net carbon fluxes from changes in biogenic carbon reservoirs are accounted for in the estimates for LULUCF.

[b] Emissions from international bunker fuels are not included in totals.

[c] LULUCF emissions of CH_4 and N_2O are reported separately from gross emissions totals. LULUCF emissions include the CH_4 and N_2O emissions reported for peatlands remaining peatlands, forest fires, drained organic soils, grassland fires, and coastal wetlands remaining coastal wetlands; CH_4 emissions from land converted to coastal wetlands, flooded land remaining flooded land, and land converted to flooded land; and N_2O emissions from forest soils and settlement soils. Refer to Table 2-8 for a breakout of emissions and removals for LULUCF by gas and source category.

[d] Small amounts of PFC emissions from this source are included under HFCs due to confidential business information.

[e] LULUCF carbon stock change is the net carbon stock change from the following categories: forest land remaining forest land, land converted to forest land, cropland remaining cropland, land converted to cropland, grassland remaining grassland, land converted to grassland, wetlands remaining wetlands, land converted to wetlands, settlements remaining settlements, and land converted to settlements. Refer to Table 2-8 for a breakout of emissions and removals for LULUCF by gas and source category.

[f] The LULUCF sector net total is the net sum of all LULUCF CH_4 and N_2O emissions to the atmosphere plus LULUCF net carbon stock changes.

Notes: Total (gross) emissions are presented without LULUCF. Net emissions are presented with LULUCF. Totals may not sum due to independent rounding. Parentheses indicate negative values or sequestration.

Table 2-2: Recent Trends in U.S. Greenhouse Gas Emissions and Sinks by Gas (kt)

Gas/Source	1990	2005	2018	2019	2020	2021	2022
CO_2	**5,131,650**	**6,126,864**	**5,362,191**	**5,234,488**	**4,688,969**	**5,017,202**	**5,053,019**
Fossil Fuel Combustion	4,752,232	5,744,134	4,988,198	4,852,631	4,341,710	4,654,265	4,699,403
Transportation	*1,468,944*	*1,858,552*	*1,813,135*	*1,816,636*	*1,572,820*	*1,753,546*	*1,751,286*
Electric Power Sector	*1,819,951*	*2,400,057*	*1,753,432*	*1,606,721*	*1,439,566*	*1,540,933*	*1,531,680*
Industrial	*876,468*	*847,640*	*810,472*	*809,807*	*761,986*	*780,453*	*801,064*
Residential	*338,568*	*358,898*	*338,940*	*342,905*	*314,795*	*318,034*	*334,065*
Commercial	*228,293*	*227,130*	*246,297*	*251,749*	*229,264*	*237,528*	*258,733*
U.S. Territories	*20,010*	*51,857*	*25,923*	*24,813*	*23,279*	*23,772*	*22,575*
Non-Energy Use of Fuels	99,104	124,988	118,382	106,474	97,757	111,624	102,808
Cement Production	33,484	46,194	38,971	40,896	40,688	41,312	41,884
Iron and Steel Production & Metallurgical Coke Production	104,740	70,082	42,863	43,095	37,724	41,873	40,672
Natural Gas Systems	32,427	26,312	32,768	38,525	36,719	35,780	36,470
Petrochemical Production	20,075	26,882	27,200	28,483	27,926	30,656	28,788
Petroleum Systems	9,585	10,210	34,777	45,498	28,937	24,140	21,967
Ammonia Production	14,404	10,234	12,669	12,401	13,006	12,192	12,610
Incineration of Waste	12,900	13,254	13,339	12,948	12,921	12,476	12,357
Lime Production	11,700	14,552	13,106	12,112	11,299	11,870	12,208
Other Process Uses of Carbonates	7,103	8,472	7,938	8,973	9,012	8,583	10,384
Urea Consumption for Non-Agricultural Purposes	3,784	3,653	6,113	6,150	5,805	6,600	7,053
Urea Fertilization	2,417	3,504	4,936	5,034	5,132	5,229	5,327
Carbon Dioxide Consumption	1,472	1,375	4,130	4,870	4,970	4,990	5,000
Liming	4,690	4,351	2,240	2,203	2,887	2,387	3,268
Coal Mining	4,606	4,169	3,139	2,992	2,197	2,455	2,474
Glass Production	2,263	2,402	1,989	1,940	1,858	1,969	1,956
Soda Ash Production	1,431	1,655	1,714	1,792	1,461	1,714	1,704
Titanium Dioxide Production	1,195	1,755	1,541	1,340	1,340	1,474	1,474
Aluminum Production	6,831	4,142	1,455	1,880	1,748	1,541	1,446
Ferroalloy Production	2,152	1,392	2,063	1,598	1,377	1,567	1,327
Zinc Production	632	1,030	999	1,026	977	1,007	947
Phosphoric Acid Production	1,529	1,342	937	909	901	874	840

Gas/Source	1990	2005	2018	2019	2020	2021	2022
Lead Production	516	553	527	531	450	439	428
Carbide Production and Consumption	243	213	184	175	154	172	210
Abandoned Oil and Gas Wells	7	7	8	8	8	8	8
Substitution of Ozone Depleting Substances	+	1	3	3	4	4	4
Magnesium Production and Processing	129	4	2	2	3	3	3
Biomass and Biodiesel Consumption[a]	*237,946*	*245,421*	*335,971*	*333,057*	*295,695*	*303,014*	*305,417*
International Bunker Fuels[b]	*103,634*	*113,328*	*124,279*	*113,632*	*69,638*	*80,180*	*98,241*
CH_4[c]	**31,131**	**28,408**	**27,553**	**26,941**	**26,262**	**25,731**	**25,084**
Enteric Fermentation	6,539	6,722	7,028	7,045	7,010	7,017	6,878
Natural Gas Systems	7,813	7,505	6,795	6,741	6,439	6,235	6,183
Landfills	7,063	5,275	4,512	4,595	4,431	4,359	4,277
Manure Management	1,398	1,964	2,418	2,382	2,390	2,373	2,312
Coal Mining	3,860	2,552	2,110	1,892	1,648	1,595	1,558
Petroleum Systems	1,765	1,723	2,108	1,865	1,904	1,737	1,415
Wastewater Treatment	811	809	763	755	748	738	743
Rice Cultivation	677	735	711	558	664	653	674
Stationary Combustion	345	313	344	351	285	286	307
Abandoned Oil and Gas Wells	279	294	301	302	303	306	303
Abandoned Underground Coal Mines	288	264	247	237	232	224	225
Mobile Combustion	258	154	101	102	91	92	93
Composting	15	75	90	91	92	92	92
Field Burning of Agricultural Residues	19	23	22	23	22	22	22
Anaerobic Digestion at Biogas Facilities	+	+	+	1	+	+	+
Carbide Production and Consumption	1	+	+	+	+	+	+
Ferroalloy Production	1	+	1	+	+	+	+
Iron and Steel Production & Metallurgical Coke Production	1	1	+	+	+	+	+
Petrochemical Production	+	+	+	+	+	+	+
Incineration of Waste	+	+	+	+	+	+	+
International Bunker Fuels[b]	*7*	*5*	*4*	*4*	*3*	*3*	*3*
N_2O[c]	**1,540**	**1,582**	**1,658**	**1,571**	**1,476**	**1,503**	**1,471**
Agricultural Soil Management	1,090	1,110	1,258	1,191	1,102	1,124	1,097
Stationary Combustion	84	115	95	84	78	83	93
Wastewater Treatment	56	68	80	81	84	83	83
Manure Management	50	57	63	63	64	65	64
Mobile Combustion	145	140	67	72	61	63	63
Nitric Acid Production	41	38	32	34	31	30	33
N_2O from Product Uses	14	14	14	14	14	14	14
Adipic Acid Production	51	24	35	18	28	25	8
Composting	1	6	7	7	7	7	7
Caprolactam, Glyoxal, and Glyoxylic Acid Production	6	7	5	5	4	5	5
Incineration of Waste	2	1	1	1	1	1	1
Electronics Industry	+	+	1	1	1	1	1

Gas/Source	1990	2005	2018	2019	2020	2021	2022
Field Burning of Agricultural Residues	1	1	1	1	1	1	1
Natural Gas Systems	+	+	+	+	+	+	1
Petroleum Systems	+	+	+	+	+	+	+
International Bunker Fuels[b]	*3*	*3*	*4*	*3*	*2*	*2*	*3*
HFCs	**M**	**M**	**M**	**M**	**M**	**M**	**M**
Substitution of Ozone Depleting Substances	M	M	M	M	M	M	M
Fluorochemical Production	M	M	M	M	M	M	M
Electronics Industry	M	M	M	M	M	M	M
Magnesium Production and Processing	0	0	+	+	+	+	+
PFCs	**M**	**M**	**M**	**M**	**M**	**M**	**M**
Fluorochemical Production	M	M	M	M	M	M	M
Electronics Industry	M	M	M	M	M	M	M
Aluminum Production	M	M	M	M	M	M	M
SF_6 and PFCs from Other Product Use	101	83	178	173	167	138	172
Substitution of Ozone Depleting Substances	+	+	+	+	+	+	+
Electrical Equipment	+	+	0	+	+	+	+
SF_6	**2**	**1**	**+**	**+**	**+**	**+**	**+**
Electrical Equipment	1	1	+	+	+	+	+
Magnesium Production and Processing	+	+	+	+	+	+	+
Electronics Industry	+	+	+	+	+	+	+
SF_6 and PFCs from Other Product Use	+	+	+	+	+	+	+
Fluorochemical Production	+	+	+	+	+	+	+
NF_3	+	+	+	+	+	+	+
Electronics Industry	+	+	+	+	+	+	+
Fluorochemical Production	+	+	+	+	+	+	+

+ Does not exceed 0.5 kt.
M (Mixture of multiple gases)
NO (Not Occurring)
[a] Emissions from biomass and biofuel consumption are not included specifically in Energy sector totals. Net carbon fluxes from changes in biogenic carbon reservoirs are accounted for in the estimates for LULUCF.
[b] Emissions from international bunker fuels are not included in totals.
[c] LULUCF emissions of LULUCF CH_4 and N_2O are reported separately from gross emissions totals. Refer to Table 2-8 for a breakout of emissions and removals for LULUCF by gas and source category.
[d] Small amounts of PFC emissions from this source are included under HFCs due to confidential business information.
Notes: Totals by gas may not sum due to independent rounding. Parentheses indicate negative values or sequestration.

Emissions and Sinks by UNFCCC/IPCC Sector

Emissions and removals of all gases can be summed from each source and sink category into a set of five sectors defined by the Paris Agreement and UNFCCC reporting guidelines and methodological framework provided by the Intergovernmental Panel on Climate Change (IPCC). Figure 2-4 and Table 2-3 illustrate that over the 33-year period of 1990 to 2022, total emissions from the Energy and Waste sectors decreased by 3.4 percent (181.2 MMT CO_2 Eq.) and 29.3 percent (69.1 MMT CO_2 Eq.), respectively. Emissions from Industrial Processes and Product Use and Agriculture grew by 3.9 percent (14.4 MMT CO_2 Eq.) and 7.7 percent (42.2 MMT CO_2 Eq.), respectively. Over the same period, total carbon sequestration in the LULUCF sector decreased by 12.5 percent (122.5 MMT CO_2), and emissions from the LULUCF sector increased by 16.5 percent (9.6 MMT CO_2 Eq.).

Figure 2-4: U.S. Greenhouse Gas Emissions and Sinks by IPCC Sector

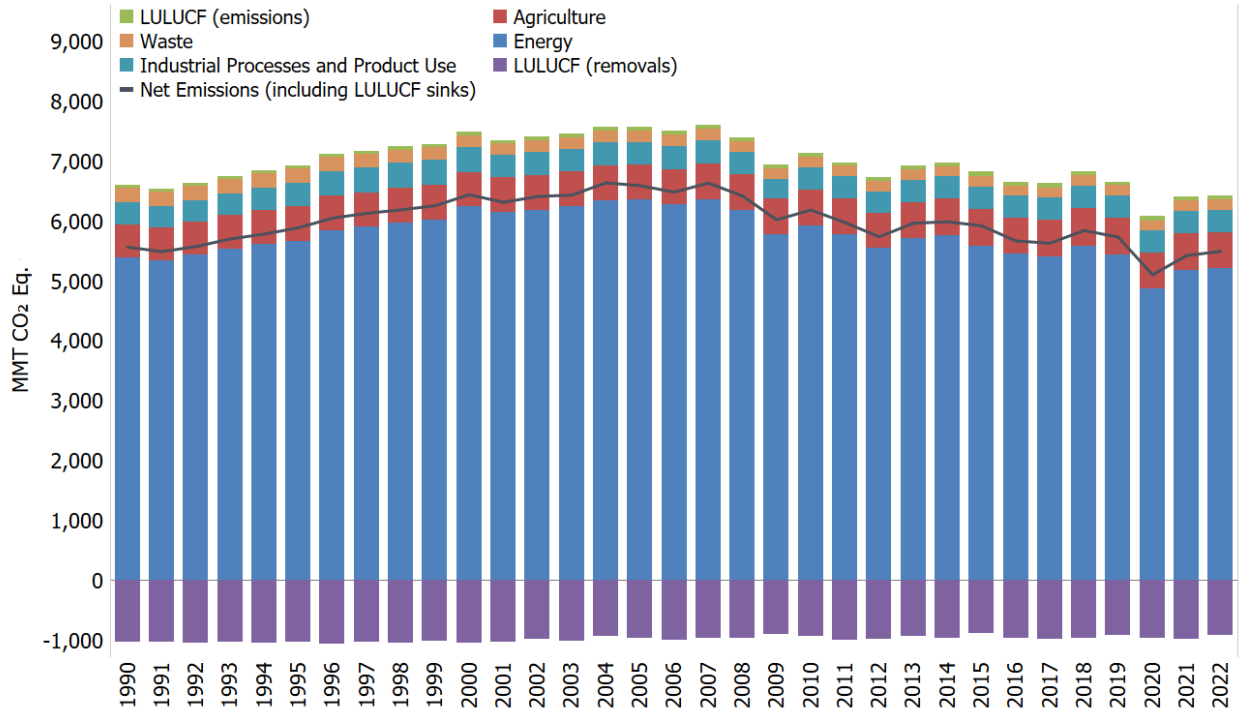


Table 2-3: Recent Trends in U.S. Greenhouse Gas Emissions and Sinks by UNFCCC/IPCC Sector/Category (MMT CO_2 Eq.)

UNFCCC/IPCC Sector/Category	1990	2005	2018	2019	2020	2021	2022
Energy	**5,381.0**	**6,349.5**	**5,570.0**	**5,422.4**	**4,862.6**	**5,173.3**	**5,199.8**
Fossil Fuel Combustion	4,752.2	5,744.1	4,988.2	4,852.6	4,341.7	4,654.3	4,699.4
Natural Gas Systems	251.2	236.5	223.0	227.3	217.0	210.4	209.7
Non-Energy Use of Fuels	99.1	125.0	118.4	106.5	97.8	111.6	102.8
Petroleum Systems	59.0	58.5	93.8	97.8	82.3	72.8	61.6
Coal Mining	112.7	75.6	62.2	56.0	48.3	47.1	46.1
Stationary Combustion[a]	32.0	39.3	34.7	32.0	28.5	30.1	33.3
Mobile Combustion	45.6	41.3	20.5	21.9	18.7	19.4	19.3
Incineration of Waste	13.3	13.6	13.7	13.3	13.3	12.8	12.7
Abandoned Oil and Gas Wells	7.8	8.2	8.4	8.5	8.5	8.6	8.5
Abandoned Underground Coal Mines	8.1	7.4	6.9	6.6	6.5	6.3	6.3
Biomass and Biodiesel Consumption[b]	*237.9*	*245.4*	*336.0*	*333.1*	*295.7*	*303.0*	*305.4*
International Bunker Fuels[c]	*104.6*	*114.3*	*125.3*	*114.6*	*70.3*	*80.9*	*99.1*
Industrial Processes and Product Use	**368.8**	**371.3**	**367.2**	**371.9**	**367.9**	**381.6**	**383.2**
Substitution of Ozone Depleting Substances	0.3	99.5	157.9	162.1	166.2	172.7	178.1
Cement Production	33.5	46.2	39.0	40.9	40.7	41.3	41.9
Iron and Steel Production & Metallurgical Coke Production	104.8	70.1	42.9	43.1	37.7	41.9	40.7
Petrochemical Production	20.1	26.9	27.2	28.5	27.9	30.7	28.8
Ammonia Production	14.4	10.2	12.7	12.4	13.0	12.2	12.6
Lime Production	11.7	14.6	13.1	12.1	11.3	11.9	12.2
Other Process Uses of Carbonates	7.1	8.5	7.9	9.0	9.0	8.6	10.4
Nitric Acid Production	10.8	10.1	8.5	8.9	8.3	7.9	8.6
Fluorochemical Production	70.9	30.0	8.7	9.3	6.9	7.1	7.8

Urea Consumption for Non-Agricultural Purposes	3.8	3.7	6.1	6.2	5.8	6.6	7.1
Electrical Equipment	24.7	11.9	5.0	6.1	5.9	6.0	5.1
Carbon Dioxide Consumption	1.5	1.4	4.1	4.9	5.0	5.0	5.0
Electronics Industry	3.3	4.5	4.8	4.5	4.5	4.8	4.7
N_2O from Product Uses	3.8	3.8	3.8	3.8	3.8	3.8	3.8
Aluminum Production	26.1	7.2	2.9	3.3	3.2	2.5	2.2
Adipic Acid Production	13.5	6.3	9.3	4.7	7.4	6.6	2.1
Glass Production	2.3	2.4	2.0	1.9	1.9	2.0	2.0
Soda Ash Production	1.4	1.7	1.7	1.8	1.5	1.7	1.7
Titanium Dioxide Production	1.2	1.8	1.5	1.3	1.3	1.5	1.5
Ferroalloy Production	2.2	1.4	2.1	1.6	1.4	1.6	1.3
Caprolactam, Glyoxal, and Glyoxylic Acid Production	1.5	1.9	1.3	1.2	1.1	1.2	1.3
Magnesium Production and Processing	5.7	3.0	1.1	1.0	0.9	1.2	1.2
Zinc Production	0.6	1.0	1.0	1.0	1.0	1.0	0.9
Phosphoric Acid Production	1.5	1.3	0.9	0.9	0.9	0.9	0.8
SF_6 and PFCs from Other Product Use	1.4	1.5	0.9	0.8	0.7	0.5	0.8
Lead Production	0.5	0.6	0.5	0.5	0.5	0.4	0.4
Carbide Production and Consumption	0.3	0.2	0.2	0.2	0.2	0.2	0.2
Agriculture	**551.1**	**581.8**	**642.4**	**620.1**	**599.7**	**604.8**	**593.4**
Agricultural Soil Management	288.8	294.1	333.4	315.6	292.1	298.0	290.8
Enteric Fermentation	183.1	188.2	196.8	197.3	196.3	196.5	192.6
Manure Management	52.5	70.2	84.3	83.5	83.8	83.6	81.7
Rice Cultivation	18.9	20.6	19.9	15.6	18.6	18.3	18.9
Urea Fertilization	2.4	3.5	4.9	5.0	5.1	5.2	5.3
Liming	4.7	4.4	2.2	2.2	2.9	2.4	3.3
Field Burning of Agricultural Residues	0.7	0.8	0.8	0.9	0.8	0.8	0.8
Waste	**235.9**	**192.0**	**173.2**	**175.8**	**171.7**	**169.2**	**166.9**
Landfills	197.8	147.7	126.3	128.7	124.1	122.0	119.8
Wastewater Treatment	37.5	40.7	42.5	42.7	43.2	42.7	42.7
Composting	0.7	3.6	4.3	4.3	4.4	4.4	4.4
Anaerobic Digestion at Biogas Facilities	+	+	+	+	+	+	+
Total Gross Emissions[d] (Sources)	**6,536.9**	**7,494.6**	**6,752.7**	**6,590.1**	**6,001.8**	**6,328.8**	**6,343.2**
LULUCF Sector Net Total[e]	**(976.7)**	**(907.7)**	**(915.5)**	**(863.6)**	**(904.4)**	**(910.6)**	**(854.2)**
Forest Land	(1,069.0)	(960.2)	(963.8)	(907.3)	(946.6)	(924.2)	(872.0)
Cropland	40.4	2.9	14.2	12.0	20.5	2.9	3.4
Grassland	59.8	46.7	54.9	54.3	45.8	36.0	39.6
Wetlands	44.0	41.2	38.9	38.9	38.8	38.8	38.8
Settlements	(51.9)	(38.1)	(59.7)	(61.4)	(63.0)	(64.1)	(64.1)
Net Emission (Sources and Sinks)[f]	**5,560.2**	**6,586.9**	**5,837.3**	**5,726.6**	**5,097.4**	**5,418.2**	**5,489.0**

+ Does not exceed 0.05 MMT CO_2 Eq.

[a] Includes CH_4 and N_2O emissions from fuel combustion.

[b] Emissions from biomass and biofuel consumption are not included specifically in summing Energy sector totals. Net carbon fluxes from changes in biogenic carbon reservoirs are accounted for in the estimates for LULUCF.

[c] Emissions from international bunker fuels are not included in totals.

[d] Total emissions without LULUCF.

[e] LULUCF emissions of CH_4 and N_2O are reported separately from gross emissions totals. LULUCF emissions include the CH_4 and N_2O emissions reported for peatlands remaining peatlands, forest fires, drained organic soils, grassland fires, and coastal wetlands remaining coastal wetlands; CH_4 emissions from land converted to coastal wetlands, flooded land remaining flooded land, and land converted to flooded land; and N_2O emissions from forest soils and settlement soils. Refer to Table 2-8 for a breakout of emissions and removals for LULUCF by gas and source category.

[f] Net emissions with LULUCF.

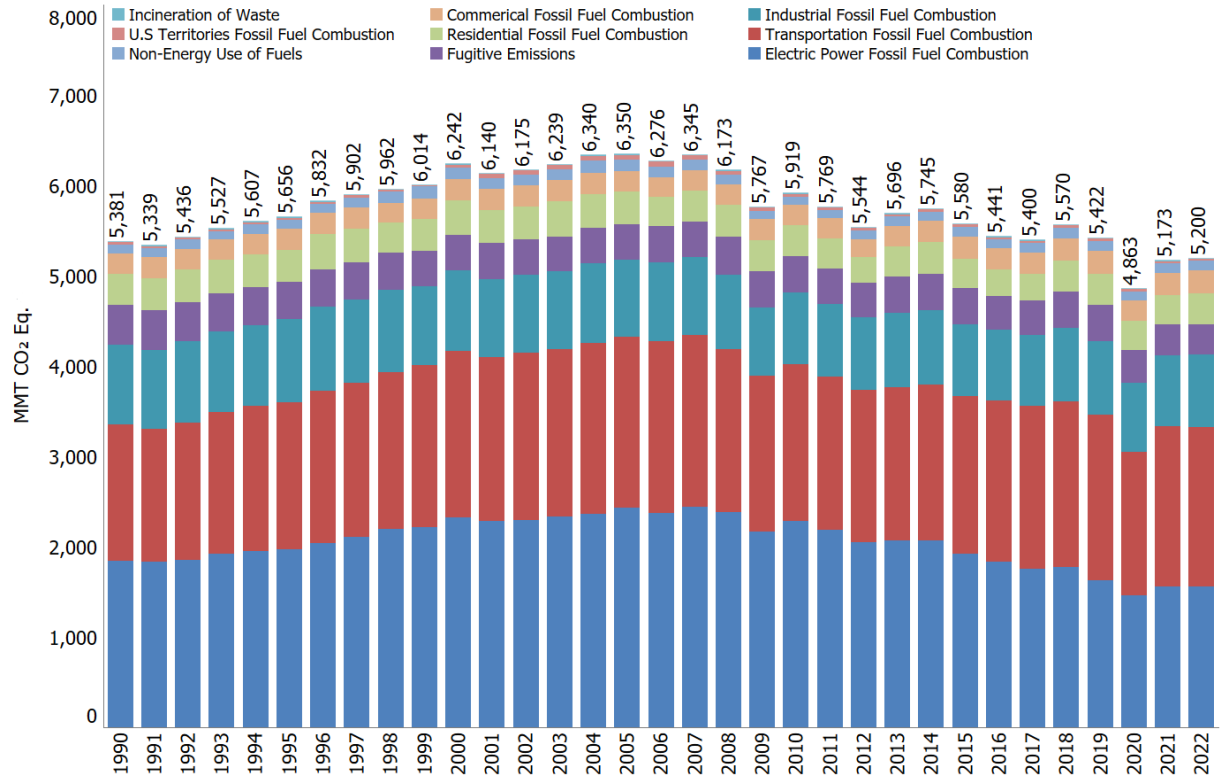
Notes: Total (gross) emissions are presented without LULUCF. Net emissions are presented with LULUCF. Totals may not sum due to independent rounding. Parentheses indicate negative values or sequestration.

Energy

Emissions from energy-related activities come from two main categories: 1) direct emissions associated with fuel use (i.e., fossil fuel combustion, non-energy use of fossil fuels and waste combustion), and 2) fugitive emissions mainly from coal, natural gas, and oil production. Energy emissions also include some categories that are not added to Energy sector totals but are instead presented as memo items, including international bunker fuels and biomass emissions. Energy-related activities, primarily fossil fuel combustion, accounted for the vast majority of U.S. CO_2 emissions from 1990 through 2022. Fossil fuel combustion is the largest source of energy-related emissions, with CO_2 being the primary gas emitted (see Figure 2-5). Due to their relative importance, fossil fuel combustion-related CO_2 emissions are considered in detail in the Energy chapter (see Chapter 3).

In 2022, 83.0 percent of the energy used in the United States on a Btu basis was produced through the combustion of fossil fuels. The remaining 17.0 percent came from other energy sources such as hydropower, biomass, nuclear, wind, and solar energy. A discussion of specific trends related to CO_2 and other greenhouse gas emissions from energy use is presented here with more detail in the Energy chapter. Energy-related activities are also responsible for CH_4 and N_2O emissions (40.2 percent and 10.8 percent of gross total U.S. emissions of each gas, respectively).[2] Table 2-4 presents greenhouse gas emissions from the Energy chapter by source and gas.

Figure 2-5: Trends in Energy Sector Greenhouse Gas Sources



[2] The contribution of energy non-CO_2 emissions is based on gross totals so excludes LULUCF methane (CH_4) and nitrous oxide (N_2O) emissions. The contribution of energy-related CH_4 and N_2O including LULUCF non-CO_2 emissions, is 37.1 percent and 9.8 percent, respectively.

Table 2-4: Emissions from Energy by Gas (MMT CO_2 Eq.)[3]

Gas/Source	1990	2005	2018	2019	2020	2021	2022	Percent Change Since 1990
CO_2	**4,910.9**	**5,923.1**	**5,190.6**	**5,059.1**	**4,520.2**	**4,840.7**	**4,875.5**	**-0.7%**
Fossil Fuel Combustion	4,752.2	5,744.1	4,988.2	4,852.6	4,341.7	4,654.3	4,699.4	-1.1%
Transportation	*1,468.9*	*1,858.6*	*1,813.1*	*1,816.6*	*1,572.8*	*1,753.5*	*1,751.3*	*19.2%*
Electricity Generation	*1,820.0*	*2,400.1*	*1,753.4*	*1,606.7*	*1,439.6*	*1,540.9*	*1,531.7*	*-15.8%*
Industrial	*876.5*	*847.6*	*810.5*	*809.8*	*762.0*	*780.5*	*801.1*	*-8.6%*
Residential	*338.6*	*358.9*	*338.9*	*342.9*	*314.8*	*318.0*	*334.1*	*-1.3%*
Commercial	*228.3*	*227.1*	*246.3*	*251.7*	*229.3*	*237.5*	*258.7*	*13.3%*
U.S. Territories	*20.0*	*51.9*	*25.9*	*24.8*	*23.3*	*23.8*	*22.6*	*12.8%*
Non-Energy Use of Fuels	99.1	125.0	118.4	106.5	97.8	111.6	102.8	3.7%
Natural Gas Systems	32.4	26.3	32.8	38.5	36.7	35.8	36.5	12.5%
Petroleum Systems	9.6	10.2	34.8	45.5	28.9	24.1	22.0	129.2%
Incineration of Waste	12.9	13.3	13.3	12.9	12.9	12.5	12.4	-4.2%
Coal Mining	4.6	4.2	3.1	3.0	2.2	2.5	2.5	-46.3%
Abandoned Oil and Gas Wells	+	+	+	+	+	+	+	13.0%
Biomass-Wood[a]	*215.2*	*206.9*	*220.0*	*217.7*	*190.6*	*192.5*	*195.3*	*-9.2%*
International Bunker Fuels[b]	*103.6*	*113.3*	*124.3*	*113.6*	*69.6*	*80.2*	*98.2*	*-5.2%*
Biofuels-Ethanol[a]	*4.2*	*22.9*	*81.9*	*82.6*	*71.8*	*79.1*	*79.6*	*1783.2%*
Biofuels-Biodiesel[a]	*0.0*	*0.9*	*17.9*	*17.1*	*17.7*	*16.1*	*15.6*	*100.0%*
Biomass-MSW[a]	*18.5*	*14.7*	*16.1*	*15.7*	*15.6*	*15.3*	*14.9*	*-19.8%*
CH_4	**409.0**	**358.5**	**336.2**	**321.7**	**305.3**	**293.3**	**282.4**	**-31.0%**
Natural Gas Systems	218.8	210.1	190.3	188.7	180.3	174.6	173.1	-20.9%
Coal Mining	108.1	71.5	59.1	53.0	46.2	44.7	43.6	-59.6%
Petroleum Systems	49.4	48.2	59.0	52.2	53.3	48.6	39.6	-19.8%
Stationary Combustion	9.7	8.8	9.6	9.8	8.0	8.0	8.6	-10.8%
Abandoned Oil and Gas Wells	7.8	8.2	8.4	8.5	8.5	8.6	8.5	8.8%
Abandoned Underground Coal Mines	8.1	7.4	6.9	6.6	6.5	6.3	6.3	-21.8%
Mobile Combustion	7.2	4.3	2.8	2.9	2.5	2.6	2.6	-63.8%
Incineration of Waste	+	+	+	+	+	+	+	-17.9%
International Bunker Fuels[b]	*0.2*	*0.1*	*0.1*	*0.1*	*0.1*	*0.1*	*0.1*	*-51.8%*
N_2O	**61.2**	**67.9**	**43.2**	**41.6**	**37.1**	**39.2**	**41.9**	**-31.5%**
Stationary Combustion	22.3	30.5	25.1	22.2	20.5	22.0	24.7	10.6%
Mobile Combustion	38.4	37.0	17.7	19.1	16.1	16.8	16.7	-56.5%
Incineration of Waste	0.4	0.3	0.4	0.4	0.3	0.4	0.3	-17.9%
Natural Gas Systems	+	+	+	+	+	+	0.2	3,204.7%
Petroleum Systems	+	+	+	+	+	+	+	282.0%
International Bunker Fuels[b]	*0.8*	*0.9*	*1.0*	*0.9*	*0.5*	*0.6*	*0.8*	*1.4%*
Total	**5,381.0**	**6,349.5**	**5,570.0**	**5,422.4**	**4,862.6**	**5,173.3**	**5,199.8**	**-3.4%**

+ Does not exceed 0.05 MMT CO_2 Eq.

[a] Emissions from biomass and biofuel consumption are not included specifically in Energy sector totals. Net carbon fluxes from changes in biogenic carbon reservoirs are accounted for in the estimates for LULUCF.

[b] Emissions from international bunker fuels are not included in totals. These values are presented for informational purposes only, in line with the *2006 IPCC Guidelines*, the Paris Agreement and the UNFCCC reporting obligations.

Note: Totals may not sum due to independent rounding.

[3] The full time series data is available in Common Reporting Tables (CRTs) included in the U.S. Paris Agreement and UNFCCC submission and in CSV format available at https://www.epa.gov/ghgemissions/inventory-us-greenhouse-gas-emissions-and-sinks.

Fossil Fuel Combustion CO_2 Emissions

As the largest contributor to U.S. greenhouse gas emissions, CO_2 from fossil fuel combustion has accounted for approximately 74.6 percent of CO_2-equivalent total gross emissions on average across the time series. Within the United States, fossil fuel combustion accounted for 93.0 percent of CO_2 emissions in 2022. Emissions from this source category include CO_2 associated with the combustion of fossil fuels (coal, natural gas, and petroleum) for energy use. Fossil fuel combustion CO_2 emissions decreased by 1.1 percent (52.8 MMT CO_2 Eq.) from 1990 to 2022 and were responsible for most of the decrease in national emissions during this period. Similarly, CO_2 emissions from fossil fuel combustion have decreased by 18.2 percent (1,044.7 MMT CO_2 Eq.) since 2005. From 2021 to 2022, these emissions increased by 1.0 percent (45.1 MMT CO_2 Eq.).

Historically, changes in emissions from fossil fuel combustion have been the main factor influencing U.S. emission trends. Changes in CO_2 emissions from fossil fuel combustion since 1990 are affected by many long-term and short-term factors, including population and economic growth, energy price fluctuations and market trends, technological changes, carbon intensity of energy fuel choices, and seasonal temperatures. On an annual basis, the overall consumption and mix of fossil fuels in the United States fluctuates in response to changes in general economic conditions, overall energy prices, the relative price of different fuels, weather, and the availability of non-fossil alternatives. For example, coal consumption for electric power is influenced by factors such as the relative price of coal and alternative sources, the ability to switch fuels, and longer-term trends in coal markets. Fossil fuel combustion CO_2 emissions also depend on the type of fuel consumed or energy used and its carbon intensity. Producing a unit of heat or electricity using natural gas instead of coal, for example, reduces CO_2 emissions because of the lower carbon content of natural gas (see Table 3-12 in Chapter 3 for more detail on electricity generation by source and see Table A-19 in Annex 2.1 for more detail on the carbon content coefficient of different fossil fuels).

Overall CO_2 emissions from electric power generation decreased by 36.2 percent from 2005 to 2022 (see Figure 2-7), reflecting the continued shift in the share of electric power generation from coal to natural gas and renewables since 2005. Carbon dioxide emissions from coal combustion for electric power generation gradually increased between 1990 and 2007, then began to decrease at a faster rate from 2008 to 2022. Carbon dioxide emissions from natural gas combustion for electric power generation remained relatively constant, with a slight increase between 1990 and 2009, then began to consistently increase between 2010 and 2022.

Petroleum use is another major driver of CO_2 emissions from fossil fuel combustion, particularly in the transportation sector, which has represented the largest source of CO_2 emissions from fossil fuel combustion since 2017. Emissions from petroleum consumption for transportation (including bunker fuels) decreased by 0.1 percent from 2021 to 2022. Fuel economy of light-duty vehicles is an important factor in transportation sector CO_2 emissions trends. The decline in new light-duty vehicle fuel economy between 1990 and 2004 reflected the increasing market share of light-duty trucks, which grew from about 29.6 percent of new vehicle sales in 1990 to 48.0 percent in 2004. Starting in 2005, average new vehicle fuel economy began to increase while light-duty VMT grew only modestly for much of the period and has slowed the rate of increase of CO_2 emissions.

Trends in CO_2 emissions from fossil fuel combustion by end-use sector are presented in Table 2-5 and Figure 2-6 based on the underlying U.S. energy consumer data collected by the U.S. Energy Information Administration (EIA). Figure 2-7 further describes trends in direct and indirect CO_2 emissions from fossil fuel combustion by end-use sector. Estimates of CO_2 emissions from fossil fuel combustion are calculated from these EIA "end-use sectors" based on total fuel consumption and appropriate fuel properties described below.[4]

- *Transportation.* EIA's fuel consumption data for the transportation sector consists of all vehicles whose primary purpose is transporting people and/or goods from one physical location to another.
- *Electric Power.* EIA's fuel consumption data for the electric power sector are composed of electricity-only and combined-heat-and-power (CHP) plants within the North American Industry Classification System (NAICS) 22 category whose primary business is to sell electricity, or electricity and heat, to the public.

[4] Additional analysis and refinement of the EIA data is further explained in the Energy chapter of this report.

(Non-utility power producers are included in this sector as long as they meet the electric power sector definition.)

- *Industry.* EIA statistics for the industrial sector include fossil fuel consumption that occurs in the fields of manufacturing, agriculture, mining, and construction. EIA's fuel consumption data for the industrial sector consist of all facilities and equipment used for producing, processing, or assembling goods. (EIA includes generators that produce electricity and/or useful thermal output primarily to support on-site industrial activities in this sector.)
- *Residential.* EIA's fuel consumption data for the residential sector consist of living quarters for private households.
- *Commercial.* EIA's fuel consumption data for the commercial sector consist of service-providing facilities and equipment from private and public organizations and businesses. (EIA includes generators that produce electricity and/or useful thermal output primarily to support the activities at commercial establishments in this sector.)

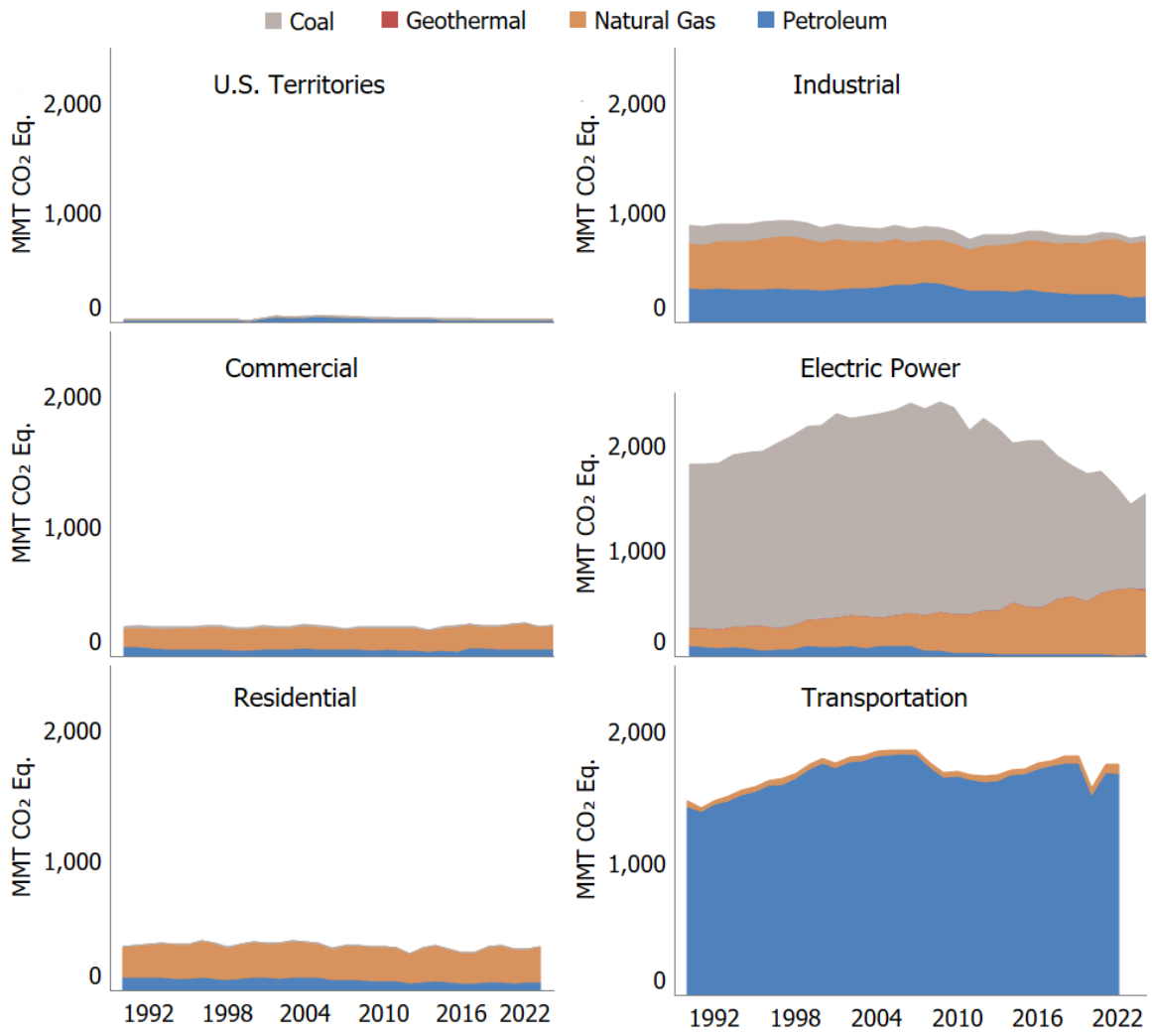
Table 2-5: CO_2 Emissions from Fossil Fuel Combustion by End-Use Sector (MMT CO_2 Eq.)

End-Use Sector	1990	2005	2018	2019	2020	2021	2022
Transportation	**1,472.0**	**1,863.3**	**1,817.9**	**1,821.4**	**1,576.9**	**1,758.6**	**1,757.4**
Combustion	1,468.9	1,858.6	1,813.1	1,816.6	1,572.8	1,753.5	1,751.3
Electricity	3.0	4.7	4.8	4.8	4.1	5.0	6.1
Industrial	**1,562.9**	**1,584.0**	**1,311.8**	**1,275.3**	**1,171.8**	**1,225.6**	**1,238.0**
Combustion	876.5	847.6	810.5	809.8	762.0	780.5	801.1
Electricity	686.4	736.3	501.3	465.5	409.8	445.1	437.0
Residential	**931.3**	**1,214.9**	**981.2**	**926.7**	**860.1**	**890.3**	**899.4**
Combustion	338.6	358.9	338.9	342.9	314.8	318.0	334.1
Electricity	592.7	856.0	642.3	583.7	545.3	572.2	565.3
Commercial	**766.0**	**1,030.1**	**851.3**	**804.4**	**709.6**	**756.1**	**782.0**
Combustion	228.3	227.1	246.3	251.7	229.3	237.5	258.7
Electricity	537.7	803.0	605.0	552.7	480.3	518.5	523.3
U.S. Territories[a]	**20.0**	**51.9**	**25.9**	**24.8**	**23.3**	**23.8**	**22.6**
Total	**4,752.2**	**5,744.1**	**4,988.2**	**4,852.6**	**4,341.7**	**4,654.3**	**4,699.4**
Electric Power	**1,820.0**	**2,400.1**	**1,753.4**	**1,606.7**	**1,439.6**	**1,540.9**	**1,531.7**

[a] Fuel consumption by U.S. Territories (i.e., American Samoa, Guam, Puerto Rico, U.S. Virgin Islands, Wake Island, and other outlying U.S. Pacific Islands) is included in this report.

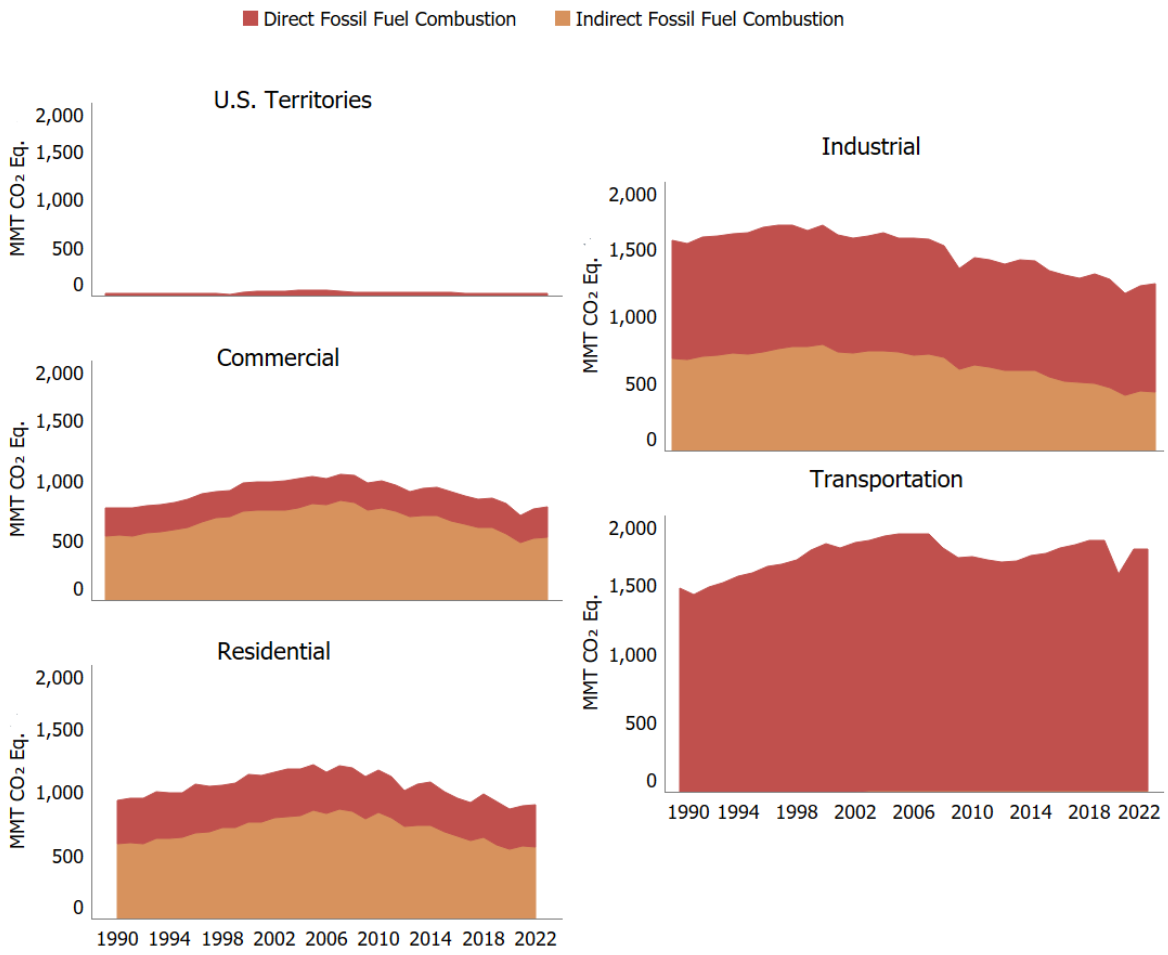
Notes: Combustion-related emissions from electric power are allocated based on aggregate national electricity use by each end-use sector. Totals may not sum due to independent rounding.

Figure 2-6: Trends in CO_2 Emissions from Fossil Fuel Combustion by End-Use Sector and Fuel Type



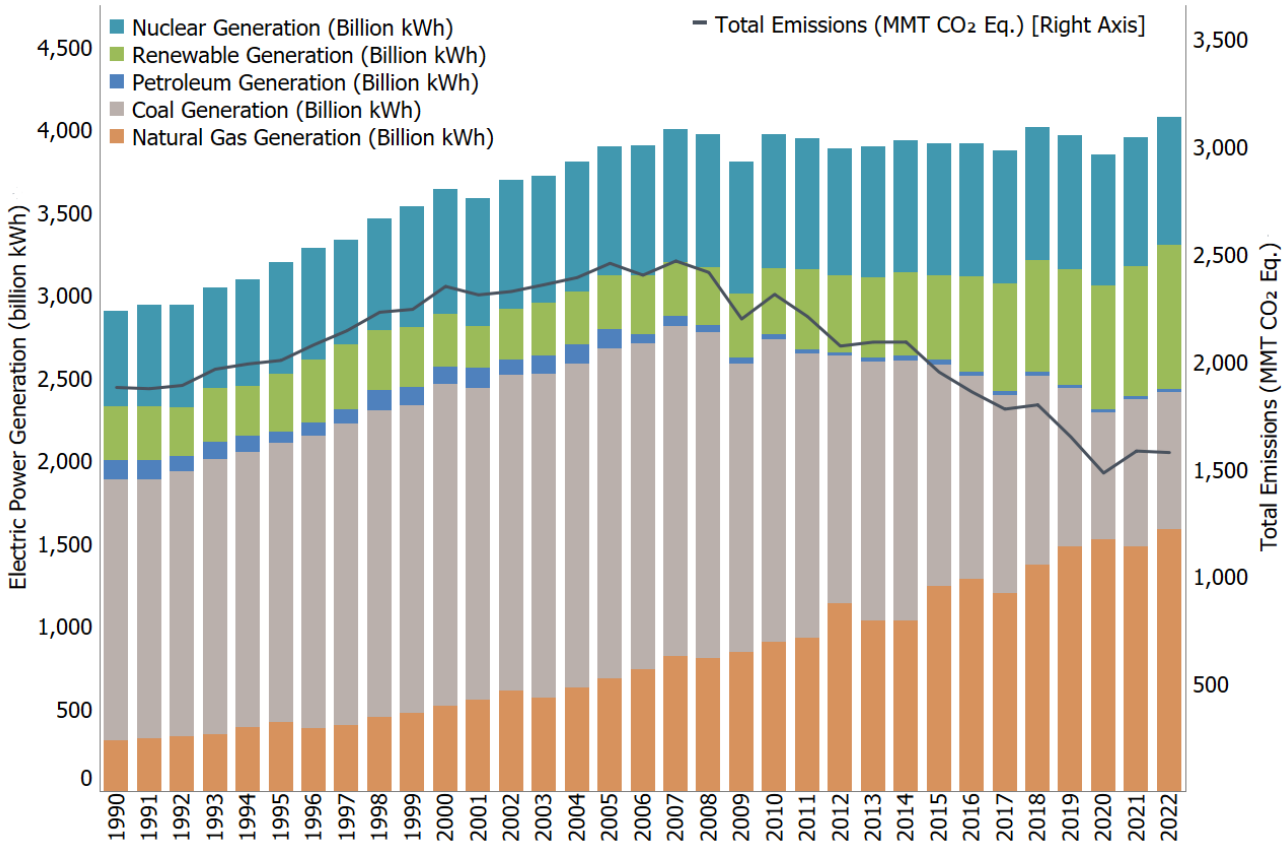
Note: Fossil fuel combustion for electric power also includes emissions of less than 0.5 MMT CO_2 Eq. from geothermal-based generation. Although not technically a fossil fuel, geothermal energy-related CO_2 emissions are included for reporting purposes. The source of CO_2 is non-condensable gases in subterranean heated water.

Figure 2-7: Trends in End-Use Sector Emissions of CO_2 from Fossil Fuel Combustion



Electric power was the second largest end-use emitter of CO_2 in 2022 (surpassed by transportation in 2017); electric power generators used 30.5 percent of U.S. energy from fossil fuels and emitted 32.6 percent of the CO_2 from fossil fuel combustion in 2022. CO_2 emissions from the fossil fuel combustion in the electric power sector decreased by 0.6 percent between 2021 and 2022 due to changes in the mix of electric generation resources. Between 2021 and 2022 overall electricity generation increased by 3 percent, coal electricity generation decreased by 10.2 percent, natural gas generation increased by 4.0 percent, and renewable energy generation increased by 7.6 percent. Changes in electricity demand and the carbon intensity of fuels used for electric power generation have a significant impact on CO_2 emissions. Carbon dioxide emissions from fossil fuel combustion from the electric power sector have decreased by 15.8 percent since 1990, and the carbon intensity of the electric power sector, in terms of CO_2 Eq. per QBtu input, has decreased by 27.6 percent during that same timeframe. This decoupling of electric power generation and the resulting CO_2 emissions is shown below in Figure 2-8.

Figure 2-8: Electric Power Generation (Billion kWh) and Emissions (MMT CO_2 Eq.)



Electric power CO_2 emissions can also be allocated to the end-use sectors that use electricity, as presented in Table 2-5. With electricity CO_2 emissions allocated to end-use sectors, the transportation end-use sector represents the largest source of fossil fuel combustion emissions accounting for 1,757.4 MMT CO_2 Eq. in 2022 or 37.4 percent of total CO_2 emissions from fossil fuel combustion, a 0.1 percent decrease since 2021. The industrial end-use sector accounted for 26.3 percent of CO_2 emissions from fossil fuel combustion when including allocated electricity emissions, an increase of 1.0 percent since 2021. From 2021 to 2022, total energy use in the industrial sector increased by 1.8 percent due to an increase in total industrial production and manufacturing output. The residential and commercial end-use sectors accounted for 19.1 and 16.6 percent, respectively, of CO_2 emissions from fossil fuel combustion when including allocated electricity emissions. Both of these end-use sectors were heavily reliant on electricity for meeting building-related energy needs, with electricity use for lighting, heating, air conditioning, and operating appliances contributing 62.9 and 66.9 percent of emissions from the residential and commercial end-use sectors, respectively. From 2021 to 2022, an increase in heating degree days (7.9 percent) increased energy demand for heating in the residential and commercial sectors; also, a 4.3 percent increase in cooling degree days compared to 2021 increased demand for air conditioning in the residential and commercial sectors. As a result, CO_2 emissions from the residential and commercial end-use sectors when including allocated electricity emissions increased by 1.0 and 3.4 percent since 2021, respectively.

Other Energy Sector Trends

Energy sector emissions increased by 0.5 percent since 2021 and decreased by 3.4 percent since 1990. Other notable trends in emissions from energy source categories (Figure 2-6 and Figure 2-7) over the 33-year period from 1990 through 2022 included the following:

- Emissions (CH_4, CO_2, and N_2O) from oil and gas systems decreased by 13.0 percent (38.8 MMT CO_2 Eq.) since 1990 and decreased by 4.2 percent (11.8 MMT CO_2 Eq.) from 2021 to 2022. Natural gas systems CH_4 emissions have decreased by 20.9 percent (45.7 MMT CO_2 Eq.) since 1990, due to a decrease in emissions from the distribution, transmission and storage, processing, and exploration segments. The decrease in distribution emissions is due mainly to reduced emissions from pipeline and distribution station leaks, and the decrease in transmission and storage emissions is due mainly to reduced compressor station emissions (including emissions from compressors and leaks). Over the same time period (i.e., since 1990), methane emissions from the natural gas production segment increased due to increased gathering and boosting emissions. Between 2021 and 2022, methane emissions from natural gas systems decreased 0.8 percent, due to a decrease in emissions from production segment pneumatic controllers. Petroleum systems CH_4 emissions decreased by 19.8 percent (9.8 MMT CO_2 Eq.) since 1990 and 18.5 percent between 2021 and 2022. This decrease is due primarily to decreases in emissions from offshore platforms, tanks, and pneumatic controllers. Carbon dioxide emissions from natural gas and petroleum systems increased by 39.1 percent (16.4 MMT CO_2) from 1990 to 2022 and decreased by 2.5 percent between 2021 and 2022. This increase since 1990 is due primarily to increases in the production segment, where emissions from associated gas flaring, tanks, and miscellaneous production flaring have increased over time. The decrease in emissions between 2021 and 2022 and is also due primarily to the production segment, where flaring emissions decreased for associated gas and tanks.
- Methane emissions from coal mining decreased by 59.6 percent (64.4 MMT CO_2 Eq.) from 1990 through 2022 and by 2.3 percent between 2021 and 2022 primarily due to a decrease in the number of active mines and annual coal production over the 1990 to 2022 time period. Between 2021 and 2022, the number of mines and coal production increased.
- Nitrous oxide emissions from mobile combustion decreased by 56.5 percent (21.7 MMT CO_2 Eq.) from 1990 through 2022 and by 0.7 percent (0.1 MMT CO_2 Eq.) between 2021 and 2022, primarily as a result of national vehicle criteria pollutant emissions standards and emission control technologies for on-road vehicles.
- Nitrous oxide emissions from stationary combustion were the third largest source of anthropogenic N_2O emissions in 2022, accounting for 6.3 percent of N_2O emissions and 0.4 percent of total gross U.S. greenhouse gas emissions in 2022. Stationary combustion emissions peaked in 2007 and have steadily decreased since then.
- Carbon dioxide emissions from non-energy uses of fossil fuels increased by 3.7 percent (3.7 MMT CO_2 Eq.) from 1990 through 2022 but decreased by 7.9 percent (8.8 MMT CO_2 Eq.) between 2021 and 2022. Emissions from non-energy uses of fossil fuels were 102.8 MMT CO_2 Eq. in 2022, which constituted 2.0 percent of total national CO_2 emissions, approximately the same proportion as in 1990.
- Carbon dioxide emissions from incineration of waste decreased slightly by 4.2 percent (0.5 MMT CO_2 Eq.) from 1990 through 2022, as the volume of scrap tires and other fossil carbon-containing materials in waste decreased. Emissions decreased 0.9 percent (0.1 MMT CO_2 Eq.) between 2021 and 2022, consistent with trends across the time series.

Industrial Processes and Product Use

Greenhouse gases can be generated and emitted by industry in two different ways. First, they are generated and emitted as the byproducts of many non-energy-related industrial activities. For example, industrial processes can chemically or physically transform raw materials, which often release waste gases such as CO_2, CH_4, N_2O, and fluorinated gases (e.g., HFC-23). In the case of byproduct emissions, the emissions are generated by an industrial process itself, and are not directly a result of energy consumed during the process.

Second, industrial manufacturing processes and use by end-consumers also release HFCs, PFCs, SF_6, and NF_3 and other man-made compounds. In addition to the use of HFCs and some PFCs as substitutes for ozone depleting substances (ODS), fluorinated compounds such as HFCs, PFCs, SF_6, NF_3, and others are also emitted through use by

a number of other industrial sources in the United States. These industries include the electronics industry, electrical equipment, and magnesium metal production and processing. In addition, N_2O is used in and emitted by the electronics industry and anesthetic and aerosol applications, PFCs and SF_6 are emitted from other product use, and CO_2 is consumed and emitted through various end-use applications.

Emission sources in the Industrial Processes and Product Use (IPPU) chapter accounted for 6.0 percent of U.S. greenhouse gas emissions in 2022. Emissions from the IPPU sector increased by 3.9 percent from 1990 to 2022. The use of HFCs as substitutes for ODS is the largest source of emissions in this sector, contributing 46.5 percent of IPPU emissions in 2022 and driving growth since 1990. From 2021 to 2022, total emissions from IPPU increased 0.4 percent between 2021 and 2022. Despite the sectoral increase in emissions, emissions from adipic acid production decreased by almost 70 percent, emissions from ferroalloy production decreased by over 10 percent, and emissions from aluminum production, petrochemical production and zinc production decreased by between 5 and 10 percent. Figure 2-9 presents greenhouse gas emissions from IPPU by source category.

Figure 2-9: Trends in Industrial Processes and Product Use Sector Greenhouse Gas Sources

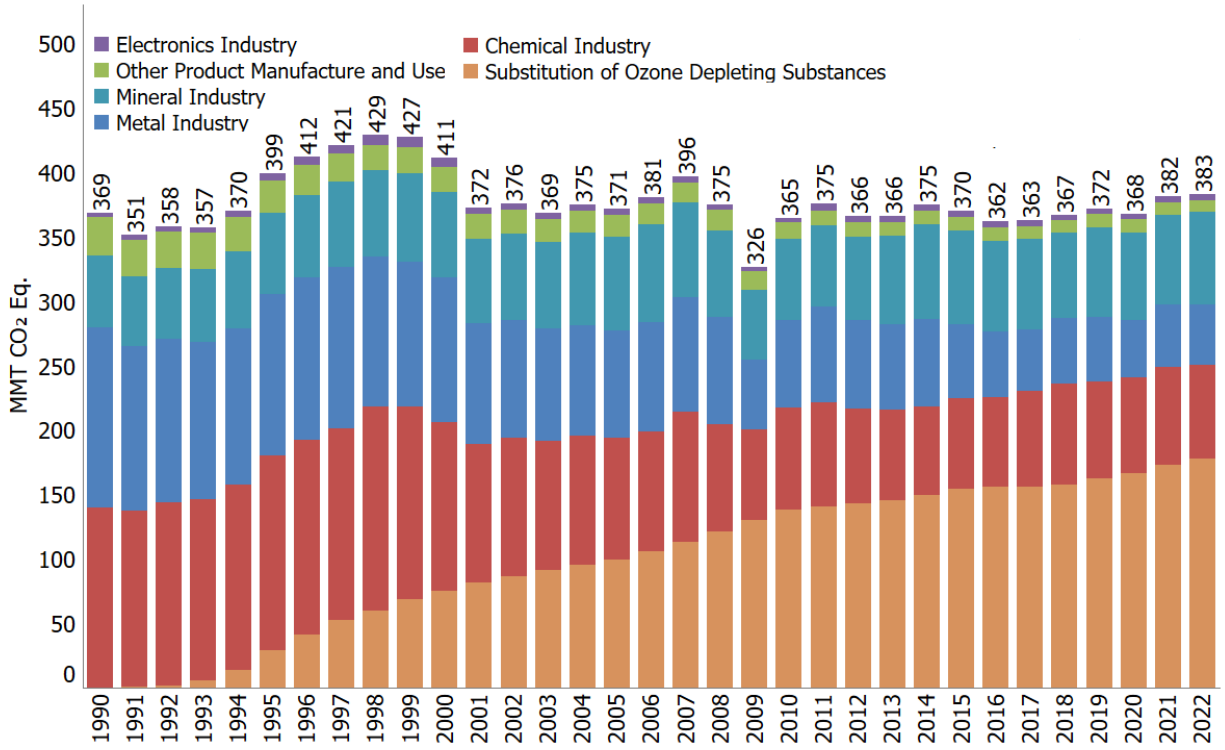


Table 2-6: Emissions from Industrial Processes and Product Use (MMT CO_2 Eq.)

	1990	2005	2018	2019	2020	2021	2022	Percent Change Since 1990
CO_2	**213.7**	**195.9**	**164.4**	**168.2**	**160.7**	**168.8**	**168.9**	**-20.9%**
Cement Production	33.5	46.2	39.0	40.9	40.7	41.3	41.9	25.1%
Iron and Steel Production & Metallurgical Coke Production	104.7	70.1	42.9	43.1	37.7	41.9	40.7	-61.2%
Iron and Steel Production	*99.1*	*66.2*	*41.6*	*40.1*	*35.4*	*38.6*	*37.7*	*-62.0%*
Metallurgical Coke Production	*5.6*	*3.9*	*1.3*	*3.0*	*2.3*	*3.2*	*3.0*	*-47.3%*
Petrochemical Production	20.1	26.9	27.2	28.5	27.9	30.7	28.8	43.4%
Ammonia Production	14.4	10.2	12.7	12.4	13.0	12.2	12.6	-12.5%

Lime Production	11.7	14.6	13.1	12.1	11.3	11.9	12.2	4.3%
Other Process Uses of Carbonates	7.1	8.5	7.9	9.0	9.0	8.6	10.4	46.2%
Urea Consumption for Non-Agricultural Purposes	3.8	3.7	6.1	6.2	5.8	6.6	7.1	86.4%
Carbon Dioxide Consumption	1.5	1.4	4.1	4.9	5.0	5.0	5.0	239.7%
Glass Production	2.3	2.4	2.0	1.9	1.9	2.0	2.0	-13.6%
Soda Ash Production	1.4	1.7	1.7	1.8	1.5	1.7	1.7	19.0%
Titanium Dioxide Production	1.2	1.8	1.5	1.3	1.3	1.5	1.5	23.3%
Aluminum Production	6.8	4.1	1.5	1.9	1.7	1.5	1.4	-78.8%
Ferroalloy Production	2.2	1.4	2.1	1.6	1.4	1.6	1.3	-38.3%
Zinc Production	0.6	1.0	1.0	1.0	1.0	1.0	0.9	49.9%
Phosphoric Acid Production	1.5	1.3	0.9	0.9	0.9	0.9	0.8	-45.0%
Lead Production	0.5	0.6	0.5	0.5	0.5	0.4	0.4	-17.1%
Carbide Production and Consumption	0.2	0.2	0.2	0.2	0.2	0.2	0.2	-13.7%
Substitution of Ozone Depleting Substances[a]	+	+	+	+	+	+	+	28,664.2%
Magnesium Production and Processing	0.1	+	+	+	+	+	+	-97.7%
CH_4	**0.1**	**+**	**+**	**+**	**+**	**+**	**+**	**-48.9%**
Carbide Production and Consumption	+	+	+	+	+	+	+	-38.5%
Ferroalloy Production	+	+	+	+	+	+	+	-45.2%
Iron and Steel Production & Metallurgical Coke Production	+	+	+	+	+	+	+	-67.8%
Petrochemical Production	+	+	+	+	+	+	+	-21.7%
N_2O	**29.6**	**22.2**	**23.1**	**18.7**	**20.8**	**19.7**	**16.1**	**-45.7%**
Nitric Acid Production	10.8	10.1	8.5	8.9	8.3	7.9	8.6	-20.2%
N_2O from Product Uses	3.8	3.8	3.8	3.8	3.8	3.8	3.8	-0.4%
Adipic Acid Production	13.5	6.3	9.3	4.7	7.4	6.6	2.1	-84.5%
Caprolactam, Glyoxal, and Glyoxylic Acid Production	1.5	1.9	1.3	1.2	1.1	1.2	1.3	-10.5%
Electronics Industry	+	0.1	0.2	0.2	0.3	0.3	0.3	720.0%
HFCs	**47.7**	**121.7**	**163.9**	**168.2**	**170.3**	**177.0**	**182.8**	**282.9%**
Substitution of Ozone Depleting Substances[a]	0.3	99.5	157.9	162.1	166.2	172.6	178.1	70,357.0%
Fluorochemical Production	47.3	22.1	5.7	5.7	3.8	4.0	4.3	-90.9%
Electronics Industry	0.2	0.2	0.3	0.3	0.3	0.4	0.3	74.0%
Magnesium Production and Processing	NO	NO	0.1	0.1	0.1	+	+	100.0%
PFCs	**39.5**	**10.2**	**7.4**	**7.3**	**6.6**	**6.3**	**6.7**	**-83.1%**
Fluorochemical Production	17.5	4.0	2.9	3.0	2.5	2.6	3.0	-83.1%
Electronics Industry	2.5	3.0	2.9	2.6	2.5	2.6	2.7	7.8%
Aluminum Production	19.3	3.1	1.4	1.4	1.4	0.9	0.8	-96.1%
SF_6 and PFCs from Other Product Use	0.1	0.1	0.2	0.2	0.2	0.1	0.2	39.4%
Substitution of Ozone Depleting Substances[a]	NO	+	+	+	+	+	+	100.0%
Electrical Equipment	+	+	NO	+	+	+	+	-99.2%
SF_6	**37.9**	**20.2**	**7.6**	**8.4**	**8.1**	**8.5**	**7.6**	**-80.0%**
Electrical Equipment	24.7	11.8	5.0	6.1	5.9	6.0	5.1	-79.4%
Magnesium Production and Processing	5.6	3.0	1.1	0.9	0.9	1.2	1.1	-80.0%
Electronics Industry	0.5	0.8	0.8	0.8	0.8	0.9	0.8	47.0%

SF_6 and PFCs from Other Product Use	1.3	1.3	0.8	0.6	0.5	0.4	0.6	-53.0%
Fluorochemical Production	5.8	3.3	+	+	+	+	+	-100.0%
NF_3	**0.3**	**1.0**	**0.7**	**1.1**	**1.3**	**1.1**	**1.1**	**238.3%**
Electronics Industry	+	0.4	0.5	0.5	0.6	0.6	0.6	1313.8%
Fluorochemical Production	0.3	0.6	0.1	0.6	0.7	0.5	0.5	72.7%
Total	**368.8**	**371.3**	**367.2**	**371.9**	**367.9**	**381.6**	**383.2**	**3.9%**

+ Does not exceed 0.05 MMT CO_2 Eq.

NO (Not Occurring)

[a] Small amounts of PFC emissions from this source are included under HFCs due to confidential business information.

Note: Totals may not sum due to independent rounding.

IPPU sector emissions increased 0.4 percent since 2021 and 3.9 percent since 1990. Some significant trends in U.S. emissions from IPPU source categories over the 33-year period from 1990 through 2022 included the following:

- HFC and PFC emissions resulting from the substitution of ODS (e.g., chlorofluorocarbons [CFCs]) increased from small amounts in 1990 to 178.1 MMT CO_2 Eq. in 2022 (an increase of 70,357 percent).
- Combined CO_2 and CH_4 emissions from iron and steel production and metallurgical coke production decreased by 2.9 percent from 2021 to 2022 to 40.7 MMT CO_2 Eq. and declined overall by 61.2 percent (64.1 MMT CO_2 Eq.) from 1990 through 2022, due to restructuring of the industry. The trend in the United States has been a shift toward fewer integrated steel mills and more electric arc furnaces (EAFs). EAFs use scrap steel as their main input and generally have lower on-site emissions.
- Carbon dioxide emissions from petrochemical production increased by 43.4 percent between 1990 and 2022, from 20.1 MMT CO_2 Eq. to 28.8 MMT CO_2 Eq. The increase in emissions is largely driven by the production of ethylene more than doubling over that period.
- Carbon dioxide emissions from ammonia production have decreased by 12.5 percent (1.8 MMT CO_2 Eq.) since 1990. Ammonia production relies on natural gas as both a feedstock and a fuel, and as such, market fluctuations and volatility in natural gas prices affect the production of ammonia from year to year. Emissions from ammonia production have increased since 2016, due to the addition of new ammonia production facilities and new production units at existing facilities. Agricultural demands continue to drive demand for nitrogen fertilizers and the need for new ammonia production capacity.
- Carbon dioxide emissions from cement production increased by 25.1 percent (8.4 MMT CO_2 Eq.) from 1990 through 2022. Emissions rose from 1990 through 2006 and then fell until 2009, due to a decrease in demand for construction materials during the economic recession. Since 2010, CO_2 emissions from cement production have risen by 33.2 percent.
- HFC, PFC, SF_6, and NF_3 emissions from fluorochemical production decreased by 89.0 percent (63.2 MMT CO_2 Eq.) from 1990 to 2022 due to a reduction in the HFC-23 emission rate from HCFC-22 production (kg HFC-23 emitted/kg HCFC-22 produced), the imposition of emissions controls at production facilities, and a decrease in SF_6 production due to the cessation of production at the major SF_6 production facility in 2010.
- PFC emissions from aluminum production decreased by 96.1 percent (18.5 MMT CO_2 Eq.) from 1990 to 2022, due to both industry emission reduction efforts and lower domestic aluminum production.
- SF_6 emissions from electrical equipment decreased by 79.4 percent (19.6 MMT CO_2 Eq.) from 1990 to 2022 due to a sharp increase in the price of SF_6 during the 1990s and industry emission reduction efforts.

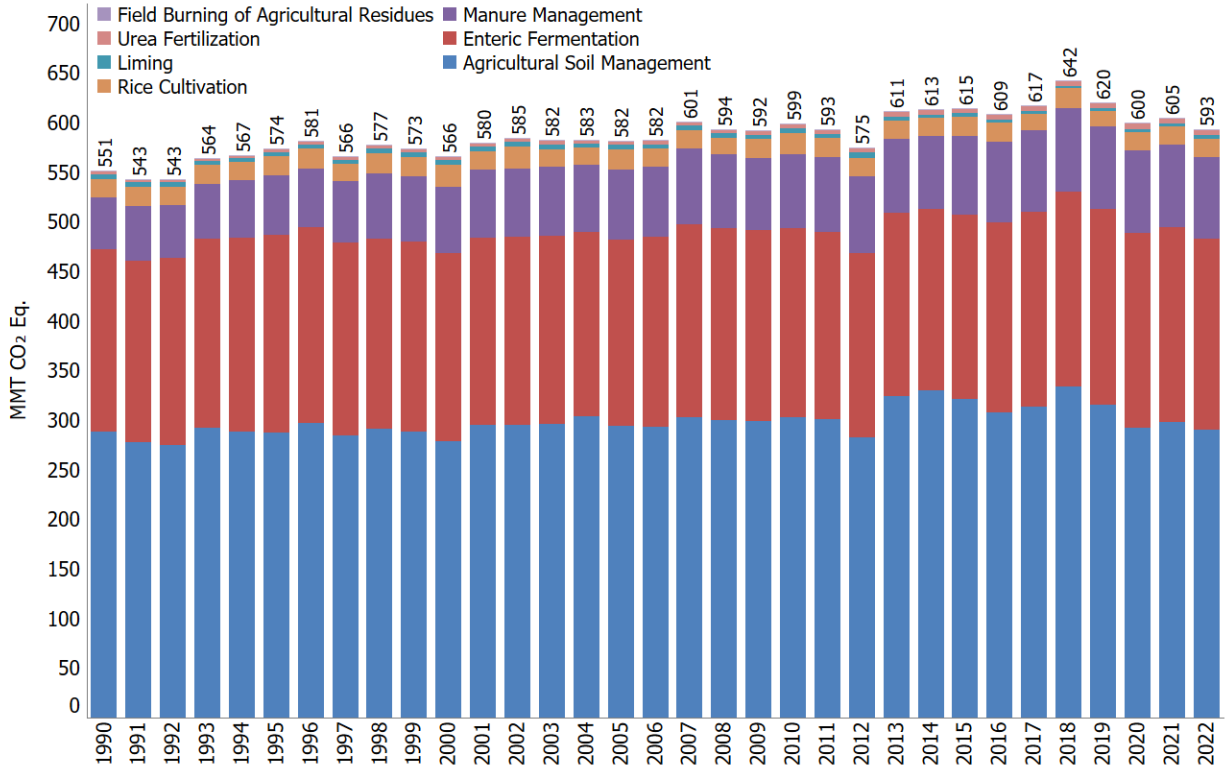
Agriculture

Agricultural activities contribute directly to emissions of greenhouse gases through a variety of processes, including the following source categories: enteric fermentation in domestic livestock, livestock manure management, rice cultivation, agricultural soil management, liming, urea fertilization, and field burning of agricultural residues. Methane and N_2O are the primary greenhouse gases emitted by agricultural activities, with

small amounts of CO_2 also emitted.[5] Carbon stock changes from agricultural soils are included in the LULUCF sector.

In 2022, agricultural activities were responsible for emissions of 593.4 MMT CO_2 Eq., or 9.4 percent of total U.S. greenhouse gas emissions. Agricultural soil management activities, such as the application of synthetic and organic fertilizers, deposition of livestock manure, and growing N-fixing plants, were the largest contributors to agricultural-related emissions (49.0 percent) and were the largest source of U.S. N_2O emissions in 2022, accounting for 74.6 percent. Methane emissions from enteric fermentation and manure management represented 27.4 percent and 9.2 percent of total CH_4 emissions from anthropogenic activities, respectively, in 2022. Carbon dioxide emissions from the application of crushed limestone and dolomite (i.e., soil liming) and urea fertilization represented 0.2 percent of total CO_2 emissions from anthropogenic activities. Figure 2-10 and Table 2-7 illustrate agricultural greenhouse gas emissions by source and gas.

Figure 2-10: Trends in Agriculture Sector Greenhouse Gas Sources



[5] The contribution of agriculture non-CO_2 emissions is based on gross totals and excludes LULUCF methane (CH_4) and nitrous oxide (N_2O) emissions. The contribution of agriculture CH_4 and N_2O including LULUCF non-CO_2 emissions, is 40.5 percent and 48.3 percent, respectively.

Table 2-7: Emissions from Agriculture (MMT CO_2 Eq.)

Gas/Source	1990	2005	2018	2019	2020	2021	2022	Percent Change Since 1990
CO_2	**7.1**	**7.9**	**7.2**	**7.2**	**8.0**	**7.6**	**8.6**	**21.0%**
Urea Fertilization	2.4	3.5	4.9	5.0	5.1	5.2	5.3	120.4%
Liming	4.7	4.4	2.2	2.2	2.9	2.4	3.3	-30.3%
CH_4	**241.7**	**264.4**	**285.0**	**280.2**	**282.4**	**281.8**	**276.8**	**14.5%**
Enteric Fermentation	183.1	188.2	196.8	197.3	196.3	196.5	192.6	5.2%
Manure Management	39.1	55.0	67.7	66.7	66.9	66.4	64.7	65.3%
Rice Cultivation	18.9	20.6	19.9	15.6	18.6	18.3	18.9	-0.4%
Field Burning of Agricultural Residues	0.5	0.6	0.6	0.7	0.6	0.6	0.6	14.4%
N_2O	**302.3**	**309.5**	**350.2**	**332.6**	**309.2**	**315.3**	**308.0**	**1.9%**
Agricultural Soil Management	288.8	294.1	333.4	315.6	292.1	298.0	290.8	0.7%
Manure Management	13.4	15.2	16.6	16.8	16.9	17.1	17.0	27.2%
Field Burning of Agricultural Residues	0.2	0.2	0.2	0.2	0.2	0.2	0.2	15.5%
Total	**551.1**	**581.8**	**642.4**	**620.1**	**599.7**	**604.8**	**593.4**	**7.7%**

Note: Totals may not sum due to independent rounding.

Agriculture sector emissions decreased by 1.9 percent since 2021 and increased by 7.7 percent since 1990. Some significant trends in U.S. emissions from Agriculture source categories (Figure 2-10) over the 33-year time series from 1990 through 2022 included the following:

- Agricultural soils are the largest anthropogenic source of agriculture-related emissions and of N_2O emissions in the United States, accounting for 74.6 percent of N_2O emissions and 4.6 percent of total emissions in the United States in 2022. Annual N_2O emissions from agricultural soils fluctuated between 1990 and 2022, and overall emissions were 0.7 percent (2.0 MMT CO_2 Eq.) higher in 2022 than in 1990. Year-to-year fluctuations are largely a reflection of annual variation in weather patterns, synthetic fertilizer use, and crop production.
- Enteric fermentation is the largest anthropogenic source of CH_4 emissions in the United States. In 2022, enteric fermentation CH_4 emissions were 27.4 percent of total CH_4 emissions, which represents an increase of 5.2 percent (9.5 MMT CO_2 Eq.) since 1990. This increase in emissions from enteric fermentation from 1990 to 2022 generally follows the increasing trends in cattle populations. For example, from 1990 to 1995, emissions increased and then generally decreased from 1996 to 2004, mainly due to fluctuations in beef cattle populations and increased digestibility of feed for feedlot cattle. Emissions increased from 2005 to 2007, as both dairy and beef populations increased. Research indicates that the feed digestibility of dairy cow diets decreased during this period. Emissions decreased again from 2008 to 2014 as beef cattle populations again decreased. Emissions increased from 2014 to 2022, consistent with an increase in beef cattle population over those same years. CH_4 emissions from enteric fermentation decreased by 2.0 percent (3.9 MMT CO_2 Eq.) from 2021 to 2022, however, largely driven by a decrease in beef cattle populations.
- Manure management is the fourth largest anthropogenic source of CH_4 and N_2O emissions in the United States and accounted for 13.8 percent of Agriculture sector emissions in 2022. Emissions from manure management increased by 55.6 percent between 1990 and 2022. This includes an increase of 65.3 percent (25.6 MMT CO_2 Eq.) for CH_4 and an increase of 27.2 percent (3.6 MMT CO_2 Eq.) for N_2O. The majority of the increase observed in CH_4 emissions resulted from swine and dairy cattle manure, where emissions increased by 37.2 and 108.7 percent, respectively, from 1990 to 2022. From 2021 to 2022, CH_4 emissions from manure management decreased by 2.6 percent, mainly due to minor shifts in the animal populations and the resultant effects on manure management system allocations.

- Liming and urea fertilization are the only sources of CO_2 emissions reported in the Agriculture sector. All other CO_2 emissions and removals (e.g., carbon stock changes from the management of croplands) are included in the LULUCF sector. Liming emissions increased by 36.9 percent relative to 2021 and decreased by 30.3 percent (1.4 MMT CO_2 Eq.) relative to 1990, while urea fertilization emissions increased by 1.9 percent relative to 2021 and 120.4 percent (2.9 MMT CO_2 Eq.) relative to 1990.

Land Use, Land-Use Change, and Forestry

When humans alter the terrestrial biosphere through land use, changes in land use, and land management practices, they also influence the carbon stock fluxes on these lands and cause emissions of CH_4 and N_2O. Overall, managed land is a net sink for CO_2 (carbon sequestration) in the United States. The primary driver of fluxes on managed lands is from management of forest lands, but also includes trees in settlements (i.e., urban areas), afforestation, conversion of forest lands to settlements and croplands, the management of croplands and grasslands, flooded lands, and the landfilling of yard trimmings and food scraps. The main drivers for net forest sequestration include net forest growth, increasing forest area, and a net accumulation of carbon stocks in harvested wood pools. The net sequestration in settlements remaining settlements is driven primarily by carbon stock gains in urban forests (i.e., settlement trees) through net tree growth and increased urban area, as well as long-term accumulation of carbon in landfills from additions of yard trimmings and food scraps.

The LULUCF sector in 2022 resulted in a net increase in carbon stocks (i.e., net CO_2 removals) of 921.8 MMT CO_2 Eq. (Table 2-8).[6] This represents an offset of 14.5 percent of total (i.e., gross) greenhouse gas emissions in 2022. Emissions of CH_4 and N_2O from LULUCF activities in 2022 were 67.6 MMT CO_2 Eq. and represented 1.2 percent of net greenhouse gas emissions.[7] Between 1990 and 2022, total net carbon sequestration in the LULUCF sector decreased by 10.9 percent, primarily due to a decrease in the rate of net carbon accumulation in forests and cropland remaining cropland, as well as an increase in CO_2 emissions from land converted to settlements.

Flooded land remaining flooded land was the largest source of CH_4 emissions from LULUCF and the fifth largest source overall of net CH_4 emissions in 2022, totaling 44.2 MMT CO_2 Eq. (1,579 kt of CH_4). Forest fires were the second largest source of CH_4 emissions from LULUCF in 2022, totaling 9.1 MMT CO_2 Eq. (327 kt of CH_4). Forest fires were the largest source of N_2O emissions from LULUCF in 2022, totaling 5.7 MMT CO_2 Eq. (22 kt of N_2O). Figure 2-11 and Table 2-8 illustrate LULUCF emissions and removals by land-use category and gas.

[6] LULUCF carbon stock change is the net carbon stock change from the following categories: forest land remaining forest land, land converted to forest land, cropland remaining cropland, land converted to cropland, grassland remaining grassland, land converted to grassland, wetlands remaining wetlands, land converted to wetlands, settlements remaining settlements, and land converted to settlements.

[7] LULUCF emissions include the CH_4 and N_2O emissions reported for peatlands remaining peatlands, forest fires, drained organic soils, grassland fires, and coastal wetlands remaining coastal wetlands; CH_4 emissions from flooded land remaining flooded land, land converted to flooded land, and land converted to coastal wetlands; and N_2O emissions from forest soils and settlement soils.

Figure 2-11: Trends in Emissions and Removals (Net CO_2 Flux) from Land Use, Land-Use Change, and Forestry

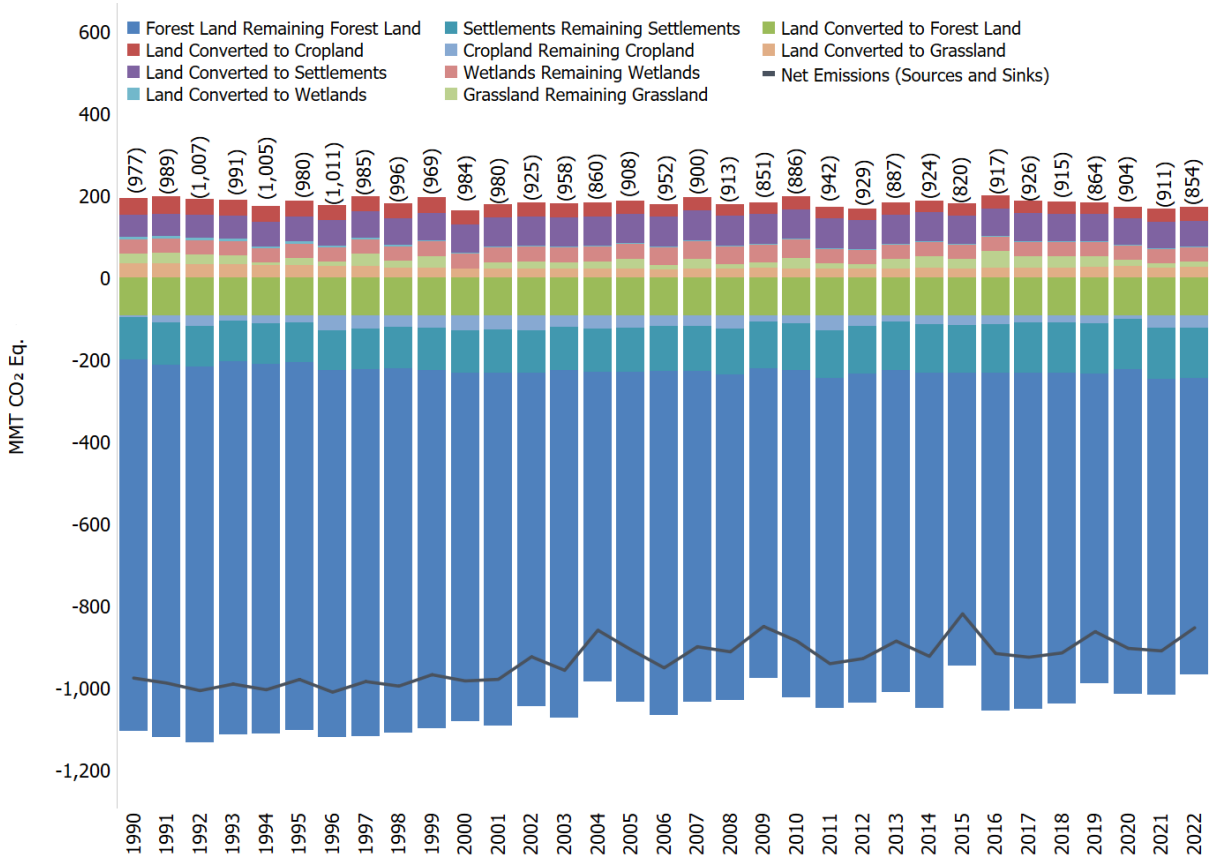


Table 2-8: U.S. Greenhouse Gas Emissions and Removals (Net Flux) from Land Use, Land-Use Change, and Forestry (MMT CO_2 Eq.)

Land-Use Category	1990	2005	2018	2019	2020	2021	2022	Percent Change Since 1990
Forest Land Remaining Forest Land	**(968.8)**	**(860.1)**	**(863.4)**	**(807.0)**	**(846.3)**	**(823.9)**	**(771.7)**	**-20.3%**
Changes in Forest Carbon Stocks[a]	(974.8)	(876.0)	(873.5)	(813.2)	(862.0)	(844.2)	(787.0)	-19.3%
Non-CO_2 Emissions from Forest Fires[b]	5.8	15.4	9.7	5.7	15.3	19.9	14.8	153.9%
N_2O Emissions from Forest Soils[c]	0.1	0.4	0.4	0.4	0.4	0.4	0.4	455.1%
Non-CO_2 Emissions from Drained Organic Soils[d]	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.0%
Land Converted to Forest Land	**(100.2)**	**(100.2)**	**(100.4)**	**(100.3)**	**(100.3)**	**(100.3)**	**(100.3)**	**0.1%**
Changes in Forest Carbon Stocks[e]	(100.2)	(100.2)	(100.4)	(100.3)	(100.3)	(100.3)	(100.3)	0.1%
Cropland Remaining Cropland	**(5.0)**	**(31.6)**	**(17.8)**	**(19.4)**	**(8.8)**	**(32.0)**	**(31.7)**	**529.0%**
Changes in Mineral and Organic Soil Carbon Stocks	(5.0)	(31.6)	(17.8)	(19.4)	(8.8)	(32.0)	(31.7)	529.0%
Land Converted to Cropland	**45.4**	**34.5**	**31.9**	**31.4**	**29.3**	**34.9**	**35.1**	**-22.7%**
Changes in all Ecosystem Carbon Stocks[f]	45.4	34.5	31.9	31.4	29.3	34.9	35.1	-22.7%
Grassland Remaining Grassland	**24.6**	**24.9**	**29.7**	**28.9**	**17.1**	**11.5**	**14.0**	**-43.1%**

Changes in Mineral and Organic Soil Carbon Stocks	24.4	24.1	28.6	28.5	16.1	10.6	13.4	-45.2%
Non-CO_2 Emissions from Grassland Fires[g]	0.2	0.8	1.1	0.3	1.1	0.9	0.6	184.1%
Land Converted to Grassland	**35.3**	**21.8**	**25.2**	**25.4**	**28.7**	**24.5**	**25.6**	**-27.3%**
Changes in all Ecosystem Carbon Stocks[f]	35.3	21.8	25.2	25.4	28.7	24.5	25.6	-27.3%
Wetlands Remaining Wetlands	**36.8**	**39.4**	**38.2**	**38.1**	**38.1**	**38.1**	**38.1**	**3.6%**
Changes in Organic Soil Carbon Stocks in Peatlands	1.1	1.1	0.7	0.6	0.6	0.5	0.6	-45.7%
Non-CO_2 Emissions from Peatlands Remaining Peatlands	+	+	+	+	+	+	+	-47.0%
Changes in Biomass, DOM, and Soil Carbon Stocks in Coastal Wetlands	(10.8)	(10.1)	(11.1)	(11.1)	(11.1)	(11.1)	(11.1)	2.8%
CH_4 Emissions from Coastal Wetlands Remaining Coastal Wetlands	4.2	4.2	4.3	4.3	4.3	4.3	4.3	3.4%
N_2O Emissions from Coastal Wetlands Remaining Coastal Wetlands	0.1	0.2	0.1	0.1	0.1	0.1	0.1	14.9%
CH_4 Emissions from Flooded Land Remaining Flooded Land	42.3	44.0	44.2	44.2	44.2	44.2	44.2	4.7%
Land Converted to Wetlands	**7.2**	**1.8**	**0.7**	**0.7**	**0.7**	**0.7**	**0.7**	**-90.3%**
Changes in Biomass, DOM, and Soil Carbon Stocks in Land Converted to Coastal Wetlands	0.5	0.5	(+)	(+)	(+)	(+)	(+)	-97.0%
CH_4 Emissions from Land Converted to Coastal Wetlands	0.3	0.3	0.2	0.2	0.2	0.2	0.2	-38.9%
Changes in Land Converted to Flooded Land	3.6	0.6	0.3	0.3	0.3	0.3	0.3	-91.7%
CH_4 Emissions from Land Converted to Flooded Land	2.9	0.4	0.2	0.2	0.2	0.2	0.2	-92.6%
Settlements Remaining Settlements	**(109.1)**	**(115.2)**	**(131.0)**	**(131.5)**	**(131.8)**	**(132.3)**	**(132.3)**	**21.2%**
Changes in Organic Soil Carbon Stocks	9.9	10.1	14.4	14.6	15.1	15.4	15.4	56.0%
Changes in Settlement Tree Carbon Stocks	(96.6)	(117.0)	(134.4)	(135.6)	(136.7)	(137.8)	(138.5)	43.4%
N_2O Emissions from Settlement Soils[h]	2.1	3.1	2.4	2.5	2.5	2.5	2.5	22.8%
Changes in Yard Trimming and Food Scrap Carbon Stocks in Landfills	(24.5)	(11.4)	(13.4)	(13.1)	(12.8)	(12.5)	(11.8)	-52.0%
Land Converted to Settlements	**57.2**	**77.1**	**71.4**	**70.2**	**68.8**	**68.2**	**68.2**	**19.1%**
Changes in all Ecosystem Carbon Stocks[f]	57.2	77.1	71.4	70.2	68.8	68.2	68.2	19.1%
LULUCF Carbon Stock Change[i]	**(1,034.7)**	**(976.6)**	**(978.3)**	**(921.6)**	**(972.8)**	**(983.4)**	**(921.8)**	**-10.9%**
LULUCF Emissions[j]	**58.0**	**68.9**	**62.8**	**58.0**	**68.4**	**72.9**	**67.6**	**16.5%**
CH_4	53.1	58.5	55.5	52.5	59.3	62.1	58.4	10.0%
N_2O	4.8	10.3	7.3	5.5	9.1	10.7	9.1	88.3%
LULUCF Sector Net Total[k]	**(976.7)**	**(907.7)**	**(915.5)**	**(863.6)**	**(904.4)**	**(910.6)**	**(854.2)**	**-12.5%**

+ Absolute value does not exceed 0.05 MMT CO_2 Eq.

[a] Includes the net changes to carbon stocks stored in all forest ecosystem pools (estimates include carbon stock changes from drained organic soils from both forest land remaining forest land and land converted to forest land) and harvested wood products.

[b] Estimates include emissions from fires on both forest land remaining forest land and land converted to forest land.

[c] Estimates include emissions from N fertilizer additions on both forest land remaining forest land and land converted to forest land.

[d] Estimates include CH_4 and N_2O emissions from drained organic soils on both forest land remaining forest land and land converted to forest land. Carbon stock changes from drained organic soils are included with the forest land remaining forest land forest ecosystem pools.
[e] Includes the net changes to carbon stocks stored in all forest ecosystem pools.
[f] Includes changes in mineral and organic soil carbon stocks for all land use conversions to cropland, grassland, and settlements. Also includes aboveground/belowground biomass, dead wood, and litter carbon stock changes for conversion of forest land to cropland, grassland, and settlements.
[g] Estimates include CH_4 and N_2O emissions from fires on both grassland remaining grassland and land converted to grassland.
[h] Estimates include N_2O emissions from N fertilizer additions on both settlements remaining settlements and land converted to settlements because it is not possible to separate the activity data at this time.
[i] LULUCF carbon stock change includes any carbon stock gains and losses from all land use and land-use conversion categories.
[j] LULUCF emissions subtotal includes the CH_4 and N_2O emissions reported for peatlands remaining peatlands, forest fires, drained organic soils, grassland fires, and coastal wetlands remaining coastal wetlands; CH_4 emissions from flooded land remaining flooded land, and land converted to flooded land, and land converted to coastal wetlands; and N_2O emissions from forest soils and settlement soils. Emissions values are included in land-use category rows.
[k] The LULUCF sector net total is the net sum of all LULUCF CH_4 and N_2O emissions to the atmosphere plus LULUCF net carbon stock changes in units of MMT CO_2 Eq.
Notes: Totals may not sum due to independent rounding. Parentheses indicate net sequestration.

Overall CH_4 and N_2O emissions from LULUCF decreased by 7.3 percent from 2021 and increased by 16.5 percent since 1990 while total net sequestration decreased by 10.9 percent since 1990 and 6.3 percent from 2021. Other trends from 1990 to 2022 in emissions from LULUCF categories (Figure 2-11) over the 33-year period included the following:

- Annual carbon sequestration by forest land (i.e., annual carbon stock accumulation in the five ecosystem carbon pools and harvested wood products for forest land remaining forest land and land converted to forest land) has decreased by 17.5 percent since 1990. This is primarily due to decreased carbon stock gains in land converted to forest land and the harvested wood products pools within forest land remaining forest land.
- Annual carbon sequestration from settlements remaining settlements (which includes organic soils, settlement trees, and landfilled yard trimmings and food scraps) has increased by 21.2 percent over the period from 1990 to 2022. This is primarily due to an increase in urbanized land area in the United States with trees growing on it.
- Annual emissions from land converted to settlements increased by 19.1 percent from 1990 to 2022 due primarily to carbon stock losses from forest land converted to settlements and mineral soils carbon stocks from grassland converted to settlements.

Waste

Waste management and treatment activities are sources of CH_4 and N_2O emissions (see Figure 2-12 and Table 2-9). Overall, emission sources accounted for in the Waste chapter generated 166.9 MMT CO_2 Eq., or 2.6 percent of total U.S. greenhouse gas emissions in 2022. In 2022, landfills were the largest source of waste emissions, accounting for 71.8 percent of waste-related emissions. Landfills are also the third-largest source of U.S. anthropogenic CH_4 emissions, generating 119.8 MMT CO_2 Eq. and accounting for 17.1 percent of total U.S. CH_4 emissions in 2022.[8] Additionally, wastewater treatment generated emissions of 42.7 MMT CO_2 Eq. and accounted for 25.6 percent of waste emissions, 3.0 percent of U.S. CH_4 emissions, and 5.6 percent of U.S. N_2O emissions in 2022. Emissions of CH_4 and N_2O from composting are also accounted for in this chapter, generating emissions of 2.6 MMT CO_2 Eq. and 1.8 MMT CO_2 Eq., accounting for 1.5 and 1.1 percent of Waste sector emissions, respectively. Anaerobic digestion

[8] Landfills also store carbon, due to incomplete degradation of organic materials such as wood products and yard trimmings, as described in the Land Use, Land-Use Change, and Forestry chapter.

at biogas facilities generated CH_4 emissions of less than 0.05 MMT CO_2 Eq., accounting for less than 0.05 percent of emissions from the Waste sector.

Figure 2-12: Trends in Waste Sector Greenhouse Gas Sources

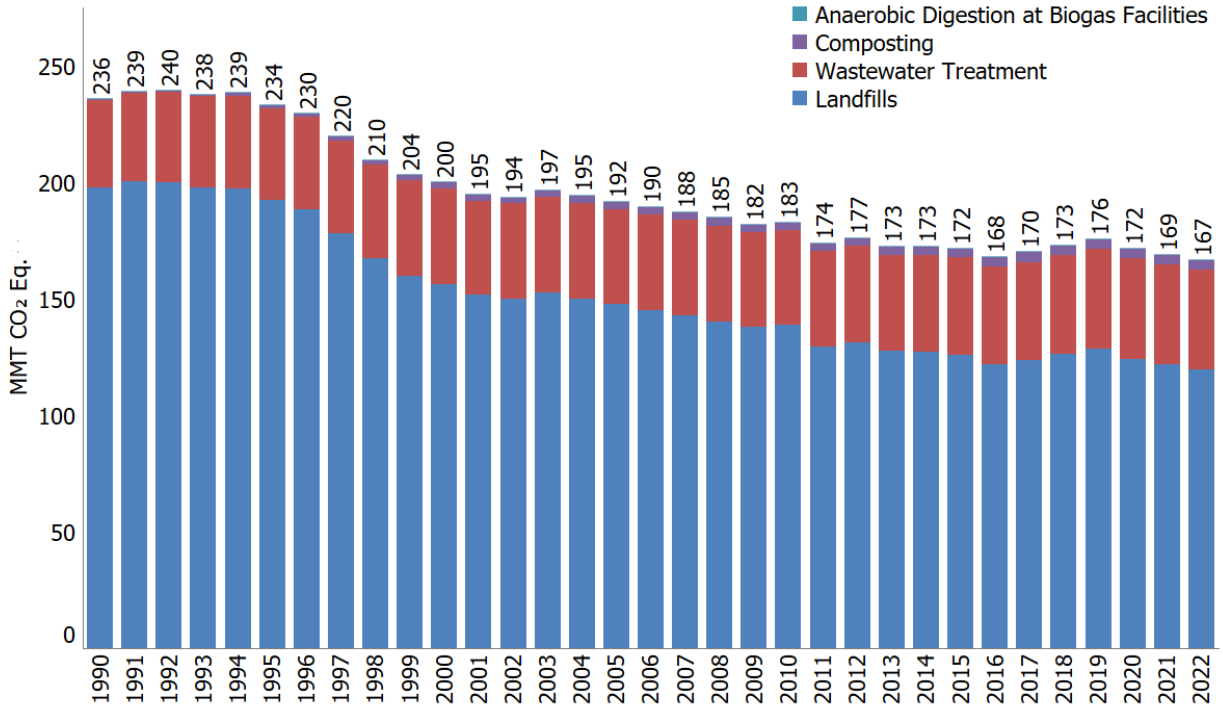


Table 2-9: Emissions from Waste (MMT CO_2 Eq.)

Gas/Source	1990	2005	2018	2019	2020	2021	2022	Percent Change Since 1990
CH_4	**220.9**	**172.4**	**150.2**	**152.4**	**147.6**	**145.3**	**143.2**	**(35.2%)**
Landfills	197.8	147.7	126.3	128.7	124.1	122.0	119.8	(39.4%)
Wastewater Treatment	22.7	22.7	21.4	21.1	21.0	20.7	20.8	(8.4%)
Composting	0.4	2.1	2.5	2.5	2.6	2.6	2.6	504.8%
Anaerobic Digestion at Biogas Facilities	+	+	+	+	+	+	+	1,109.3%
N_2O	**15.1**	**19.5**	**23.0**	**23.4**	**24.1**	**23.9**	**23.7**	**57.4%**
Wastewater Treatment	14.8	18.1	21.2	21.6	22.3	22.1	21.9	48.2%
Composting	0.3	1.5	1.8	1.8	1.8	1.8	1.8	504.8%
Total	**235.9**	**192.0**	**173.2**	**175.8**	**171.7**	**169.2**	**166.9**	**(29.3%)**

+ Does not exceed 0.05 MMT CO_2 Eq.

Note: Totals may not sum due to independent rounding.

Waste sector emissions decreased by 1.4 percent since 2021 and 29.3 percent since 1990. Some notable trends in U.S. emissions from Waste source categories (Figure 2-12) over the 33-year period from 1990 through 2022 included the following:

- Net CH_4 emissions from landfills decreased by 78.0 MMT CO_2 Eq. (39.4 percent), with small increases occurring in interim years. This downward trend in emissions coincided with increased landfill gas

collection and control systems, and a reduction of decomposable materials (i.e., paper and paperboard, food scraps, and yard trimmings) discarded in municipal solid waste (MSW) landfills over the time series.

- CH_4 and N_2O emissions from wastewater treatment decreased by 8.4 percent (1.9 MMT CO_2 Eq.) and increased by 48.2 percent (7.1 MMT CO_2 Eq.), respectively. Methane emissions from domestic wastewater treatment have decreased since 1999 due to decreasing percentages of wastewater being treated in anaerobic systems, including reduced use of on-site septic systems and central anaerobic treatment systems. N_2O emissions from wastewater treatment processes gradually increased across the time series as a result of increasing U.S. population and protein consumption.
- Combined CH_4 and N_2O emissions from composting have increased by 504.8 percent (3.7 MMT CO_2 Eq.) since 1990. The growth in composting since the 1990s is attributable to primarily four factors: (1) the enactment of legislation by state and local governments that discouraged the disposal of yard trimmings and food waste in landfills; (2) an increase in yard trimming collection and yard trimming drop-off sites provided by local solid waste management districts; (3) an increased awareness of the environmental benefits of composting; and (4) loans or grant programs to establish or expand composting infrastructure.

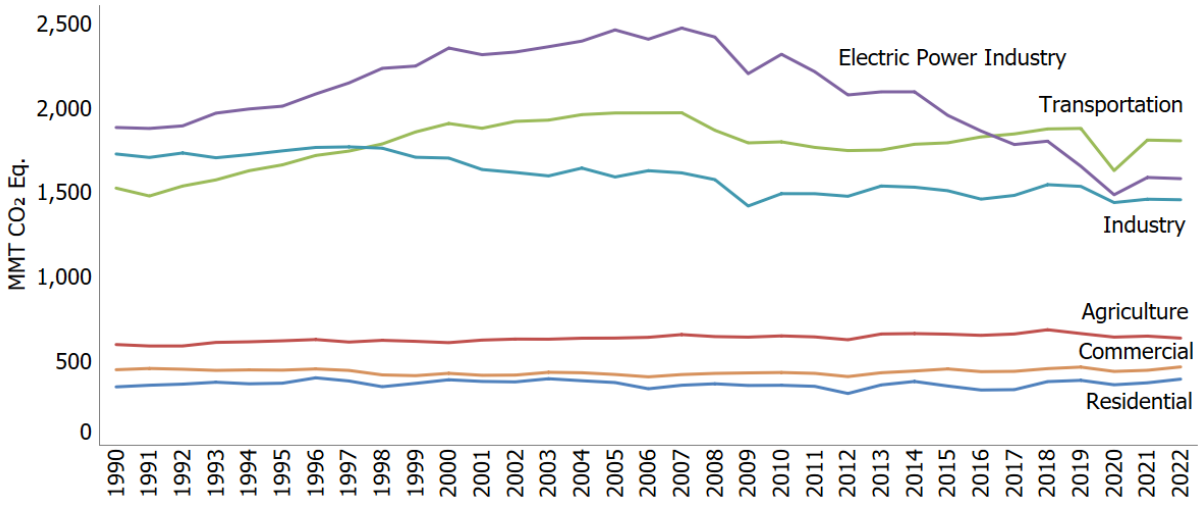
2.2 Emissions and Sinks by Economic Sector

In addition to the Paris Agreement and UNFCCC reporting sectors and methods defined by the IPCC, this report also characterizes gross emissions according to commonly used economic sector categories: residential, commercial, industry, transportation, electric power, and agriculture. Emissions from U.S. Territories are reported as their own end-use sector due to a lack of specific consumption data for the individual end-use sectors within U.S. Territories. See Box 2-1 for more information on how economic sectors are defined. For more information on trends in the LULUCF sector, see Section 2.1.

Using this categorization, transportation activities accounted for the largest portion (28.4 percent) of total U.S. greenhouse gas emissions in 2022. Emissions from electric power accounted for the second largest portion (24.9 percent), while emissions from industry accounted for the third-largest portion (22.9 percent) of total U.S. greenhouse gas emissions in 2022. Emissions from industry have in general declined over the past decade due to a number of factors, including structural changes in the U.S. economy (i.e., shifts from a manufacturing-based to a service-based economy), fuel switching, and efficiency improvements.

The remaining 23.8 percent of U.S. greenhouse gas emissions were contributed by, in order of magnitude, the agriculture, commercial, and residential sectors, plus emissions from U.S. Territories. Activities related to agriculture accounted for 10.0 percent of emissions; unlike other economic sectors, agricultural sector emissions were dominated by N_2O emissions from agricultural soil management and CH_4 emissions from enteric fermentation, rather than CO_2 from fossil fuel combustion. An increasing amount of carbon is stored in agricultural soils each year, but this carbon sequestration is assigned to the LULUCF sector rather than the agriculture economic sector. The commercial and residential sectors accounted for roughly 7.3 percent and 6.2 percent of greenhouse gas emissions, respectively, and U.S. Territories accounted for 0.4 percent of emissions; emissions from these sectors primarily consisted of CO_2 emissions from fossil fuel combustion. Carbon dioxide was also emitted and sequestered (in the form of carbon) by a variety of activities related to forest management practices, tree planting in urban areas, the management of agricultural soils, landfilling of yard trimmings, and changes in carbon stocks in coastal wetlands. Table 2-10 presents a detailed breakdown of emissions from each of these economic sectors by source category, as they are defined in this report. Figure 2-13 shows the trend in emissions by sector from 1990 to 2022.

Figure 2-13: U.S. Greenhouse Gas Emissions Allocated to Economic Sectors



Note: Emissions and removals from Land Use, Land-Use Change, and Forestry are excluded from figure above. Excludes U.S. Territories.

Table 2-10: U.S. Greenhouse Gas Emissions Allocated to Economic Sectors (MMT CO_2 Eq. and Percent of Total in 2022)

Sector/Source	1990	2005	2018	2019	2020	2021	2022	Percent of Total Emissions[a]
Transportation	**1,521.4**	**1,965.9**	**1,871.6**	**1,874.6**	**1,625.3**	**1,805.5**	**1,801.5**	**28.4%**
CO_2 from Fossil Fuel Combustion	1,468.9	1,858.6	1,813.1	1,816.6	1,572.8	1,753.5	1,751.3	27.6%
Substitution of Ozone Depleting Substances	+	63.1	35.5	34.0	32.5	31.2	29.6	0.5%
Mobile Combustion[b]	40.6	34.1	13.7	15.1	12.2	12.7	12.2	0.2%
Non-Energy Use of Fuels	11.8	10.2	9.2	8.8	7.8	8.0	8.4	0.1%
Electric Power Industry	**1,880.2**	**2,457.4**	**1,799.2**	**1,650.8**	**1,482.2**	**1,584.4**	**1,577.5**	**24.9%**
CO_2 from Fossil Fuel Combustion	1,820.0	2,400.1	1,753.4	1,606.7	1,439.6	1,540.9	1,531.7	24.1%
Stationary Combustion[b]	18.7	27.7	23.1	20.2	18.9	20.4	22.9	0.4%
Incineration of Waste	13.3	13.6	13.7	13.3	13.3	12.8	12.7	0.2%
Other Process Uses of Carbonates	3.6	4.2	4.0	4.5	4.5	4.3	5.2	0.1%
Electrical Equipment	24.7	11.9	5.0	6.1	5.9	6.0	5.1	0.1%
Industry	**1,723.3**	**1,587.3**	**1,541.9**	**1,531.8**	**1,435.9**	**1,455.8**	**1,452.5**	**22.9%**
CO_2 from Fossil Fuel Combustion	833.1	796.8	770.7	770.1	722.9	740.7	761.8	12.0%
Natural Gas Systems	251.2	236.5	223.0	227.3	217.0	210.4	209.7	3.3%
Non-Energy Use of Fuels	83.9	107.2	108.9	97.4	89.9	103.5	94.3	1.5%
Petroleum Systems	59.0	58.5	93.8	97.8	82.3	72.8	61.6	1.0%
Coal Mining	112.7	75.6	62.2	56.0	48.3	47.1	46.1	0.7%
Cement Production	33.5	46.2	39.0	40.9	40.7	41.3	41.9	0.7%
Iron and Steel Production	104.8	70.1	42.9	43.1	37.7	41.9	40.7	0.6%
Substitution of Ozone Depleting Substances	+	8.0	31.9	33.1	33.9	32.2	33.4	0.5%

Petrochemical Production	20.1	26.9	27.2	28.5	27.9	30.7	28.8	0.5%
Landfills (Industrial)	12.2	16.1	18.7	18.8	18.9	18.9	18.9	0.3%
Ammonia Production	14.4	10.2	12.7	12.4	13.0	12.2	12.6	0.2%
Lime Production	11.7	14.6	13.1	12.1	11.3	11.9	12.2	0.2%
Nitric Acid Production	10.8	10.1	8.5	8.9	8.3	7.9	8.6	0.1%
Abandoned Oil and Gas Wells	7.8	8.2	8.4	8.5	8.5	8.6	8.5	0.1%
Fluorochemical Production	70.9	30.0	8.7	9.3	6.9	7.1	7.8	+%
Wastewater Treatment	6.6	7.1	7.5	7.6	7.6	7.6	7.7	+%
Urea Consumption for Non-Agricultural Purposes	3.8	3.7	6.1	6.2	5.8	6.6	7.1	+%
Abandoned Underground Coal Mines	8.1	7.4	6.9	6.6	6.5	6.3	6.3	+%
Mobile Combustion[b]	3.6	5.6	5.5	5.6	5.3	5.5	5.9	+%
Other Process Uses of Carbonates	3.6	4.2	4.0	4.5	4.5	4.3	5.2	+%
Carbon Dioxide Consumption	1.5	1.4	4.1	4.9	5.0	5.0	5.0	+%
Electronics Industry	3.3	4.5	4.8	4.5	4.5	4.8	4.7	+%
N_2O from Product Uses	3.8	3.8	3.8	3.8	3.8	3.8	3.8	+%
Stationary Combustion[b]	4.8	4.5	3.9	3.8	3.6	3.6	3.5	+%
Aluminum Production	26.1	7.2	2.9	3.3	3.2	2.5	2.2	+%
Adipic Acid Production	13.5	6.3	9.3	4.7	7.4	6.6	2.1	+%
Glass Production	2.3	2.4	2.0	1.9	1.9	2.0	2.0	+%
Soda Ash Production	1.4	1.7	1.7	1.8	1.5	1.7	1.7	+%
Titanium Dioxide Production	1.2	1.8	1.5	1.3	1.3	1.5	1.5	+%
Ferroalloy Production	2.2	1.4	2.1	1.6	1.4	1.6	1.3	+%
Caprolactam, Glyoxal, and Glyoxylic Acid Production	1.5	1.9	1.3	1.2	1.1	1.2	1.3	+%
Magnesium Production and Processing	5.7	3.0	1.1	1.0	0.9	1.2	1.2	+%
Zinc Production	0.6	1.0	1.0	1.0	1.0	1.0	0.9	+%
Phosphoric Acid Production	1.5	1.3	0.9	0.9	0.9	0.9	0.8	+%
SF_6 and PFCs from Other Product Use	1.4	1.5	0.9	0.8	0.7	0.5	0.8	+%
Lead Production	0.5	0.6	0.5	0.5	0.5	0.4	0.4	+%
Carbide Production and Consumption	0.3	0.2	0.2	0.2	0.2	0.2	0.2	+%
Agriculture	**595.9**	**634.3**	**683.5**	**661.0**	**640.0**	**645.9**	**634.0**	**10.0%**
N_2O from Agricultural Soil Management	288.8	294.1	333.4	315.6	292.1	298.0	290.8	4.6%
Enteric Fermentation	183.1	188.2	196.8	197.3	196.3	196.5	192.6	3.0%
Manure Management	52.5	70.2	84.3	83.5	83.8	83.6	81.7	1.3%
CO_2 from Fossil Fuel Combustion	43.4	50.8	39.8	39.7	39.1	39.8	39.3	0.6%
Rice Cultivation	18.9	20.6	19.9	15.6	18.6	18.3	18.9	0.3%
Urea Fertilization	2.4	3.5	4.9	5.0	5.1	5.2	5.3	0.1%
Liming	4.7	4.4	2.2	2.2	2.9	2.4	3.3	0.1%

Mobile Combustion[b]	1.4	1.6	1.2	1.2	1.2	1.2	1.2	+%
Field Burning of Agricultural Residues	0.7	0.8	0.8	0.9	0.8	0.8	0.8	+%
Stationary Combustion[b]	0.1	+	0.1	0.1	0.1	0.1	0.1	+%
Commercial	**447.0**	**418.9**	**453.5**	**462.6**	**436.9**	**443.7**	**463.7**	**7.3%**
CO_2 from Fossil Fuel Combustion	228.3	227.1	246.3	251.7	229.3	237.5	258.7	4.1%
Landfills (Municipal)	185.5	131.6	107.7	109.9	105.2	103.1	100.9	1.6%
Substitution of Ozone Depleting Substances	+	21.4	58.5	59.8	60.8	61.9	62.9	1.0%
Wastewater Treatment	30.9	33.6	35.0	35.1	35.6	35.1	35.0	0.6%
Composting	0.7	3.6	4.3	4.3	4.4	4.4	4.4	0.1%
Stationary Combustion[b]	1.5	1.5	1.7	1.7	1.6	1.6	1.7	0.0%
Anaerobic Digestion at Biogas Facilities	+	+	+	+	+	+	+	+%
Residential	**345.6**	**371.2**	**376.8**	**384.2**	**358.0**	**369.6**	**391.3**	**6.2%**
CO_2 from Fossil Fuel Combustion	338.6	358.9	338.9	342.9	314.8	318.0	334.1	5.3%
Substitution of Ozone Depleting Substances	0.2	7.0	31.9	35.1	39.0	47.3	52.2	0.8%
Stationary Combustion[b]	6.8	5.3	6.0	6.2	4.2	4.2	5.0	0.1%
U.S. Territories	**23.4**	**59.7**	**26.3**	**25.1**	**23.4**	**23.9**	**22.7**	**0.4%**
CO_2 from Fossil Fuel Combustion	20.0	51.9	25.9	24.8	23.3	23.8	22.6	0.4%
Non-Energy Use of Fuels	3.4	7.6	0.2	0.2	0.1	0.1	0.1	+%
Stationary Combustion[b]	0.1	0.2	0.1	0.1	0.1	0.1	0.1	+%
Total Gross Emissions (Sources)	**6,536.9**	**7,494.6**	**6,752.7**	**6,590.1**	**6,001.8**	**6,328.8**	**6,343.2**	**100.0%**
LULUCF Sector Net Total[c]	**(976.7)**	**(907.7)**	**(915.5)**	**(863.6)**	**(904.4)**	**(910.6)**	**(854.2)**	**(13.5%)**
Net Emissions (Sources and Sinks)	**5,560.2**	**6,586.9**	**5,837.3**	**5,726.6**	**5,097.4**	**5,418.2**	**5,489.0**	**86.5%**

+ Does not exceed 0.05 MMT CO_2 Eq. or 0.05 percent.

[a] Percent of total (gross) emissions excluding emissions from LULUCF for 2022.

[b] Includes CH_4 and N_2O emissions from fuel combustion.

[c] The LULUCF sector net total is the net sum of all LULUCF CH_4 and N_2O emissions to the atmosphere plus LULUCF net carbon stock changes.

Notes: Total gross emissions presented are without LULUCF. Total net emissions are presented with LULUCF. Totals may not sum due to independent rounding. Parentheses indicate negative values or sequestration.

Box 2-1: Methodology for Aggregating Emissions by Economic Sector

In presenting the economic sectors in the annual *Inventory of U.S. Greenhouse Gas Emissions and Sinks*, the *Inventory* expands upon the standard sectors common for reporting under the Paris Agreement and the UNFCCC. Discussing greenhouse gas emissions relevant to U.S.-specific economic sectors improves communication of the report's findings.

The electric power economic sector includes CO_2, CH_4 and N_2O emissions from the combustion of fossil fuels that are included in the EIA electric power sector. Carbon dioxide, CH_4, and N_2O emissions from waste incineration are included in the electric power economic sector, as the majority of MSW is combusted in plants that produce electricity. The electric power economic sector also includes SF_6 from electrical equipment, and a portion of CO_2 from other process uses of carbonates (from pollution control equipment installed in electric power plants).

The transportation economic sector includes CO_2 emissions from the combustion of fossil fuels that are included in the EIA transportation fuel-consuming sector. (Additional analyses and refinement of the EIA data are further explained in the Energy chapter of this report.) Emissions of CH_4 and N_2O from mobile combustion are also

apportioned to the transportation economic sector based on the EIA transportation fuel-consuming sector. Emissions of ODS substitutes are apportioned to the transportation economic sector based on emissions from refrigerated transport and motor vehicle air-conditioning systems. Finally, CO_2 emissions from non-energy uses of fossil fuels identified as lubricants for transportation vehicles are included in the transportation economic sector.

The industry economic sector includes CO_2 emissions from the combustion of fossil fuels that are included in the EIA industrial fuel-consuming sector, minus the agricultural use of fuel explained below. The CH_4 and N_2O emissions from stationary and mobile combustion are also apportioned to the industry economic sector based on the EIA industrial fuel-consuming sector, minus emissions apportioned to the agriculture economic sector. Emissions of ODS substitutes are apportioned based on their specific end-uses within the source category, with most emissions falling within the industry economic sector. Finally, CH_4 emissions from industrial landfills and CH_4 and N_2O from industrial wastewater treatment are included in the industry economic sector.

Additionally, all process-related emissions from sources with methods considered within the IPCC IPPU sector are apportioned to the industry economic sector. This includes the process-related emissions (i.e., emissions from the actual process to make the material, not from fuels to power the plant) from activities such as cement production, iron and steel production and metallurgical coke production, and ammonia production. Additionally, fugitive emissions from energy production sources, such as natural gas systems, coal mining, and petroleum systems are included in the industry economic sector. A portion of CO_2 from other process uses of carbonates (from pollution control equipment installed in large industrial facilities) is also included in the industry economic sector. Finally, all remaining CO_2 emissions from non-energy uses of fossil fuels are assumed to be industrial in nature (besides the lubricants for transportation vehicles specified above) and are attributed to the industry economic sector.

The agriculture economic sector includes CO_2 emissions from the combustion of fossil fuels that are based on supplementary sources of agriculture fuel use data, because EIA includes agriculture equipment in the industrial fuel-consuming sector. Agriculture fuel use estimates are obtained from U.S. Department of Agriculture survey data, in combination with EIA Fuel Oil and Kerosene Sales (FOKS) data (EIA 1991 through 2022). Agricultural operations are based on annual energy expense data from the Agricultural Resource Management Survey (ARMS) conducted by the National Agricultural Statistics Service (NASS) of the USDA. NASS collects information on farm production expenditures including expenditures on diesel fuel, gasoline, LP gas, natural gas, and electricity use on the farm with the annual ARMS. A USDA publication (USDA/NASS 2023) shows national totals, as well as selected States and ARMS production regions. These supplementary data are subtracted from the industrial fuel use reported by EIA to obtain agriculture fuel use. Carbon dioxide emissions from fossil fuel combustion, and CH_4 and N_2O emissions from stationary and mobile combustion, are then apportioned to the agriculture economic sector based on agricultural fuel use.

The other IPCC Agriculture emission source categories apportioned to the agriculture economic sector include N_2O emissions from agricultural soils, CH_4 from enteric fermentation, CH_4 and N_2O from manure management, CH_4 from rice cultivation, CO_2 emissions from liming and urea application, and CH_4 and N_2O from field burning of agricultural residues.

The residential economic sector includes CO_2 emissions from the combustion of fossil fuels that are included in the EIA residential fuel-consuming sector. Stationary combustion emissions of CH_4 and N_2O are also based on the EIA residential fuel-consuming sector. Emissions of ODS substitutes are apportioned to the residential economic sector based on emissions from residential air-conditioning systems. N_2O emissions from the application of fertilizers to developed land (termed “settlements” by the IPCC) are also included in the residential economic sector.

The commercial economic sector includes CO_2 emissions from the combustion of fossil fuels that are included in the EIA commercial fuel-consuming sector. Emissions of CH_4 and N_2O from mobile combustion are also apportioned to the commercial economic sector based on the EIA commercial fuel-consuming sector. Emissions of ODS substitutes are apportioned to the commercial economic sector based on emissions from commercial refrigeration/air-conditioning systems. Public works sources, including direct CH_4 from municipal landfills, CH_4

from anaerobic digestion at biogas facilities, CH_4 and N_2O from domestic wastewater treatment, and composting, are also included in the commercial economic sector.

Emissions with Electricity Distributed to Economic Sectors

It is also useful to view greenhouse gas emissions from economic sectors with emissions related to electric power distributed into end-use categories (i.e., emissions from the electric power sector are allocated to the economic end-use sectors in which the electricity is used). For example, greenhouse gas emissions from some economic sectors, i.e., commercial and residential and industry, increase substantially when indirect emissions from electricity end-use are included, due to the relatively large share of electricity use by buildings (75 percent of the electricity generated in the United States for heating, ventilation, and air conditioning; lighting; and appliances, etc.)[9] and use of electricity for powering industrial machinery.

The generation, transmission, and distribution of electricity directly accounted for 24.9 percent of total U.S. greenhouse gas emissions in 2022. Electric power-related emissions decreased by 16.1 percent since 1990 mainly due to fuel switching in the electric power sector. From 2021 to 2022, electric power-related emissions decreased by 0.4 percent. Between 2021 and 2022, the consumption of natural gas and petroleum for electric power generation increased by 7.6 percent and 18.9 percent, respectively, while the consumption of coal decreased by 6.4 percent. Electric power-related emissions are still lower than pre-pandemic 2019 levels. Table 2-11 provides a detailed summary of emissions from electric power-related activities.

From 2021 to 2022, electricity sales to the residential end-use sector increased by 2.6 percent. Electricity sales to the commercial end-use and industrial sectors increased by 4.7 percent and 2.0 percent, respectively. Overall, from 2021 to 2022, the amount of electricity retail sales (in kWh) increased by 3.2 percent.

Table 2-11: Electric Power-Related Greenhouse Gas Emissions (MMT CO_2 Eq.)

Gas/Fuel Type or Source	1990	2005	2018	2019	2020	2021	2022
CO_2	**1,836.4**	**2,417.5**	**1,770.7**	**1,624.2**	**1,457.0**	**1,557.7**	**1,549.2**
Fossil Fuel Combustion	1,820.0	2,400.1	1,753.4	1,606.7	1,439.6	1,540.9	1,531.7
Coal	*1,546.5*	*1,982.8*	*1,152.9*	*973.5*	*788.2*	*910.1*	*851.5*
Natural Gas	*175.4*	*318.9*	*577.9*	*616.6*	*634.8*	*612.8*	*659.3*
Petroleum	*97.5*	*98.0*	*22.2*	*16.2*	*16.2*	*17.7*	*20.5*
Geothermal	*0.5*	*0.5*	*0.4*	*0.4*	*0.4*	*0.4*	*0.4*
Incineration of Waste	12.9	13.3	13.3	12.9	12.9	12.5	12.4
Other Process Uses of Carbonates	3.6	4.2	4.0	4.5	4.5	4.3	5.2
CH_4	**0.5**	**1.0**	**1.4**	**1.4**	**1.4**	**1.4**	**1.3**
Stationary Sources[a]	0.5	1.0	1.4	1.4	1.4	1.4	1.3
Incineration of Waste	+	+	+	+	+	+	+
N_2O	**18.6**	**27.1**	**22.1**	**19.1**	**17.9**	**19.4**	**21.9**
Stationary Sources[a]	18.2	26.7	21.7	18.8	17.5	19.0	21.6
Incineration of Waste	0.4	0.3	0.4	0.4	0.3	0.4	0.3
SF_6	**24.7**	**11.8**	**5.0**	**6.1**	**5.9**	**6.0**	**5.1**
Electrical Equipment	24.7	11.8	5.0	6.1	5.9	6.0	5.1
CF_4	**+**	**+**	**+**	**+**	**+**	**+**	**+**
Electrical Equipment	+	+	+	+	+	+	+
Total	**1,880.2**	**2,457.4**	**1,799.2**	**1,650.8**	**1,482.2**	**1,584.4**	**1,577.5**

+ Does not exceed 0.05 MMT CO_2 Eq.

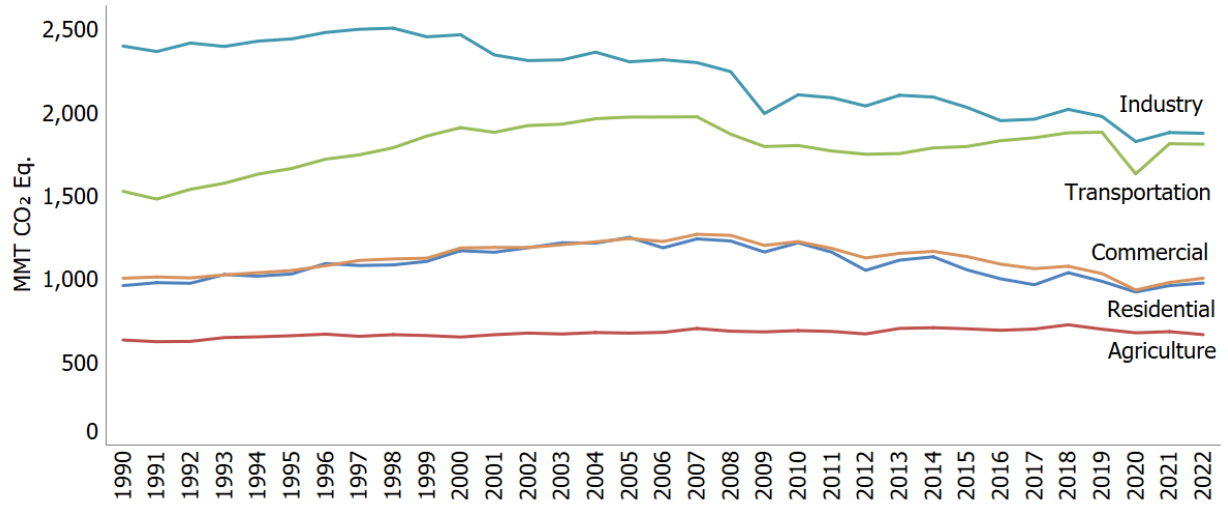
[9] See https://www.nrel.gov/news/features/2023/nrel-researcher-reveal-how-buildings-across-the-united-states-do-and-could-use-energy.html#:~:text=Buildings%20are%20responsible%20for%2040,buildings%20stock%20is%20also%20essential.

[a] Includes only stationary combustion emissions related to the generation of electricity.
Note: Totals may not sum due to independent rounding.

To distribute electricity emissions among economic end-use sectors, emissions from the source categories assigned to the electric power sector were allocated to the residential, commercial, industry, transportation, and agriculture economic sectors according to each economic sector's share of retail sales of electricity (EIA 2020; USDA/NASS 2023). These source categories include CO_2 from fossil fuel combustion, CH_4 and N_2O from stationary combustion, incineration of waste, other process uses of carbonates, and SF_6 from electrical equipment. Note that only 50 percent of the emissions from other process uses of carbonates were associated with electric power and distributed as described; the remaining emissions from other process uses of carbonates were attributed to the industry economic end-use sector.[10]

When emissions from electricity use are distributed among these economic end-use sectors, 2022 emissions from industrial activities account for the largest share of total U.S. greenhouse gas emissions (29.5 percent), followed closely by emissions from transportation (28.5 percent). Emissions from the commercial and residential sectors also increase substantially when emissions from electricity are included (15.8 and 15.3 percent, respectively). In all economic end-use sectors except agriculture, CO_2 accounts for more than 78 percent of greenhouse gas emissions, primarily from the combustion of fossil fuels. Table 2-12 presents a detailed breakdown of emissions from each of these economic sectors, with emissions from electric power distributed to them. Figure 2-14 shows the trend in these emissions by sector from 1990 to 2022.

Figure 2-14: U.S. Greenhouse Gas Emissions with Electricity-Related Emissions Distributed to Economic Sectors



Note: Emissions and removals from Land Use, Land-Use Change, and Forestry are excluded from figure above. Excludes U.S. Territories.

Table 2-12: U.S. Greenhouse Gas Emissions by Economic Sector and Gas with Electricity-Related Emissions Distributed (MMT CO_2 Eq.) and Percent of Total in 2022

Emissions by Gas	1990	2005	2018	2019	2020	2021	2022	Percent[a]
Industry	**2,397.3**	**2,302.9**	**2,017.1**	**1,974.8**	**1,823.5**	**1,877.8**	**1,872.9**	**29.5%**
Direct Emissions	**1,723.3**	**1,587.3**	**1,541.9**	**1,531.8**	**1,435.9**	**1,455.8**	**1,452.5**	**22.9%**

[10] Emissions were not distributed to U.S. Territories, since the electric power sector only includes emissions related to the generation of electricity in the 50 states and the District of Columbia.

CO_2	1,173.8	1,136.4	1,110.7	1,118.3	1,036.9	1,071.1	1,080.8	17.0%
CH_4	413.3	371.2	352.2	337.7	323.3	311.3	299.8	4.7%
N_2O	35.7	29.8	30.3	26.0	27.6	26.8	23.6	0.4%
HFCs, PFCs, SF_6 and NF_3	100.6	49.8	48.6	49.8	48.1	46.5	48.3	0.8%
Electricity-Related	**674.0**	**715.6**	**475.3**	**443.0**	**387.6**	**422.0**	**420.3**	**6.6%**
CO_2	658.3	704.0	467.7	435.9	381.0	414.9	412.8	6.5%
CH_4	0.2	0.3	0.4	0.4	0.4	0.4	0.3	+%
N_2O	6.7	7.9	5.8	5.1	4.7	5.2	5.8	0.1%
SF_6	8.8	3.5	1.3	1.6	1.5	1.6	1.4	+%
Transportation	**1,524.6**	**1,970.8**	**1,876.5**	**1,879.5**	**1,629.5**	**1,810.6**	**1,807.8**	**28.5%**
Direct Emissions	**1,521.4**	**1,965.9**	**1,871.6**	**1,874.6**	**1,625.3**	**1,805.5**	**1,801.5**	**28.4%**
CO_2	1,480.8	1,868.7	1,822.3	1,825.5	1,580.6	1,761.6	1,759.7	27.7%
CH_4	6.4	3.1	1.7	1.7	1.4	1.5	1.5	+%
N_2O	34.3	31.0	12.1	13.4	10.7	11.2	10.7	0.2%
HFCs[b]	+	63.1	35.5	34.0	32.5	31.2	29.6	0.5%
Electricity-Related	**3.1**	**4.8**	**4.9**	**4.9**	**4.2**	**5.2**	**6.3**	**0.1%**
CO_2	3.1	4.8	4.8	4.9	4.1	5.1	6.2	0.1%
CH_4	+	+	+	+	+	+	+	+%
N_2O	+	0.1	0.1	0.1	0.1	0.1	0.1	+%
SF_6	+	+	+	+	+	+	+	+%
Residential	**958.0**	**1,247.7**	**1,035.9**	**984.0**	**919.5**	**958.0**	**973.5**	**15.3%**
Direct Emissions	**345.6**	**371.2**	**376.8**	**384.2**	**358.0**	**369.6**	**391.3**	**6.2%**
CO_2	338.6	358.9	338.9	342.9	314.8	318.0	334.1	5.3%
CH_4	5.9	4.5	5.1	5.3	3.6	3.6	4.3	0.1%
N_2O	0.9	0.8	0.8	0.8	0.6	0.6	0.7	+%
SF_6	0.2	7.0	31.9	35.1	39.0	47.3	52.2	0.8%
Electricity-Related	**612.4**	**876.5**	**659.1**	**599.7**	**561.5**	**588.4**	**582.2**	**9.2%**
CO_2	598.1	862.2	648.6	590.1	551.9	578.5	571.8	9.0%
CH_4	0.2	0.3	0.5	0.5	0.5	0.5	0.5	+%
N_2O	6.1	9.7	8.1	6.9	6.8	7.2	8.1	0.1%
SF_6	8.0	4.2	1.8	2.2	2.2	2.2	1.9	+%
Commercial	**1,002.5**	**1,241.1**	**1,074.3**	**1,030.5**	**931.5**	**976.8**	**1,002.6**	**15.8%**
Direct Emissions	**447.0**	**418.9**	**453.5**	**462.6**	**436.9**	**443.7**	**463.7**	**7.3%**
CO_2	228.3	227.1	246.3	251.7	229.3	237.5	258.7	4.1%
CH_4	203.6	150.9	125.9	127.8	122.9	120.5	118.5	1.9%
N_2O	15.1	19.4	22.8	23.2	23.9	23.7	23.6	0.4%
HFCs	+	21.4	58.5	59.8	60.8	61.9	62.9	1.0%
Electricity-Related	**555.5**	**822.2**	**620.8**	**567.8**	**494.6**	**533.2**	**539.0**	**8.5%**
CO_2	542.6	808.9	611.0	558.7	486.2	524.2	529.3	8.3%
CH_4	0.1	0.3	0.5	0.5	0.5	0.5	0.4	+%
N_2O	5.5	9.1	7.6	6.6	6.0	6.5	7.5	0.1%
SF_6	7.3	4.0	1.7	2.1	2.0	2.0	1.7	+%
Agriculture	**631.1**	**672.6**	**722.7**	**696.3**	**674.4**	**681.6**	**663.6**	**10.5%**
Direct Emissions	**595.9**	**634.3**	**683.5**	**661.0**	**640.0**	**645.9**	**634.0**	**10.0%**
CO_2	50.5	58.7	47.0	46.9	47.1	47.4	47.9	0.8%
CH_4	241.9	264.6	285.2	280.4	282.6	282.0	277.0	4.4%
N_2O	303.5	311.0	351.3	333.7	310.3	316.4	309.1	4.9%
Electricity-Related	**35.2**	**38.3**	**39.2**	**35.2**	**34.4**	**35.7**	**29.7**	**0.5%**
CO_2	34.3	37.7	38.6	34.7	33.8	35.1	29.2	0.5%
CH_4	+	+	+	+	+	+	+	+%
N_2O	0.3	0.4	0.5	0.4	0.4	0.4	0.4	+%
SF_6	0.5	0.2	0.1	0.1	0.1	0.1	0.1	+%
U.S. Territories	**23.4**	**59.7**	**26.3**	**25.1**	**23.4**	**23.9**	**22.7**	**0.4%**
Total Gross Emissions (Sources)	**6,536.9**	**7,494.6**	**6,752.7**	**6,590.1**	**6,001.8**	**6,328.8**	**6,343.2**	**100.0%**
LULUCF Sector Net Total[c]	(976.7)	(907.7)	(915.5)	(863.6)	(904.4)	(910.6)	(854.2)	(13.5%)
Net Emissions (Sources and Sinks)	**5,560.2**	**6,586.9**	**5,837.3**	**5,726.6**	**5,097.4**	**5,418.2**	**5,489.0**	**86.5%**

+ Does not exceed 0.05 MMT CO_2 Eq. or 0.05 percent.
[a] Percent of total (gross) emissions excluding emissions from LULUCF for the year 2022.
[b] Includes primarily HFC-134a.
[c] The LULUCF sector net total is the net sum of all LULUCF CH_4 and N_2O emissions to the atmosphere plus LULUCF net carbon stock changes.
Notes: Total gross emissions are presented without LULUCF. Net emissions are presented with LULUCF. Emissions from electric power are allocated based on aggregate electricity use in each end-use sector. Totals may not sum due to independent rounding.

Industry

The industry economic sector includes CO_2 emissions from fossil fuel combustion from all manufacturing facilities, in aggregate, and with the distribution of electricity-related emissions (e.g., powering industrial machinery), accounted for 29.5 percent of U.S. greenhouse gas emissions in 2022. This end-use sector also includes emissions that are produced as a byproduct of the non-energy-related industrial process activities. The variety of activities producing these non-energy-related emissions includes CH_4 emissions from petroleum and natural gas systems, fugitive CH_4 and CO_2 emissions from coal mining, byproduct CO_2 emissions from cement production, and HFC, PFC, SF_6, and NF_3 byproduct emissions from the electronics industry, to name a few.

Since 1990, industry sector emissions have declined by 21.9 percent. The decline has occurred both in direct emissions and indirect emissions associated with electricity use. Structural changes within the U.S. economy that led to shifts in industrial output away from energy-intensive manufacturing products to less energy-intensive products (e.g., shifts from producing steel to computer equipment) have had a significant effect on industrial emissions.

Transportation

When electricity-related emissions are distributed to economic end-use sectors, transportation activities accounted for 28.5 percent of U.S. greenhouse gas emissions in 2022. The largest sources of transportation greenhouse gas emissions in 2022 were light-duty trucks, which include sport utility vehicles, pickup trucks, and minivans (36.5 percent); medium- and heavy-duty trucks (22.9 percent); passenger cars (20.4 percent); commercial aircraft (7.2 percent); pipelines (3.8 percent); ships and boats (2.8 percent); other aircraft (2.0 percent), and rail (2.0 percent). These figures include direct CO_2, CH_4, and N_2O emissions from fossil fuel combustion used in transportation, indirect emissions from electricity use, and emissions from non-energy use (i.e., lubricants) used in transportation, as well as HFC emissions from mobile air conditioners and refrigerated transport allocated to these vehicle types.

From 1990 to 2022, total transportation emissions from fossil fuel combustion increased by 19.4 percent due, in large part, to increased demand for travel. From 2021 to 2022, emissions decreased by 0.1 percent. Vehicle miles traveled (VMT) by light-duty motor vehicles (passenger cars and light-duty trucks) increased by 46.7 percent from 1990 to 2022 as a result of a confluence of factors including population growth, economic growth, urban sprawl, and periods of low fuel prices. The primary driver of transportation-related emissions was CO_2 from fossil fuel combustion, which increased by 19.4 percent from 1990 to 2022 when including electricity. This rise in CO_2 emissions, combined with an increase in HFCs from close to zero emissions in 1990 to 29.6 MMT CO_2 Eq. in 2022, led to an increase in overall greenhouse gas emissions from transportation activities of 18.6 percent.

The decline in new light-duty vehicle fuel economy between 1990 and 2004 reflected the increasing market share of light-duty trucks, which grew from approximately 29.6 percent of new vehicle sales in 1990 to 48.0 percent in 2004. Starting in 2005, average new vehicle fuel economy began to increase while light-duty VMT grew only modestly between 2005 and 2013. Light-duty VMT grew by less than one percent or declined each year between 2005 and 2013, then grew at a faster rate until 2016 (2.6 percent from 2014 to 2015, and 2.5 percent from 2015 to 2016). Since 2016, the rate of light-duty VMT growth has slowed to one percent or less each year. Average new vehicle fuel economy has increased almost every year since 2005, while light-duty truck market share decreased to

33.0 percent in 2009 and has since varied from year to year between 35.6 and 63.1 percent. Light-duty truck market share was about 63.1 percent of new vehicles in model year 2022 (EPA 2023b).

Table 2-13 provides a detailed summary of greenhouse gas emissions from transportation-related activities with electricity-related emissions included in the totals. Historically, the majority of electricity use in the transportation sector was for rail transport. However, more recently there has been increased electricity use in on-road electric and plug-in hybrid vehicles. Despite this increase, almost all of the energy used for transportation was supplied by petroleum-based products, with more than half being related to gasoline consumption in automobiles and other highway vehicles. Other fuel uses, especially diesel fuel for freight trucks and jet fuel for aircraft, accounted for the remainder. Indirect emissions from electricity are less than 1 percent of direct emissions in the transportation sector. For a more detailed breakout of emissions by fuel type by vehicle see Table A-93 in Annex 3.

Figure 2-15: Trends in Transportation-Related Greenhouse Gas Emissions

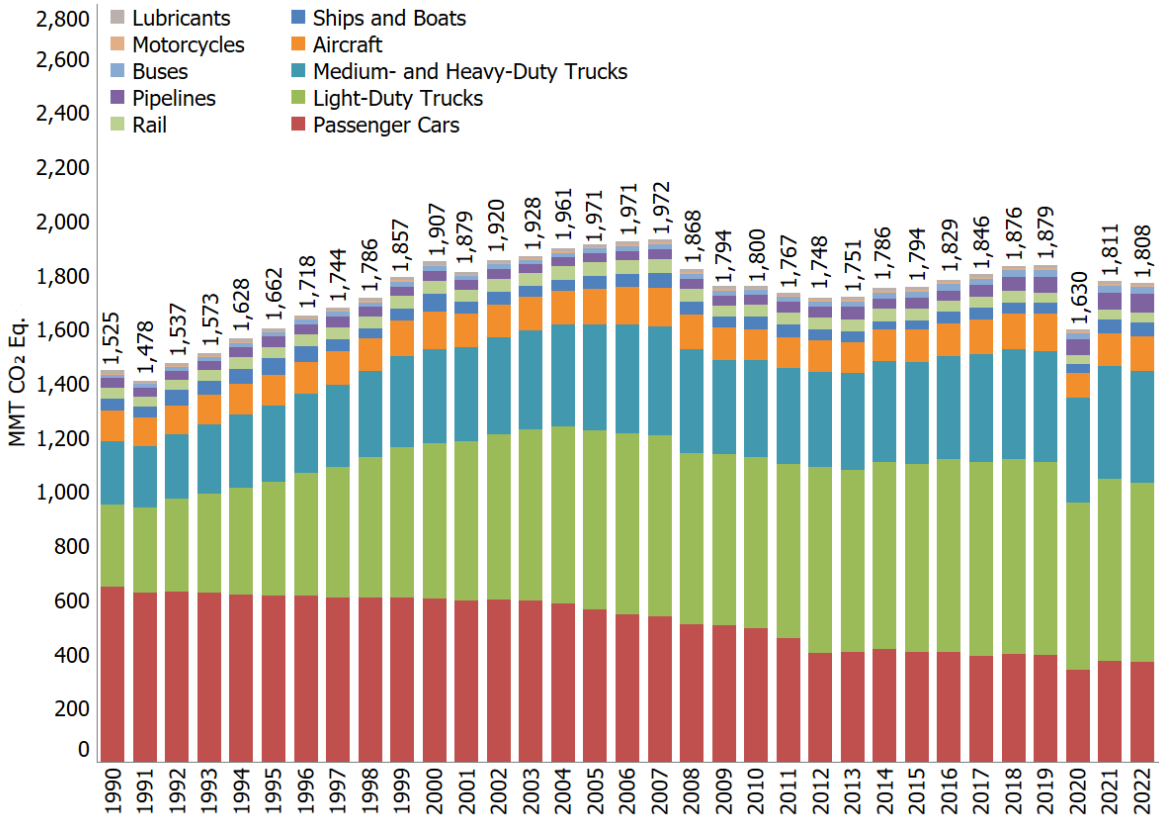


Table 2-13: Transportation-Related Greenhouse Gas Emissions (MMT CO_2 Eq.)

Gas/Vehicle Type	1990	2005	2018	2019	2020	2021	2022
Passenger Cars	**648.4**	**564.4**	**398.7**	**395.5**	**341.7**	**374.2**	**369.5**
CO_2	622.2	521.1	386.5	384.2	331.9	365.0	361.0
CH_4	3.8	1.2	0.3	0.3	0.3	0.3	0.2
N_2O	22.5	13.3	2.5	2.6	2.0	1.9	1.7
HFCs	0.0	28.8	9.4	8.4	7.6	7.0	6.6
Light-Duty Trucks	**302.4**	**659.3**	**720.6**	**711.7**	**615.3**	**671.7**	**660.2**
CO_2	292.1	614.0	699.0	690.1	596.2	654.0	644.5
CH_4	1.5	1.0	0.6	0.6	0.5	0.5	0.5
N_2O	8.7	14.0	4.6	5.6	4.4	4.2	3.8
HFCs	0.0	30.2	16.4	15.4	14.2	13.0	11.4

Medium- and Heavy-Duty Trucks	**234.5**	**391.0**	**406.5**	**409.3**	**386.7**	**417.0**	**413.1**
CO_2	233.1	386.2	397.9	400.3	377.8	407.7	403.6
CH_4	0.5	0.2	0.1	0.1	0.1	0.1	0.1
N_2O	1.0	1.5	2.8	3.0	2.7	3.0	3.1
HFCs	0.0	3.2	5.6	5.8	6.1	6.3	6.3
Buses	**13.3**	**17.8**	**24.9**	**25.3**	**24.0**	**26.1**	**26.3**
CO_2	13.2	17.5	24.3	24.7	23.4	25.6	25.7
CH_4	+	+	+	+	+	+	+
N_2O	0.1	0.1	0.2	0.2	0.2	0.2	0.2
HFCs	0.0	0.2	0.4	0.4	0.4	0.4	0.4
Motorcycles	**3.4**	**5.0**	**7.4**	**7.5**	**6.7**	**7.5**	**7.6**
CO_2	3.4	4.9	7.3	7.4	6.6	7.4	7.4
CH_4	+	+	+	+	+	+	+
N_2O	+	+	0.1	0.1	0.1	0.1	0.1
Commercial Aircraft[a]	**110.8**	**133.8**	**130.7**	**137.8**	**92.0**	**120.0**	**130.8**
CO_2	109.9	132.7	129.6	136.7	91.3	119.0	129.7
CH_4	0.0	0.0	0.0	0.0	0.0	0.0	0.0
N_2O	0.9	1.1	1.1	1.1	0.7	1.0	1.1
Other Aircraft[b]	**78.0**	**59.5**	**44.6**	**45.6**	**31.0**	**35.5**	**37.0**
CO_2	77.3	59.0	44.2	45.2	30.7	35.1	36.7
CH_4	0.1	0.1	+	+	+	+	+
N_2O	0.6	0.5	0.4	0.4	0.2	0.3	0.3
Ships and Boats[c]	**47.0**	**45.5**	**41.1**	**40.0**	**32.2**	**50.7**	**49.9**
CO_2	46.3	44.3	36.9	35.5	27.5	45.4	44.4
CH_4	0.4	0.5	0.5	0.4	0.4	0.5	0.5
N_2O	0.2	0.2	0.2	0.2	0.1	0.3	0.3
HFCs	0.0	0.5	3.6	3.9	4.2	4.5	4.8
Rail	**39.0**	**51.4**	**42.5**	**39.7**	**34.2**	**35.5**	**35.6**
CO_2	38.5	50.8	41.9	39.1	33.7	34.9	35.0
CH_4	0.1	0.1	0.1	0.1	0.1	0.1	0.1
N_2O	0.3	0.4	0.3	0.3	0.3	0.3	0.3
HFCs	0.0	0.1	0.1	0.1	0.1	0.1	0.1
Other Emissions from Electric Power[d]	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Pipelines[e]	**36.0**	**32.8**	**50.3**	**58.3**	**58.0**	**64.4**	**69.3**
CO_2	36.0	32.8	50.3	58.3	58.0	64.4	69.3
Lubricants	**11.8**	**10.2**	**9.2**	**8.8**	**7.8**	**8.0**	**8.4**
CO_2	11.8	10.2	9.2	8.8	7.8	8.0	8.4
Total Transportation	**1,524.6**	**1,970.8**	**1,876.5**	**1,879.5**	**1,629.5**	**1,810.6**	**1,807.8**
International Bunker Fuels[f]	*54.7*	*44.6*	*32.4*	*26.2*	*22.7*	*22.7*	*25.3*
Ethanol CO_2[g]	*4.1*	*21.6*	*78.6*	*78.7*	*68.1*	*75.4*	*75.0*
Biodiesel CO_2[g]	*0.0*	*0.9*	*17.9*	*17.1*	*17.7*	*16.1*	*15.6*

+ Does not exceed 0.05 MMT CO_2 Eq.

[a] Consists of emissions from jet fuel consumed by domestic operations of commercial aircraft (no bunkers).

[b] Consists of emissions from jet fuel and aviation gasoline consumption by general aviation and military aircraft.

[c] Fluctuations in emission estimates are associated with fluctuations in reported fuel consumption and may reflect issues with data sources.

[d] Other emissions from electric power are a result of waste incineration (as the majority of MSW is combusted in "trash-to-steam" electric power plants), electrical equipment, and a portion of other process uses of carbonates (from pollution control equipment installed in electric power plants).

[e] CO_2 estimates reflect natural gas used to power pipelines, but not electricity. While the operation of pipelines produces CH_4 and N_2O, these emissions are not directly attributed to pipelines in the Inventory.

[f] Emissions from International Bunker Fuels include emissions from both civilian and military activities; these emissions are not included in the transportation totals.

[g] Ethanol and biodiesel CO_2 estimates are presented for informational purposes only. See Section 3.11 and the estimates in LULUCF (see Chapter 6), in line with IPCC methodological guidance and reporting obligations under the Paris Agreement and the UNFCCC, for more information on ethanol and biodiesel.

Notes: Passenger cars and light-duty trucks include vehicles typically used for personal travel and less than 8,500 lbs; medium- and heavy-duty trucks include vehicles larger than 8,500 lbs. HFC emissions primarily reflect HFC-134a. Totals may not sum due to independent rounding.

Residential

The residential end-use sector, including electricity-related emissions, accounted for 15.3 percent of U.S. greenhouse gas emissions in 2022. This sector is heavily reliant on electricity for meeting energy needs, with electricity use for building-related activities like lighting, heating, air conditioning, and operating appliances. The remaining emissions were largely due to the direct consumption of natural gas and petroleum products, primarily for heating and cooking needs. Emissions from the residential sector have generally been increasing since 1990, and annual variations are often correlated with short-term fluctuations in energy use caused by weather conditions, rather than prevailing economic conditions. In the long term, the residential sector is also affected by population growth, migration trends toward warmer areas, and changes in housing and building attributes (e.g., larger sizes and improved insulation). A shift toward energy-efficient products and more stringent energy efficiency standards for household equipment has also contributed to recent trends in energy demand in households.

Commercial

The commercial end-use sector, including electricity-related emissions, accounted for 15.8 percent of U.S. greenhouse gas emissions in 2022. Like the residential sector it is heavily reliant on electricity for meeting energy needs, with electricity use for building-related activities like lighting, heating, air conditioning, and operating appliances. The remaining emissions were largely due to the direct consumption of natural gas and petroleum products, primarily for heating and cooking needs. Energy-related emissions from the commercial sector have generally been increasing since 1990, and annual variations are often correlated with short-term fluctuations in energy use caused by weather conditions, rather than prevailing economic conditions. Decreases in energy-related emissions in the commercial sector in recent years can be largely attributed to an overall reduction in energy use driven by a reduction in heating degree days and increases in energy efficiency.

Municipal landfills and wastewater treatment are included in the commercial sector, with landfill emissions decreasing since 1990 and wastewater treatment emissions increasing slightly.

Agriculture

The agriculture end-use sector accounted for 10.5 percent of U.S. greenhouse gas emissions in 2022 when electricity-related emissions are distributed, and includes a variety of processes, including enteric fermentation in domestic livestock, livestock manure management, and agricultural soil management. In 2022, agricultural soil management was the largest source of N_2O emissions, and enteric fermentation was the largest source of CH_4 emissions in the United States. This sector also includes small amounts of CO_2 emissions from fossil fuel combustion by motorized farm equipment such as tractors. Indirect emissions from electricity use in agricultural activities (e.g., powering buildings and equipment) are about 5 percent of direct emissions.

Box 2-2: Trends in Various U.S. Greenhouse Gas Emissions-Related Data

Total (gross) greenhouse gas emissions can be compared to other economic and social indices to highlight changes over time. These comparisons include: (1) aggregate energy use, because energy-related activities are the largest sources of emissions; (2) energy use per capita as a measure of efficiency; (3) emissions per unit of total gross domestic product as a measure of national economic activity; and (4) emissions per capita.

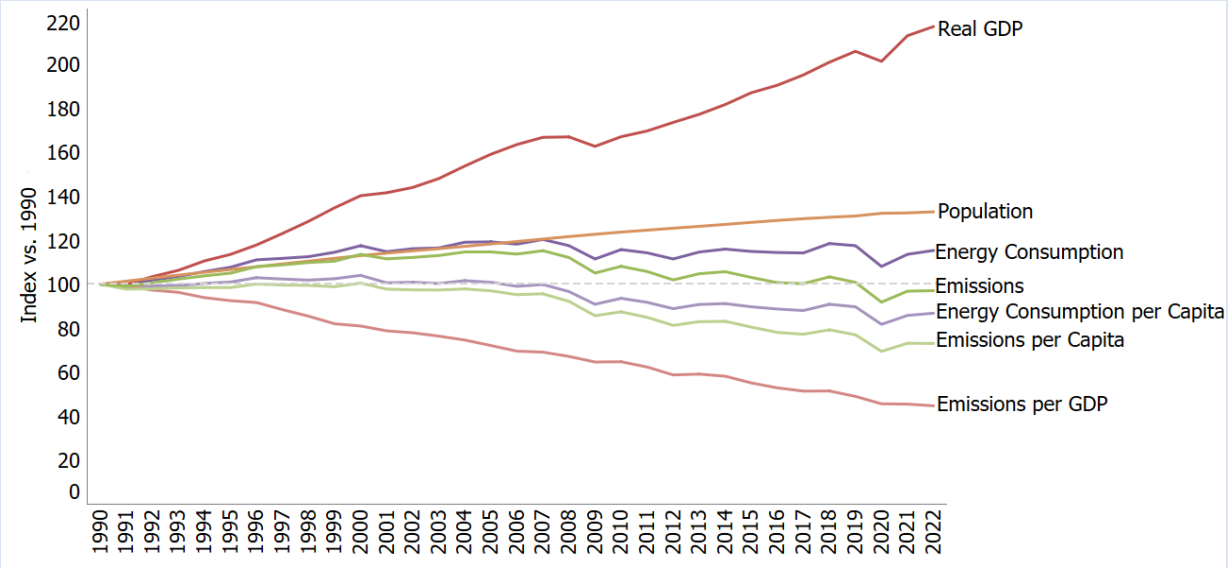
Table 2-14 provides data on various statistics related to U.S. greenhouse gas emissions normalized to 1990 as a baseline year. These values represent the relative change in each statistic since 1990. Greenhouse gas emissions in the United States have decreased at an average annual rate of 0.1 percent since 1990, although changes from year to year have been significantly larger. This growth rate is slightly slower than that for total energy use, overall gross domestic product (GDP) and national population (see Table 2-14 and Figure 2-16). The direction of these trends started to change after 2005, when greenhouse gas emissions, total energy use and associated fossil fuel consumption began to peak. Greenhouse gas emissions in the United States have decreased at an average annual rate of 0.9 percent since 2005. Since 2005, GDP, and national population, generally continued to increase, and energy use has decreased slightly, noting 2020 was impacted by the COVID-19 pandemic.

Table 2-14: Recent Trends in Various U.S. Data (Index 1990 = 100)

Variable	1990	2005	2018	2019	2020	2021	2022	Avg. Annual Change Since 1990[a]	Avg. Annual Change Since 2005[a]
Greenhouse Gas Emissions[b]	100	115	103	101	92	97	97	-0.1%	-0.9%
Energy Use[c]	100	119	118	117	107	113	115	0.5%	-0.2%
GDP[d]	100	159	201	206	201	213	217	2.5%	1.9%
Population[e]	100	118	130	131	132	132	133	0.9%	0.7%

[a] Average annual growth rate.
[b] Gross total GWP-weighted values.
[c] Energy-content-weighted values (EIA 2024).
[d] GDP in chained 2017 dollars (BEA 2024).
[e] U.S. Census Bureau (2024).

Figure 2-16: U.S. Greenhouse Gas Emissions Per Capita and Per Dollar of Gross Domestic Product



Source: BEA (2024), U.S. Census Bureau (2024), and gross emission estimates in this report.

2.3 Precursor Greenhouse Gas Emissions (CO, NO_x, NMVOCs, and SO_2)

The reporting requirements of the Paris Agreement and the UNFCCC[11] request that information be provided on emissions of compounds that are precursors to greenhouse gases, which include carbon monoxide (CO), nitrogen oxides (NO_x), non-methane volatile organic compounds (NMVOCs), and sulfur dioxide (SO_2). These gases are not direct greenhouse gases, but can indirectly impact Earth's radiative balance, by altering the concentrations of other greenhouse gases (e.g., tropospheric ozone) and atmospheric aerosol (e.g., particulate sulfate). Carbon monoxide is produced when carbon-containing fuels are combusted incompletely in energy, transportation, and industrial processes, and is also emitted from practices such as agricultural burning and waste disposal and treatment. Anthropogenic sources of nitrogen oxides (i.e., NO and NO_2) are primarily fossil fuel combustion (for energy, transportation, industrial process) and agricultural burning. Anthropogenic sources of NMVOCs, which include hundreds of organic compounds that participate in atmospheric chemical reactions (propane, butane, xylene, toluene, ethane, and many others)—are emitted primarily from transportation, industrial processes, oil and natural gas production, waste practices, agricultural burning, and non-industrial consumption of organic solvents. In the United States, SO_2 is primarily emitted from coal combustion for electric power generation and the metals industry.

As noted above and summarized in Chapter 6 of IPCC (2021), these compounds can have important indirect effects on Earth's radiative balance. For example, reactions between NMVOCs and NO_x in the presence of sunlight lead to formation of tropospheric ozone, a greenhouse gas. Concentrations of NMVOCs, NO_x, and CO can also impact the abundance and lifetime of primary greenhouse gases. This largely occurs by altering the atmospheric concentrations of the hydroxyl radical (OH), which is the main sink for atmospheric CH_4. For example, NO_x emissions can lead to increases in O_3 concentrations and subsequent OH production, which will increase the amount of OH molecules that are available to destroy CH_4. In contrast, NMVOCs and CO can both react directly with OH, leading to lower OH concentrations, a longer atmospheric lifetime of CH_4, and a decrease in CO_2 production (i.e., CO+OH→ CO_2). Changes in atmospheric CH_4 can also feedback on background concentrations of tropospheric O_3. Other indirect impacts include the formation of sulfate and nitrate aerosol from emissions of NO_x and SO_2, both of which have a net negative impact on radiative forcing.

Since 1970, the United States has published triennial estimates of emissions of CO, NO_x, NMVOCs, and SO_2 (EPA 2023a), which are regulated under the Clean Air Act. Emissions of each of these precursor greenhouse gases has decreased significantly since 1990 as a result of implementation of Clean Air Act programs, as well as technological improvements.[12] Precursor emission estimates for this report for 1990 through 2022 were obtained from data published on EPA's National Emissions Inventory (NEI) Air Pollutants Emissions Trends Data website (EPA 2023a). For Table 2-15, NEI-reported emissions of CO, NO_x, SO_2, and NMVOCs are recategorized from NEI Emissions Inventory System (EIS) source categories to those more closely aligned with reporting sectors and categories under the Paris Agreement and the UNFCCC, based on the crosswalk detailed in Annex 6.3. Table 2-15 shows that fuel combustion accounts for the majority of emissions of these precursors. Industrial processes—such as the manufacture of chemical and allied products, metals processing, and industrial uses of solvents—are also significant sources of CO, NO_x, and NMVOCs. Precursor emissions from Agriculture and LULUCF categories are estimated separately and therefore are not taken from EPA (2023a).

[11] See paragraph 51 of Annex to 18/CMA.1 available online at: https://unfccc.int/sites/default/files/resource/CMA2018_03a02E.pdf.

[12] More information is available online at: https://www.epa.gov/clean-air-act-overview/progress-cleaning-air-and-improving-peoples-health and https://gispub.epa.gov/neireport/2017/.

Table 2-15: Emissions of NO_x, CO, NMVOCs, and SO_2 (kt)

Gas/Activity	1990	2005	2018	2019	2020	2021	2022
NO_x	**22,896**	**19,754**	**8,064**	**7,639**	**6,879**	**6,996**	**6,589**
Energy	21,966	18,863	7,384	7,048	6,235	6,308	5,964
IPPU	774	672	461	440	393	403	389
Agriculture	16	18	17	18	17	18	19
LULUCF	56	149	130	61	158	190	142
Waste	84	51	73	73	76	76	75
CO	**133,549**	**76,691**	**38,656**	**36,234**	**38,911**	**41,677**	**38,853**
Energy	124,713	64,455	30,760	30,349	28,427	28,845	28,173
IPPU	4,099	1,701	1,022	1,011	855	902	897
Agriculture	407	480	433	468	446	480	501
LULUCF	3,301	8,877	5,259	3,224	7,841	10,107	7,939
Waste	1,028	1,178	1,182	1,182	1,342	1,343	1,343
NMVOCs	**20,918**	**12,708**	**8,987**	**8,804**	**9,040**	**9,454**	**9,325**
Energy	13,067	8,694	5,506	5,444	5,306	5,568	5,442
IPPU	6,982	3,668	3,119	2,996	3,366	3,508	3,505
Agriculture	+	194	206	208	196	206	206
LULUCF	NA	NA	NA	NA	NA	NA	NA
Waste	870	152	156	157	173	172	172
SO_2	**20,924**	**13,108**	**2,001**	**1,676**	**1,471**	**1,621**	**1,522**
Energy	19,400	12,312	1,643	1,344	1,173	1,315	1,229
IPPU	1,488	776	335	309	266	274	261
Agriculture	+	0	0	0	+	+	+
LULUCF	NA	NA	NA	NA	NA	NA	NA
Waste	36	20	23	23	33	32	31

+ Does not exceed 0.5 kt.

NA (Not Available)

Note: Totals by gas may not sum due to independent rounding.

Source: (EPA 2023a) except for estimates from forest fires, grassland fires, and field burning of agricultural residues. Emission categories from EPA (2023a) are aggregated into sectors and categories reported under the Paris Agreement and the UNFCCC as shown in Table ES-3.

3. Energy

Energy-related activities were the primary sources of U.S. anthropogenic greenhouse gas emissions, accounting for 82.0 percent of total gross greenhouse gas emissions on a carbon dioxide (CO_2) equivalent basis in 2022.[1] This included 96.5, 40.2, and 10.8 percent of the nation's CO_2, methane (CH_4), and nitrous oxide (N_2O) emissions, respectively.[2] Energy-related CO_2 emissions alone constituted 76.9 percent of total gross U.S. greenhouse gas emissions from all sources on a CO_2-equivalent basis, while the non-CO_2 emissions from energy-related activities represented a much smaller portion of total gross national emissions (5.1 percent collectively).

Emissions from fossil fuel combustion contribute the vast majority of energy-related emissions, with CO_2 being the primary gas emitted (see Figure 3-1 and Figure 3-2). Globally, approximately 33,500 million metric tons (MMT) of CO_2 were added to the atmosphere through the combustion of fossil fuels in 2022, of which the United States accounted for approximately 14 percent.[3] Due to their relative importance over time (see Figure 3-2), fossil fuel combustion-related CO_2 emissions are considered in more detail than other energy-related emissions in this report (see Figure 3-3).

Fossil fuel combustion also emits CH_4 and N_2O. Stationary combustion of fossil fuels was the second largest source of N_2O emissions in the United States and mobile fossil fuel combustion was the fifth largest source. Energy-related activities other than fuel combustion, such as the production, transmission, storage, and distribution of fossil fuels, also emit greenhouse gases. These emissions consist primarily of fugitive CH_4 emissions from natural gas systems, coal mining, and petroleum systems.

[1] Estimates are presented in units of million metric tons of carbon dioxide equivalent (MMT CO_2 Eq.), which weight each gas by its global warming potential, or GWP, value. See section on global warming potentials in the Executive Summary.

[2] The contribution of energy non-CO_2 emissions is based on gross totals so excludes LULUCF methane (CH_4) and nitrous oxide (N_2O) emissions. The contribution of energy-related methane (CH_4) and (N_2O) including LULUCF non-CO_2 emissions, is 37.1 percent and 9.8 percent respectively.

[3] Global CO_2 emissions from fossil fuel combustion were taken from International Energy Agency *Global energy-related CO_2 emissions, 2022.* Available at: https://www.iea.org/reports/co2-emissions-in-2022 (IEA 2022).

Figure 3-1: 2022 Energy Sector Greenhouse Gas Sources

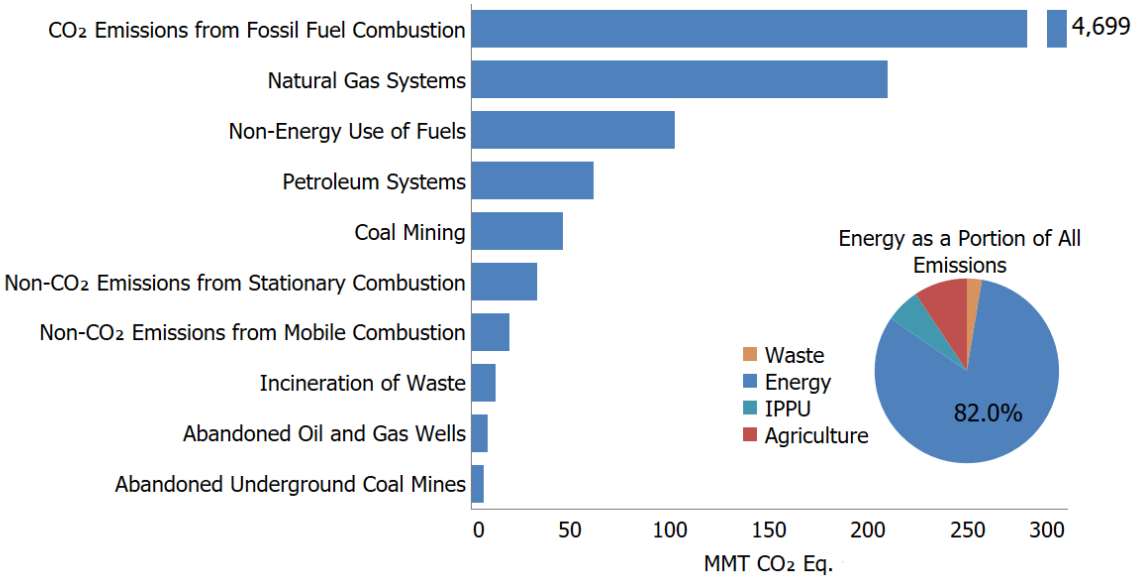


Figure 3-2: Trends in Energy Sector Greenhouse Gas Sources

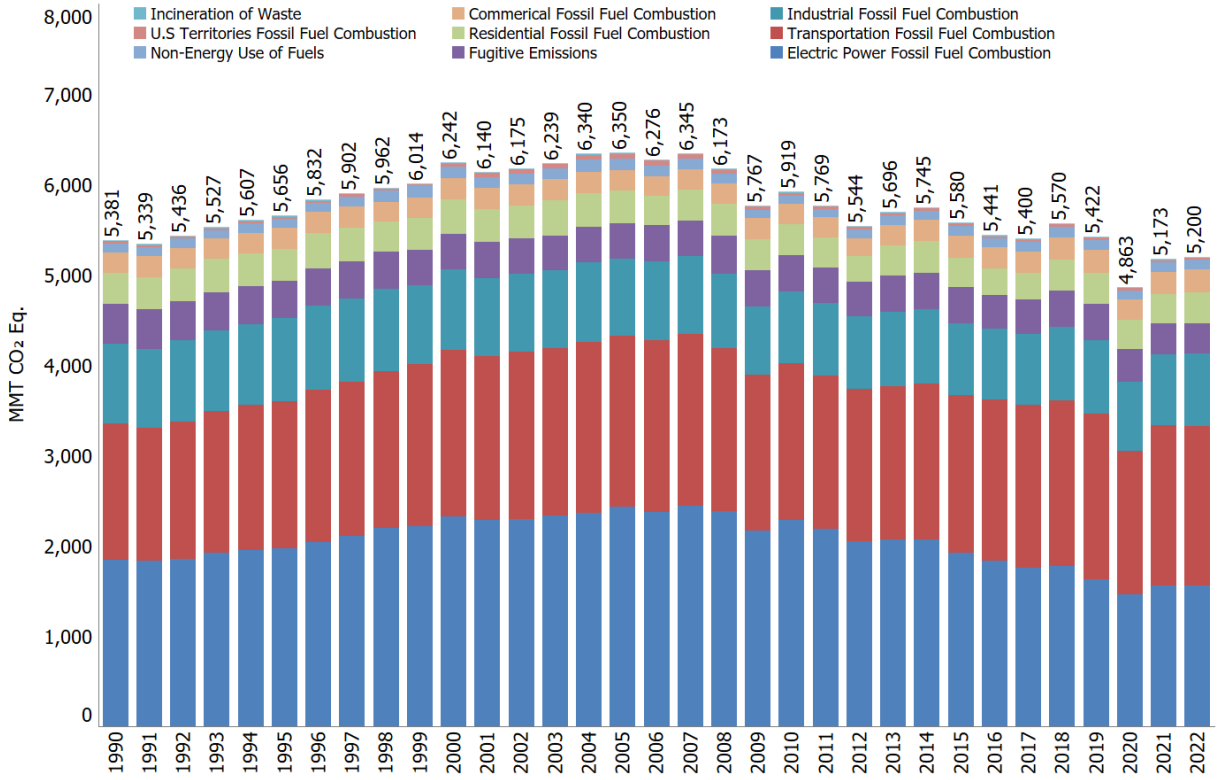


Figure 3-3: 2022 U.S. Fossil Carbon Flows (MMT CO_2 Eq.)

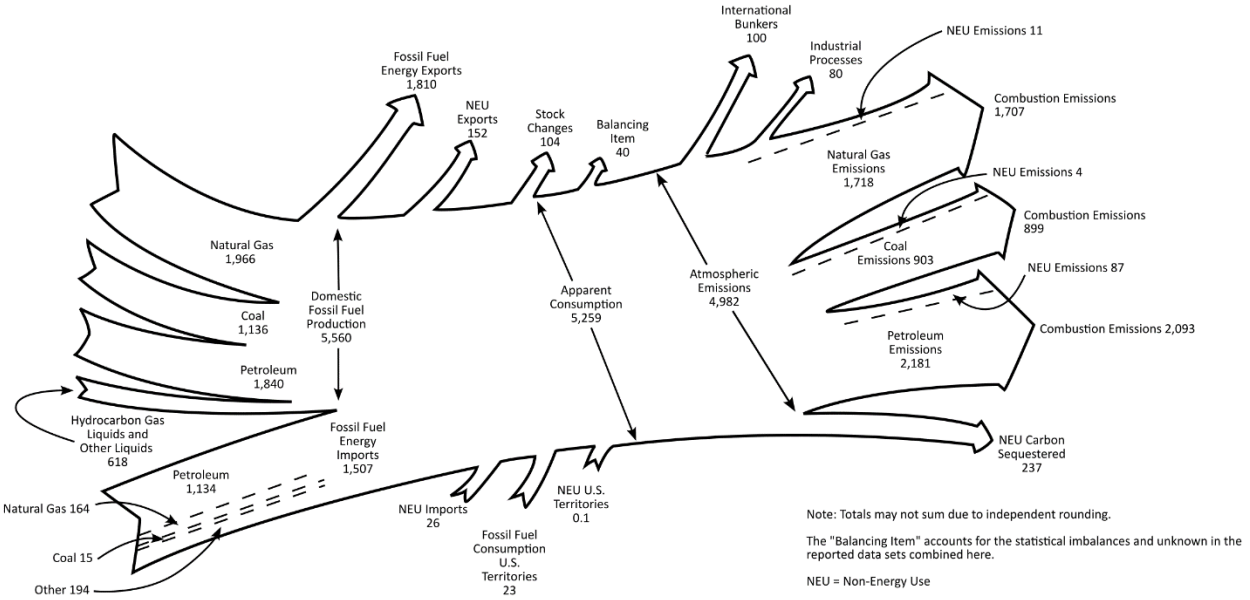


Table 3-1 summarizes emissions from the Energy sector in units of MMT CO_2 Eq., while unweighted gas emissions in kilotons (kt) are provided in Table 3-2. Overall, emissions due to energy-related activities were 5,199.8 MMT CO_2 Eq. in 2022,[4] a decrease of 3.4 percent since 1990 and an increase of 0.5 percent since 2021. The increase in emissions in 2021 and 2022 was due to continued rebounding activity levels after the coronavirus (COVID-19) pandemic reduced overall demand for fossil fuels across all sectors in 2020. Longer term trends are driven by a number of factors including a shift from coal to natural gas and renewables in the electric power sector.

Table 3-1: CO_2, CH_4, and N_2O Emissions from Energy (MMT CO_2 Eq.)

Gas/Source	1990	2005	2018	2019	2020	2021	2022
CO_2	**4,910.9**	**5,923.1**	**5,190.6**	**5,059.1**	**4,520.2**	**4,840.7**	**4,875.5**
Fossil Fuel Combustion	4,752.2	5,744.1	4,988.2	4,852.6	4,341.7	4,654.3	4,699.4
Transportation	*1,468.9*	*1,858.6*	*1,813.1*	*1,816.6*	*1,572.8*	*1,753.5*	*1,751.3*
Electricity Generation	*1,820.0*	*2,400.1*	*1,753.4*	*1,606.7*	*1,439.6*	*1,540.9*	*1,531.7*
Industrial	*876.5*	*847.6*	*810.5*	*809.8*	*762.0*	*780.5*	*801.1*
Residential	*338.6*	*358.9*	*338.9*	*342.9*	*314.8*	*318.0*	*334.1*
Commercial	*228.3*	*227.1*	*246.3*	*251.7*	*229.3*	*237.5*	*258.7*
U.S. Territories	*20.0*	*51.9*	*25.9*	*24.8*	*23.3*	*23.8*	*22.6*
Non-Energy Use of Fuels	99.1	125.0	118.4	106.5	97.8	111.6	102.8
Natural Gas Systems	32.4	26.3	32.8	38.5	36.7	35.8	36.5
Petroleum Systems	9.6	10.2	34.8	45.5	28.9	24.1	22.0
Incineration of Waste	12.9	13.3	13.3	12.9	12.9	12.5	12.4
Coal Mining	4.6	4.2	3.1	3.0	2.2	2.5	2.5
Abandoned Oil and Gas Wells	+	+	+	+	+	+	+
Biomass-Wood[a]	*215.2*	*206.9*	*220.0*	*217.7*	*190.6*	*192.5*	*195.3*
International Bunker Fuels[b]	*103.6*	*113.3*	*124.3*	*113.6*	*69.6*	*80.2*	*98.2*
Biofuels-Ethanol[a]	*4.2*	*22.9*	*81.9*	*82.6*	*71.8*	*79.1*	*79.6*

[4] Following the current reporting requirements under the UNFCCC, this Inventory report presents CO_2 equivalent values based on the IPCC *Fifth Assessment Report* (AR5) GWP values. See Chapter 1, Introduction for more information.

Gas/Source	1990	2005	2018	2019	2020	2021	2022
Biofuels-Biodiesel[a]	*0.0*	*0.9*	*17.9*	*17.1*	*17.7*	*16.1*	*15.6*
Biomass-MSW[a]	*18.5*	*14.7*	*16.1*	*15.7*	*15.6*	*15.3*	*14.9*
CH_4	**409.0**	**358.5**	**336.2**	**321.7**	**305.3**	**293.3**	**282.4**
Natural Gas Systems	218.8	210.1	190.3	188.7	180.3	174.6	173.1
Coal Mining	108.1	71.5	59.1	53.0	46.2	44.7	43.6
Petroleum Systems	49.4	48.2	59.0	52.2	53.3	48.6	39.6
Stationary Combustion	9.7	8.8	9.6	9.8	8.0	8.0	8.6
Abandoned Oil and Gas Wells	7.8	8.2	8.4	8.5	8.5	8.6	8.5
Abandoned Underground Coal Mines	8.1	7.4	6.9	6.6	6.5	6.3	6.3
Mobile Combustion	7.2	4.3	2.8	2.9	2.5	2.6	2.6
Incineration of Waste	+	+	+	+	+	+	+
International Bunker Fuels[b]	*0.2*	*0.1*	*0.1*	*0.1*	*0.1*	*0.1*	*0.1*
N_2O	**61.2**	**67.9**	**43.2**	**41.6**	**37.1**	**39.2**	**41.9**
Stationary Combustion	22.3	30.5	25.1	22.2	20.5	22.0	24.7
Mobile Combustion	38.4	37.0	17.7	19.1	16.1	16.8	16.7
Incineration of Waste	0.4	0.3	0.4	0.4	0.3	0.4	0.3
Natural Gas Systems	+	+	+	+	+	+	0.2
Petroleum Systems	+	+	+	+	+	+	+
International Bunker Fuels[b]	*0.8*	*0.9*	*1.0*	*0.9*	*0.5*	*0.6*	*0.8*
Total	**5,381.0**	**6,349.5**	**5,570.0**	**5,422.4**	**4,862.6**	**5,173.3**	**5,199.8**

+ Does not exceed 0.05 MMT CO_2 Eq.

[a] Emissions from biomass and biofuel consumption are not included specifically in summing energy sector totals. Net carbon fluxes from changes in biogenic carbon reservoirs are accounted for in the estimates for LULUCF.

[b] Emissions from international bunker fuels are not included in totals. These values are presented for informational purposes only, in line with the *2006 IPCC Guidelines* and Paris Agreement and UNFCCC reporting obligations.

Note: Totals may not sum due to independent rounding.

Table 3-2: CO_2, CH_4, and N_2O Emissions from Energy (kt)

Gas/Source	1990	2005	2018	2019	2020	2021	2022
CO_2	**4,910,861**	**5,923,075**	**5,190,611**	**5,059,075**	**4,520,249**	**4,840,748**	**4,875,487**
Fossil Fuel Combustion	4,752,232	5,744,134	4,988,198	4,852,631	4,341,710	4,654,265	4,699,403
Non-Energy Use of Fuels	99,104	124,988	118,382	106,474	97,757	111,624	102,808
Natural Gas Systems	32,427	26,312	32,768	38,525	36,719	35,780	36,470
Petroleum Systems	9,585	10,210	34,777	45,498	28,937	24,140	21,967
Incineration of Waste	12,900	13,254	13,339	12,948	12,921	12,476	12,357
Coal Mining	4,606	4,169	3,139	2,992	2,197	2,455	2,474
Abandoned Oil and Gas Wells	7	7	8	8	8	8	8
Biomass-Wood[a]	*215,186*	*206,901*	*220,003*	*217,690*	*190,554*	*192,509*	*195,338*
International Bunker Fuels[b]	*103,634*	*113,328*	*124,279*	*113,632*	*69,638*	*80,180*	*98,241*
Biofuels-Ethanol[a]	*4,227*	*22,943*	*81,917*	*82,578*	*71,848*	*79,064*	*79,593*
Biofuels-Biodiesel[a]	*0*	*856*	*17,936*	*17,080*	*17,678*	*16,112*	*15,622*
Biomass-MSW[a]	*18,534*	*14,722*	*16,115*	*15,709*	*15,614*	*15,329*	*14,864*
CH_4	**14,607**	**12,804**	**12,007**	**11,490**	**10,903**	**10,476**	**10,084**
Natural Gas Systems	7,813	7,505	6,795	6,741	6,439	6,235	6,183
Coal Mining	3,860	2,552	2,110	1,892	1,648	1,595	1,558
Petroleum Systems	1,765	1,723	2,108	1,865	1,904	1,737	1,415
Stationary Combustion	345	313	344	351	285	286	307
Abandoned Oil and Gas Wells	279	294	301	302	303	306	303
Abandoned Underground Coal Mines	288	264	247	237	232	224	225
Mobile Combustion	258	154	101	102	91	92	93
Incineration of Waste	+	+	+	+	+	+	+

Gas/Source	1990	2005	2018	2019	2020	2021	2022
International Bunker Fuels[b]	*7*	*5*	*4*	*4*	*3*	*3*	*3*
N_2O	**231**	**256**	**163**	**157**	**140**	**148**	**158**
Stationary Combustion	84	115	95	84	78	83	93
Mobile Combustion	145	140	67	72	61	63	63
Incineration of Waste	2	1	1	1	1	1	1
Natural Gas Systems	+	+	+	+	+	+	0.6
Petroleum Systems	+	+	+	+	+	+	+
International Bunker Fuels[b]	*3*	*3*	*4*	*3*	*2*	*2*	*3*

+ Does not exceed 0.5 kt.

[a] Emissions from biomass and biofuel consumption are not included specifically in summing Energy sector totals. Net carbon fluxes from changes in biogenic carbon reservoirs are accounted for in the estimates for LULUCF.

[b] Emissions from international bunker fuels are not included in totals. These values are presented for informational purposes only, in line with the *2006 IPCC Guidelines* and UNFCCC reporting obligations.

Note: Totals by gas may not sum due to independent rounding.

Emissions estimates reported in the Energy chapter from fossil fuel combustion and fugitive sources include those from all 50 states, including Hawaii and Alaska, and the District of Columbia. Emissions are also included from U.S. Territories to the extent they are known to occur (e.g., coal mining does not occur in U.S. Territories). For some sources there is a lack of detailed information on U.S. Territories including some non-CO_2 emissions from biomass combustion. As part of continuous improvement efforts, EPA reviews this on an ongoing basis to ensure emission sources are included across all geographic areas including U.S. Territories if they are occurring. See Annex 5 for more information on EPA's assessment of the sources not included in this *Inventory*.

Each year, some emission and sink estimates in the *Inventory* are recalculated and revised with improved methods and/or data. In general, recalculations are made to the U.S. greenhouse gas emission estimates either to incorporate new methodologies or, most commonly, to update recent historical data. These improvements are implemented consistently across the previous *Inventory's* time series (i.e., 1990 to 2021) to ensure that the trend is accurate. Key updates in this year's *Inventory* include, updated methodologies for completion and workover emissions estimates and transmission compressor station activity from both natural gas systems and petroleum systems, a shift of all product supplied of natural gasoline and unfinished oils to crude oil transfers for the time series and changes to the non-energy use of fossil fuel methodology (e.g., updates to some of the data and updated methodology for the amount of NEU HGLs). The impact of these recalculations averaged a decrease of 0.2 MMT CO_2 Eq. (less than 0.1 percent) per year across the time series. For more information on specific methodological updates, please see the Recalculations Discussion section for each category in this chapter.

Box 3-1: Methodological Approach for Estimating and Reporting U.S. Emissions and Removals, including Relationship to EPA's Greenhouse Gas Reporting Program

Consistent with Article 13.7(a) of the Paris Agreement and Article 4.1(a) of the UNFCCC as well as relevant decisions under those agreements, the emissions and removals presented in this report and this chapter are organized by source and sink categories and calculated using internationally accepted methods in the *2006 IPCC Guidelines for National Greenhouse Gas Inventories (2006 IPCC Guidelines)*. Additionally, the calculated emissions and removals in a given year for the United States are presented in a common format in line with the reporting guidelines for the reporting of inventories under the Paris Agreement and the UNFCCC. The Parties' use of consistent methods to calculate emissions and removals for their inventories helps to ensure that these reports are comparable. The presentation of emissions and removals provided in the Energy chapter do not preclude alternative examinations (e.g., economic sectors). Rather, this chapter presents emissions and removals in a common format consistent with how Parties are to report their national inventories under the Paris Agreement and the UNFCCC. The report itself, and this chapter, follows this common format, and provides an explanation of the application of methods used to calculate emissions and removals from energy-related activities.

Energy Data from EPA's Greenhouse Gas Reporting Program

EPA's Greenhouse Gas Reporting Program (GHGRP)[5] dataset and the data presented in this Inventory are complementary. The *Inventory* was used to guide the development of the GHGRP, particularly in terms of scope and coverage of both sources and gases. The GHGRP dataset continues to be an important resource for the Inventory, providing not only annual emissions information, but also other annual information, such as activity data and emission factors that can improve and refine national emission estimates and trends over time. GHGRP data also allow EPA to disaggregate national inventory estimates in new ways that can highlight differences across regions and sub-categories of emissions, along with enhancing application of QA/QC procedures and assessment of uncertainties.

EPA uses annual GHGRP data in a number of Energy sector categories to improve the national estimates presented in this Inventory consistent with IPCC guidelines (see Box 3-3 of this chapter, and Sections 3.3 Incineration of Waste, 3.4 Coal Mining, 3.6 Petroleum Systems, and 3.7 Natural Gas Systems).[6] Methodologies used in EPA's GHGRP are consistent with IPCC guidelines, including higher tier methods. Under EPA's GHGRP, facilities collect detailed information specific to their operations according to detailed measurement standards. It should be noted that the definitions and provisions for reporting fuel types in EPA's GHGRP may differ from those used in the Inventory in meeting the Paris Agreement and UNFCCC reporting guidelines. In line with the Paris Agreement and UNFCCC reporting guidelines, the Inventory report is a comprehensive accounting of all emissions from fuel types identified in the IPCC guidelines and provides a separate reporting of emissions from biomass.

In addition to using GHGRP data to estimate emissions (Sections 3.3 Incineration of Waste, 3.4 Coal Mining, 3.6 Petroleum Systems, and 3.7 Natural Gas Systems), EPA also uses the GHGRP fuel consumption activity data in the Energy sector to disaggregate industrial end-use sector emissions in the category of CO_2 emissions from fossil fuel combustion, for use in reporting emissions in Common Reporting Tables (CRTs) (see Box 3-3). The industrial end-use sector activity data collected for the *Inventory* (EIA 2024) represent aggregated data for the industrial end-use sector. EPA's GHGRP collects industrial fuel consumption activity data by individual categories within the industrial end-use sector. Therefore, GHGRP data are used to provide a more detailed breakout of total emissions in the industrial end-use sector within that source category.

As indicated in the respective Planned Improvements sections for source categories in this chapter, EPA continues to examine the uses of facility-level GHGRP data to improve the national estimates presented in this *Inventory*. See Annex 9 for more information on use of EPA's GHGRP in the *Inventory*.

3.1 Fossil Fuel Combustion (CRT Source Category 1A)

Emissions from the combustion of fossil fuels for energy include the greenhouse gases CO_2, CH_4, and N_2O. Given that CO_2 is the primary gas emitted from fossil fuel combustion and represents the largest share of U.S. total emissions, CO_2 emissions from fossil fuel combustion are discussed at the beginning of this section. An overview of CH_4 and N_2O emissions from the combustion of fuels in stationary sources is then presented, followed by fossil fuel

[5] On October 30, 2009, the U.S. Environmental Protection Agency (EPA) published a rule requiring annual reporting of greenhouse gas data from large greenhouse gas emission sources in the United States. Implementation of the rule, codified at 40 CFR Part 98, is referred to as EPA's Greenhouse Gas Reporting Program (GHGRP).

[6] See http://www.ipcc-nggip.iges.or.jp/public/tb/TFI_Technical_Bulletin_1.pdf.

combustion emissions for all three gases by sector: electric power, industrial, residential, commercial, U.S. Territories, and transportation.

Methodologies for estimating CO_2 emissions from fossil fuel combustion differ from the estimation of CH_4 and N_2O emissions from stationary combustion and mobile combustion. Thus, three separate descriptions of methodologies, uncertainties, recalculations, and planned improvements are provided at the end of this section. Total CO_2, CH_4, and N_2O emissions from fossil fuel combustion are presented in Table 3-3 and Table 3-4.

Table 3-3: CO_2, CH_4, and N_2O Emissions from Fossil Fuel Combustion (MMT CO_2 Eq.)

Gas	1990	2005	2018	2019	2020	2021	2022
CO_2	4,752.2	5,744.1	4,988.2	4,852.6	4,341.7	4,654.3	4,699.4
CH_4	16.9	13.1	12.5	12.7	10.5	10.6	11.2
N_2O	60.8	67.6	42.8	41.2	36.7	38.9	41.4
Total	**4,829.9**	**5,824.8**	**5,043.4**	**4,906.6**	**4,388.9**	**4,703.7**	**4,752.0**

Note: Totals may not sum due to independent rounding.

Table 3-4: CO_2, CH_4, and N_2O Emissions from Fossil Fuel Combustion (kt)

Gas	1990	2005	2018	2019	2020	2021	2022
CO_2	4,752,232	5,744,134	4,988,198	4,852,631	4,341,710	4,654,265	4,699,403
CH_4	602	467	445	453	376	379	401
N_2O	229	255	161	156	138	147	156

CO_2 from Fossil Fuel Combustion

Carbon dioxide is the primary gas emitted from fossil fuel combustion and represents the largest share of U.S. total greenhouse gas emissions. Carbon dioxide emissions from fossil fuel combustion are presented in Table 3-5. In 2022, CO_2 emissions from fossil fuel combustion increased by 1.0 percent relative to the previous year (as shown in Table 3-6). The increase in CO_2 emissions from fossil fuel combustion was a result of a 1.8 percent increase in fossil fuel energy use. This increase in fossil fuel energy use was due primarily to the continued rebound in economic activity after the COVID-19 pandemic. Carbon dioxide emissions from natural gas increased by 84.8 MMT CO_2 Eq., a 5.2 percent increase from 2021. In a shift from last year's trend, CO_2 emissions from coal consumption decreased by 58.6 MMT CO_2 Eq., a 6.1 percent decrease from 2021. Both the increase in natural gas and decrease in coal consumption and emissions in 2022 are observed across all sectors. Emissions from petroleum use also increased 19.0 MMT CO_2 Eq. (0.9 percent) from 2021 to 2022. In 2022, CO_2 emissions from fossil fuel combustion were 4,699,4 MMT CO_2 Eq., or 1.1 percent below emissions in 1990 (see Table 3-5).[7]

[7] An additional discussion of fossil fuel emission trends is presented in the Trends in U.S. Greenhouse Gas Emissions chapter.

Table 3-5: CO_2 Emissions from Fossil Fuel Combustion by Fuel Type and Sector (MMT CO_2 Eq.)

Fuel/Sector	1990	2005	2018	2019	2020	2021	2022
Coal	**1,719.8**	**2,113.7**	**1,211.6**	**1,028.1**	**835.6**	**957.4**	**898.8**
Residential	3.0	0.8	NO	NO	NO	NO	NO
Commercial	12.0	9.3	1.8	1.6	1.4	1.4	1.4
Industrial	157.8	117.8	54.4	49.4	43.0	43.0	43.0
Transportation	NO	NO	NO	NO	NO	NO	NO
Electric Power	1,546.5	1,982.8	1,152.9	973.5	788.2	910.1	851.5
U.S. Territories	0.5	3.0	2.6	3.6	3.1	2.9	2.9
Natural Gas	**998.6**	**1,166.2**	**1,592.0**	**1,649.2**	**1,615.7**	**1,622.1**	**1,706.8**
Residential	237.8	262.2	273.8	275.5	256.4	258.6	272.0
Commercial	142.0	162.9	192.5	192.9	173.5	180.4	192.3
Industrial	407.4	387.8	493.5	501.5	489.7	501.2	510.4
Transportation	36.0	33.1	50.9	58.9	58.7	65.2	70.2
Electric Power	175.4	318.9	577.9	616.6	634.8	612.8	659.3
U.S. Territories	NO	1.3	3.3	3.8	2.6	3.9	2.7
Petroleum	**2,033.3**	**2,463.8**	**2,184.2**	**2,174.9**	**1,890.0**	**2,074.4**	**2,093.4**
Residential	97.8	95.9	65.1	67.4	58.4	59.4	62.1
Commercial	74.3	54.9	52.0	57.2	54.4	55.7	65.1
Industrial	311.2	342.0	262.6	258.9	229.3	236.3	247.6
Transportation	1,432.9	1,825.5	1,762.2	1,757.7	1,514.2	1,688.4	1,681.1
Electric Power	97.5	98.0	22.2	16.2	16.2	17.7	20.5
U.S. Territories	19.5	47.6	20.1	17.5	17.5	17.0	17.0
Geothermal[a]	**0.5**	**0.5**	**0.4**	**0.4**	**0.4**	**0.4**	**0.4**
Electric Power	0.5	0.5	0.4	0.4	0.4	0.4	0.4
Total	**4,752.2**	**5,744.1**	**4,988.2**	**4,852.6**	**4,341.7**	**4,654.3**	**4,699.4**

NO (Not Occurring)

[a] Although not technically a fossil fuel, geothermal energy-related CO_2 emissions are included for reporting purposes. The source of CO_2 is non-condensable gases in subterranean heated water.

Note: Totals may not sum due to independent rounding.

Trends in CO_2 emissions from fossil fuel combustion are influenced by many long-term and short-term factors. On a year-to-year basis, the overall demand for fossil fuels in the United States and other countries generally fluctuates in response to changes in general economic conditions, energy prices, weather, and the availability of non-fossil alternatives. For example, in a year with increased consumption of goods and services, low fuel prices, severe summer and winter weather conditions, nuclear plant closures, and lower precipitation feeding hydroelectric dams, there would likely be proportionally greater fossil fuel consumption than a year with poor economic performance, high fuel prices, mild temperatures, and increased output from nuclear and hydroelectric plants. The 2021 to 2022 trends reflect ongoing impacts of the COVID-19 pandemic which generally led to a reduction in demand for fossil fuels in 2020, but an increase in demand as activities continued to rebound in 2022.

Longer-term changes in energy usage patterns, however, tend to be more a function of aggregate societal trends that affect the scale of energy use (e.g., population, number of cars, size of houses, and number of houses), the efficiency with which energy is used in equipment (e.g., cars, HVAC systems, power plants, steel mills, and light bulbs), and social planning and consumer behavior (e.g., walking, bicycling, or telecommuting to work instead of driving).

Carbon dioxide emissions also depend on the source of energy and its carbon intensity. The amount of carbon in fuels varies significantly by fuel type. For example, coal contains the highest amount of carbon per unit of useful energy. Petroleum has roughly 75 percent of the carbon per unit of energy as coal, and natural gas has only about

55 percent.[8] Table 3-6 shows annual changes in emissions during the last five years for coal, petroleum, and natural gas in selected sectors.

Table 3-6: Annual Change in CO_2 Emissions and Total 2022 CO_2 Emissions from Fossil Fuel Combustion for Selected Fuels and Sectors (MMT CO_2 Eq. and Percent)

Sector	Fuel Type	2018 to 2019		2019 to 2020		2020 to 2021		2021 to 2022		Total 2022
Transportation	Petroleum	-4.5	-0.3%	-243.5	-13.9%	174.2	11.5%	-7.2	-0.4%	1,681.1
Electric Power	Coal	-179.3	-15.6%	-185.4	-19.0%	121.9	15.5%	-58.6	-6.4%	851.5
Electric Power	Natural Gas	38.7	6.7%	18.2	3.0%	-22.1	-3.5%	46.5	7.6%	659.3
Industrial	Natural Gas	8.0	1.6%	-11.8	-2.4%	11.4	2.3%	9.2	1.8%	510.4
Residential	Natural Gas	1.7	0.6%	-19.1	-6.9%	2.3	0.9%	13.3	5.2%	272.0
Commercial	Natural Gas	0.4	0.2%	-19.5	-10.1%	6.9	4.0%	11.9	6.6%	192.3
Transportation	**All Fuels[a]**	**3.5**	**0.2%**	**-243.8**	**-13.4%**	**180.7**	**11.5%**	**-2.3**	**-0.1%**	**1,751.3**
Electric Power	**All Fuels[a]**	**-146.7**	**-8.4%**	**-167.2**	**-10.4%**	**101.4**	**7.0%**	**-9.3**	**-0.6%**	**1,531.7**
Industrial	**All Fuels[a]**	**-0.7**	**-0.1%**	**-47.8**	**-5.9%**	**18.5**	**2.4%**	**20.6**	**2.6%**	**801.1**
Residential	**All Fuels[a]**	**4.0**	**1.2%**	**-28.1**	**-8.2%**	**3.2**	**1.0%**	**16.0**	**5.0%**	**334.1**
Commercial	**All Fuels[a]**	**5.5**	**2.2%**	**-22.5**	**-8.9%**	**8.3**	**3.6%**	**21.2**	**8.9%**	**258.7**
All Sectors[a,b]	**All Fuels[a]**	**-135.6**	**-2.7%**	**-510.9**	**-10.5%**	**312.6**	**7.2%**	**45.1**	**1.0%**	**4,699.4**

[a] Includes sector and fuel combinations not shown in this table.

[b] Includes U.S. Territories.

Note: Totals may not sum due to independent rounding.

As shown in Table 3-6, recent trends in CO_2 emissions from fossil fuel combustion show a 2.7 percent decrease from 2018 to 2019, a 10.5 percent decrease from 2019 to 2020, a 7.2 percent increase from 2020 to 2021, and a 1.0 percent increase from 2021 to 2022. These changes contributed to an overall 5.8 percent decrease in CO_2 emissions from fossil fuel combustion from 2018 to 2022.

The overall 2021 to 2022 trends were largely driven by the gradual recovery from the COVID-19 pandemic, which saw reduced economic activity in 2020 and caused changes in energy demand and supply patterns across different sectors. The continued recovery from the COVID-19 pandemic has generally led to increased energy use and emissions across all economic sectors except electric power and transportation from 2021 to 2022. The decrease in emissions from 2021 to 2022 from electric power was due to the reduction in coal consumption for electricity generation, in a return to a pre-pandemic trend in declining coal-fired power generation.

Recent trends in CO_2 emissions from fossil fuel combustion are largely driven by the electric power sector, which until 2017 has accounted for the largest portion of these emissions. The types of fuels consumed to produce electricity have changed in recent years. Electric power sector consumption of natural gas primarily increased due to increased production capacity as natural gas-fired plants replaced coal-fired plants and increased electricity demand related to heating and cooling needs (EIA 2018; EIA 2023a). Total net electric power generation from all fossil and non-fossil sources decreased by 1.3 percent from 2018 to 2019, decreased by 2.9 percent from 2019 to 2020, increased by 2.7 percent from 2020 to 2021, and increased by 3.0 percent from 2021 to 2022 (EIA 2024a). Carbon dioxide emissions from the electric power sector decreased from 2021 to 2022 by 0.6 percent due to increased production and use of natural gas and decreased production and use of coal for electric power generation. Carbon dioxide emissions from coal consumption for electric power generation decreased by 26.1 percent overall since 2018, including a 6.4 percent decrease from 2021 to 2022.

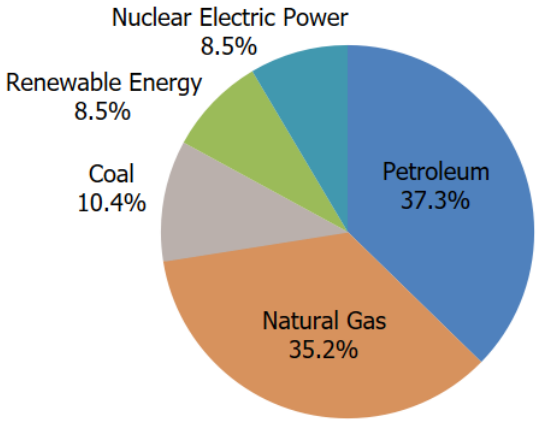
Petroleum use in the transportation sector is another major driver of emissions, representing the largest source of CO_2 emissions from fossil fuel combustion in 2022. Emissions from petroleum consumption for transportation have decreased by 4.6 percent since 2018 and are primarily attributed to a 1.4 percent decrease in VMT over the same

[8] Based on national aggregate carbon content of all coal, natural gas, and petroleum fuels combusted in the United States. See Annex 2.2 for more details on fuel carbon contents.

time period. As of 2017, the transportation sector is the largest source of national CO_2 emissions–whereas in prior years, electric power was the largest source sector.

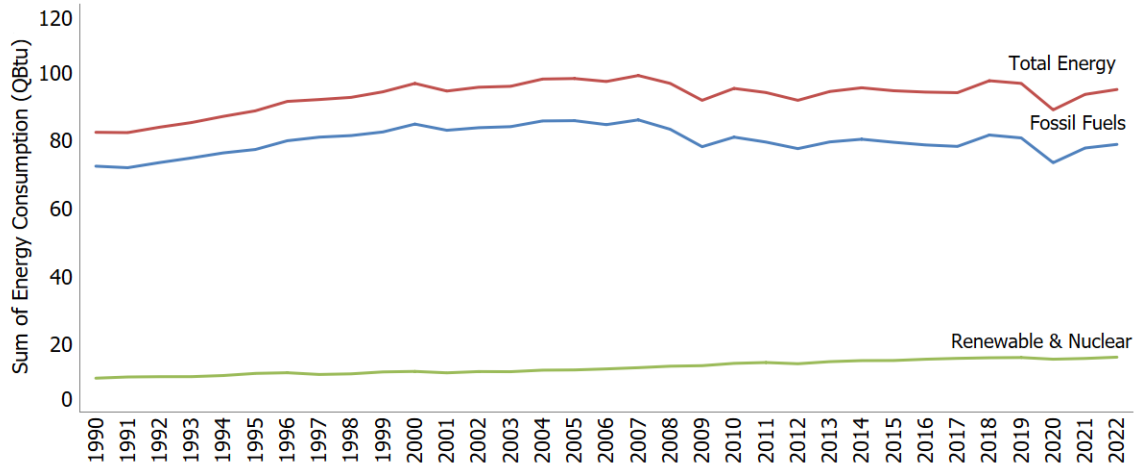
In the United States, 83.0 percent of the energy used in 2022 was produced through the combustion of fossil fuels such as petroleum, natural gas, and coal (see Figure 3-4 and Figure 3-5). Specifically, petroleum supplied the largest share of domestic energy demands, accounting for 37 percent of total U.S. energy used in 2022. Natural gas and coal followed in order of fossil fuel energy demand significance, accounting for approximately 35 percent and 10 percent of total U.S. energy used, respectively. Petroleum was consumed primarily in the transportation end-use sector and the majority of coal was used in the electric power sector. Natural gas was broadly consumed in all end-use sectors except transportation (see Figure 3-6) (EIA 2024a). The remaining portion of energy used in 2022 was supplied by nuclear electric power (8 percent) and by a variety of renewable energy sources (9 percent), primarily wind energy, hydroelectric power, solar, geothermal and biomass (EIA 2024a).[9]

Figure 3-4: 2022 U.S. Energy Use by Energy Source



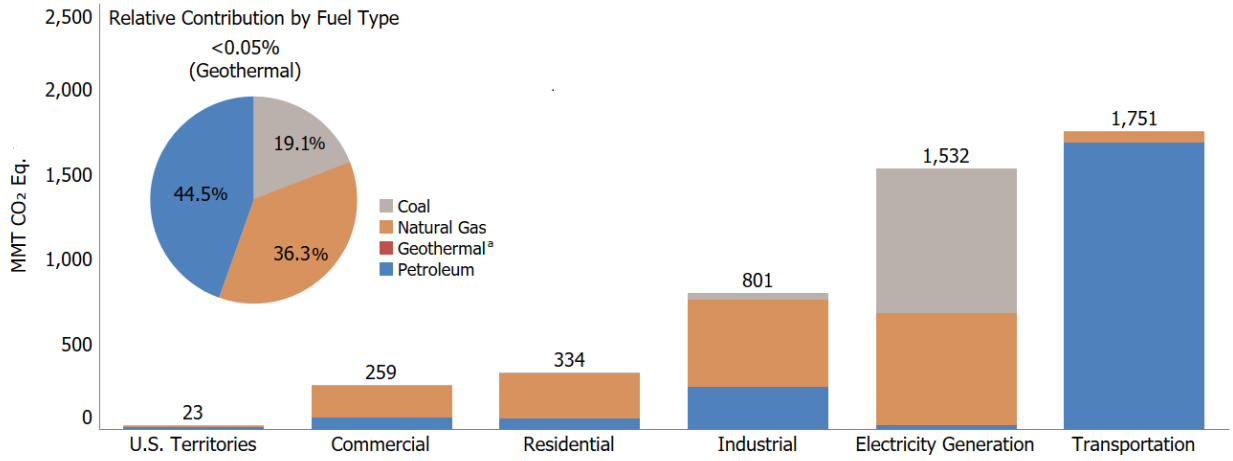
Note: Totals may not sum due to independent rounding.

Figure 3-5: Annual U.S. Energy Use



[9] Renewable energy, as defined in EIA's energy statistics, includes the following energy sources: hydroelectric power, geothermal energy, biomass, solar energy, and wind energy.

Figure 3-6: 2022 CO_2 Emissions from Fossil Fuel Combustion by Sector and Fuel Type



[a] Although not technically a fossil fuel, geothermal energy-related CO_2 emissions are included for reporting purposes. The source of CO_2 is non-condensable gases in subterranean heated water.

Fossil fuels are generally combusted for the purpose of producing energy for useful heat and work. During the combustion process, the carbon stored in the fuels is oxidized and emitted as CO_2 and smaller amounts of other gases, including CH_4, carbon monoxide (CO), and non-methane volatile organic compounds (NMVOCs).[10] These other C-containing non-CO_2 gases are emitted as a byproduct of incomplete fuel combustion, but are, for the most part, eventually oxidized to CO_2 in the atmosphere. Therefore, as per IPCC guidelines, it is assumed that all of the carbon in fossil fuels used to produce energy is eventually converted to atmospheric CO_2.

Box 3-2: Weather and Non-Fossil Energy Effects on CO_2 Emissions from Fossil Fuel Combustion Trends

The United States in 2022 experienced a colder winter overall compared to 2021, with a 7.9 percent increase in heating degree days, although 2022 heating degree days were 2.3 percent below normal (see Figure 3-7). Along with a colder winter, 2022 experienced a warmer summer, with cooling degree days 16.9 percent above normal and 4.3 percent higher compared to 2021 (see Figure 3-8) (EIA 2024a).[11] Warmer summers and colder winters can lead to increased energy use to heat and cool building spaces in the residential and commercial sectors. The combination of colder winter and warmer summer conditions in 2022 as compared to 2021 led to an overall increase in direct emissions from fossil fuel combustion in the residential and commercial sectors of 5.0 and 8.9 percent, respectively.

[10] See the sections entitled Stationary Combustion and Mobile Combustion in this chapter for information on non-CO_2 gas emissions from fossil fuel combustion.

[11] Degree days are relative measurements of outdoor air temperature. Heating degree days are deviations of the mean daily temperature below 65 degrees Fahrenheit, while cooling degree days are deviations of the mean daily temperature above 65 degrees Fahrenheit. Heating degree days have a considerably greater effect on energy demand and related emissions than do cooling degree days. Excludes Alaska and Hawaii. Normals are based on data from 1991 through 2020. The variation in these normals during this time period was ±16 percent and ±27 percent for heating and cooling degree days, respectively (99 percent confidence interval).

Figure 3-7: Annual Deviations from Normal Heating Degree Days for the United States (1970–2022, Index Normal = 100)

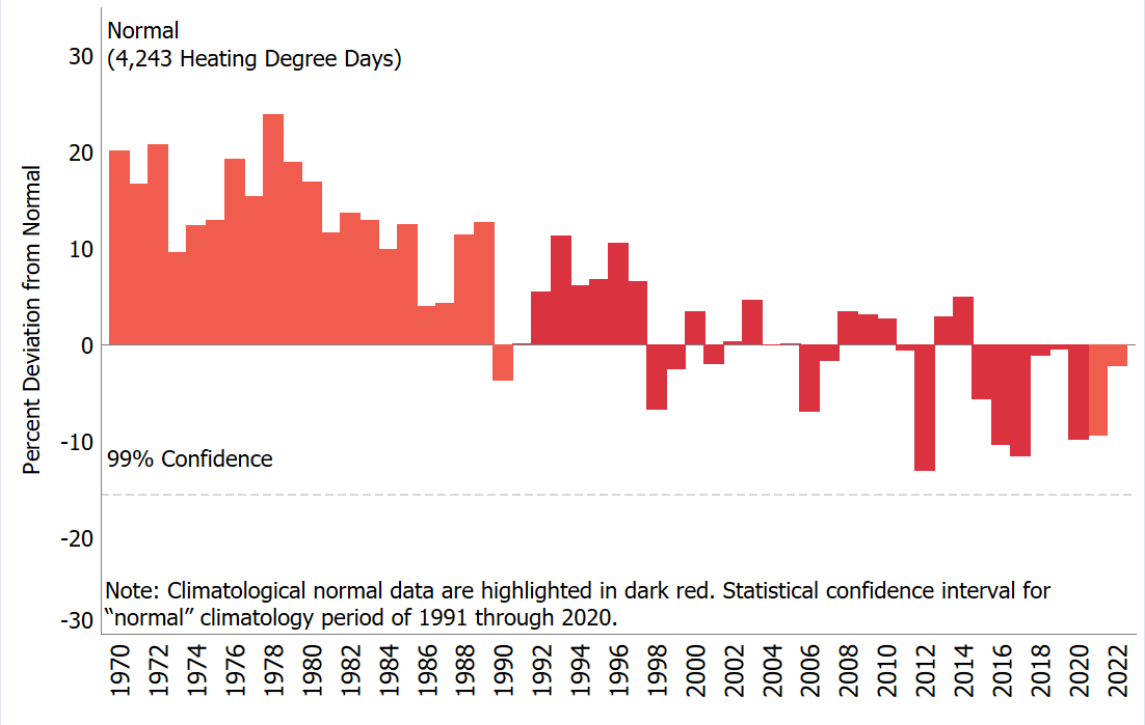
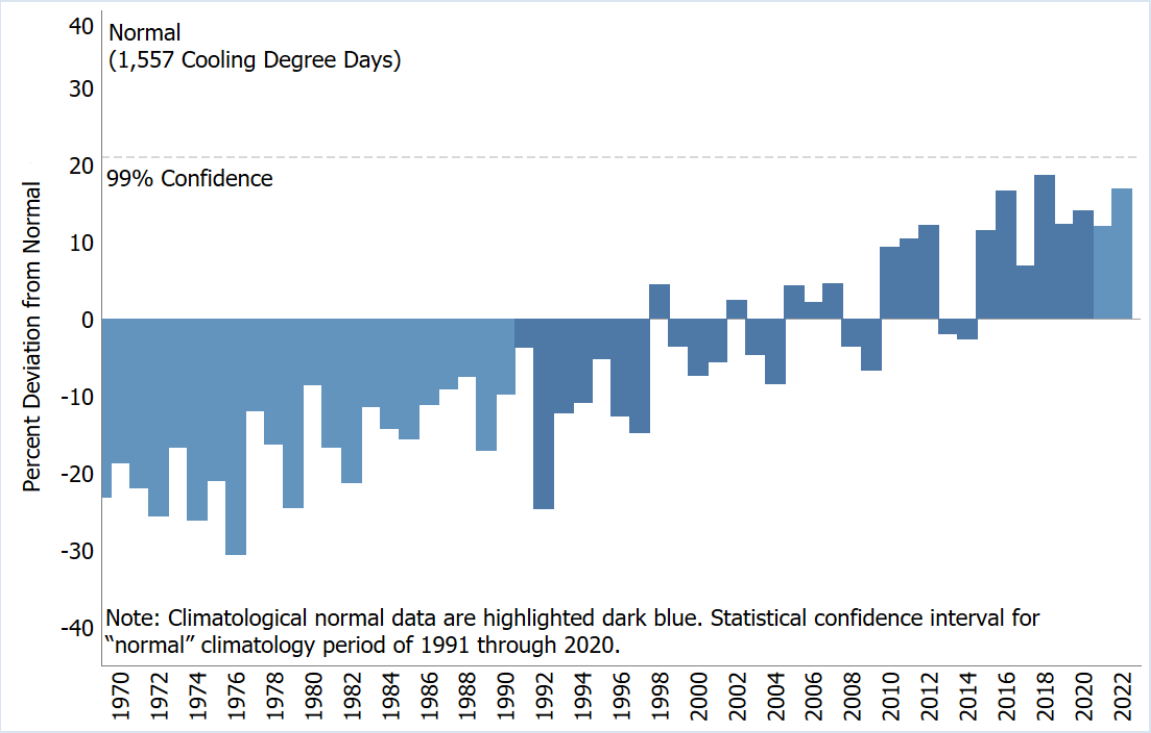


Figure 3-8: Annual Deviations from Normal Cooling Degree Days for the United States (1970–2022, Index Normal = 100)



The carbon intensity of the electric power sector is impacted by the amount of non-fossil energy sources of electricity. The utilization (i.e., capacity factors)[12] of nuclear power plants in 2022 remained high at 93 percent. In 2022, nuclear power represented 19 percent of total electricity generation. Since 1990, the wind and solar power sectors have shown strong growth and have become relatively important sources of electricity. Between 1990 and 2022, renewable energy generation (in kWh) from solar and wind energy have increased from 0.1 percent in 1990 to 14 percent of total electricity generation in 2022, which helped drive the decrease in the carbon intensity of the electricity supply in the United States.

Stationary Combustion

The direct combustion of fuels by stationary sources in the electric power, industrial, commercial, and residential sectors represent the greatest share of U.S. greenhouse gas emissions. Table 3-7 presents CO_2 emissions from fossil fuel combustion by stationary sources. The CO_2 emitted is closely linked to the type of fuel being combusted in each sector (see the Methodology section of CO_2 from Fossil Fuel Combustion). In addition to CO_2 emissions, CH_4 and N_2O are emitted from fossil fuel combustion as well. Table 3-8 and Table 3-9 present CH_4 and N_2O emissions from the combustion of fuels in stationary sources. The CH_4 and N_2O emissions are linked to the type of fuel being combusted as well as the combustion technology (see the Methodology section for CH_4 and N_2O from Stationary Combustion).

Table 3-7: CO_2 Emissions from Stationary Fossil Fuel Combustion (MMT CO_2 Eq.)

Sector/Fuel Type	1990	2005	2018	2019	2020	2021	2022
Electric Power	**1,820.0**	**2,400.1**	**1,753.4**	**1,606.7**	**1,439.6**	**1,540.9**	**1,531.7**
Coal	1,546.5	1,982.8	1,152.9	973.5	788.2	910.1	851.5
Natural Gas	175.4	318.9	577.9	616.6	634.8	612.8	659.3
Fuel Oil	97.5	98.0	22.2	16.2	16.2	17.7	20.5
Geothermal	0.5	0.5	0.4	0.4	0.4	0.4	0.4
Industrial	**876.5**	**847.6**	**810.5**	**809.8**	**762.0**	**780.5**	**801.1**
Coal	157.8	117.8	54.4	49.4	43.0	43.0	43.0
Natural Gas	407.4	387.8	493.5	501.5	489.7	501.2	510.4
Fuel Oil	311.2	342.0	262.6	258.9	229.3	236.3	247.6
Residential	**338.6**	**358.9**	**338.9**	**342.9**	**314.8**	**318.0**	**334.1**
Coal	3.0	0.8	NO	NO	NO	NO	NO
Natural Gas	237.8	262.2	273.8	275.5	256.4	258.6	272.0
Fuel Oil	97.8	95.9	65.1	67.4	58.4	59.4	62.1
Commercial	**228.3**	**227.1**	**246.3**	**251.7**	**229.3**	**237.5**	**258.7**
Coal	12.0	9.3	1.8	1.6	1.4	1.4	1.4
Natural Gas	142.0	162.9	192.5	192.9	173.5	180.4	192.3
Fuel Oil	74.3	54.9	52.0	57.2	54.4	55.7	65.1
U.S. Territories	**20.0**	**51.9**	**25.9**	**24.8**	**23.3**	**23.8**	**22.6**
Coal	0.5	3.0	2.6	3.6	3.1	2.9	2.9
Natural Gas	NO	1.3	3.3	3.8	2.6	3.9	2.7
Fuel Oil	19.5	47.6	20.1	17.5	17.5	17.0	17.0
Total	**3,283.3**	**3,885.6**	**3,175.1**	**3,036.0**	**2,768.9**	**2,900.7**	**2,948.1**

NO (Not Occurring)

Note: Totals may not sum due to independent rounding.

[12] The capacity factor equals generation divided by net summer capacity. Summer capacity is defined as "The maximum output that generating equipment can supply to system load, as demonstrated by a multi-hour test, at the time of summer peak demand (period of June 1 through September 30)" (EIA 2020a). Data for both the generation and net summer capacity are from EIA (2024a).

Table 3-8: CH_4 Emissions from Stationary Combustion (MMT CO_2 Eq.)

Sector/Fuel Type	1990	2005	2018	2019	2020	2021	2022
Electric Power	**0.5**	**1.0**	**1.4**	**1.4**	**1.4**	**1.4**	**1.3**
Coal	0.4	0.4	0.3	0.2	0.2	0.2	0.2
Fuel Oil	+	+	+	+	+	+	+
Natural gas	0.1	0.5	1.1	1.2	1.2	1.2	1.0
Wood	+	+	+	+	+	+	+
Industrial	**2.1**	**1.9**	**1.7**	**1.7**	**1.6**	**1.6**	**1.6**
Coal	0.5	0.3	0.2	0.1	0.1	0.1	0.1
Fuel Oil	0.2	0.2	0.2	0.2	0.1	0.1	0.2
Natural gas	0.2	0.2	0.2	0.3	0.2	0.3	0.3
Wood	1.2	1.2	1.1	1.1	1.1	1.1	1.0
Commercial	**1.2**	**1.2**	**1.4**	**1.4**	**1.3**	**1.3**	**1.4**
Coal	+	+	+	+	+	+	+
Fuel Oil	0.3	0.2	0.2	0.2	0.2	0.2	0.3
Natural gas	0.4	0.4	0.5	0.5	0.4	0.5	0.5
Wood	0.5	0.6	0.7	0.7	0.7	0.7	0.7
Residential	**5.9**	**4.5**	**5.1**	**5.3**	**3.6**	**3.6**	**4.3**
Coal	0.3	0.1	NO	NO	NO	NO	NO
Fuel Oil	0.4	0.4	0.3	0.3	0.2	0.2	0.3
Natural Gas	0.6	0.7	0.7	0.7	0.6	0.6	0.7
Wood	4.6	3.4	4.2	4.4	2.8	2.7	3.4
U.S. Territories	**+**	**0.1**	**+**	**+**	**+**	**+**	**+**
Coal	+	+	+	+	+	+	+
Fuel Oil	+	0.1	+	+	+	+	+
Natural Gas	NO	+	+	+	+	+	+
Wood	NE	NE	NE	NE	NE	NE	NE
Total	**9.7**	**8.8**	**9.6**	**9.8**	**8.0**	**8.0**	**8.6**

+ Does not exceed 0.05 MMT CO_2 Eq.

NO (Not Occurring)

NE (Not Estimated)

Note: Totals may not sum due to independent rounding.

Table 3-9: N_2O Emissions from Stationary Combustion (MMT CO_2 Eq.)

Sector/Fuel Type	1990	2005	2018	2019	2020	2021	2022
Electric Power	**18.2**	**26.7**	**21.7**	**18.8**	**17.5**	**19.0**	**21.6**
Coal	17.9	24.9	18.1	14.8	13.5	15.1	18.2
Fuel Oil	0.1	0.1	+	+	+	+	+
Natural Gas	0.3	1.7	3.6	3.9	4.0	3.9	3.4
Wood	+	+	+	+	+	+	+
Industrial	**2.8**	**2.6**	**2.2**	**2.2**	**2.0**	**2.1**	**2.0**
Coal	0.7	0.5	0.2	0.2	0.2	0.2	0.2
Fuel Oil	0.5	0.5	0.3	0.3	0.3	0.3	0.3
Natural Gas	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Wood	1.5	1.5	1.4	1.4	1.4	1.4	1.3
Commercial	**0.3**	**0.3**	**0.3**	**0.3**	**0.3**	**0.3**	**0.3**
Coal	+	+	+	+	+	+	+
Fuel Oil	0.2	0.1	0.1	0.1	0.1	0.1	0.1
Natural Gas	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Wood	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Residential	**0.9**	**0.8**	**0.8**	**0.8**	**0.6**	**0.6**	**0.7**
Coal	+	+	NO	NO	NO	NO	NO
Fuel Oil	0.2	0.2	0.2	0.2	0.1	0.1	0.1

Natural Gas	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Wood	0.6	0.4	0.5	0.5	0.3	0.3	0.4
U.S. Territories	**+**	**0.1**	**0.1**	**0.1**	**0.1**	**0.1**	**0.1**
Coal	+	+	+	+	+	+	+
Fuel Oil	+	0.1	+	+	+	+	+
Natural Gas	NO	+	+	+	+	+	+
Wood	NE	NE	NE	NE	NE	NE	NE
Total	**22.3**	**30.5**	**25.1**	**22.2**	**20.5**	**22.0**	**24.7**

+ Does not exceed 0.05 MMT CO_2 Eq.
NO (Not Occurring)
NE (Not Estimated)
Note: Totals may not sum due to independent rounding.

Fossil Fuel Combustion Emissions by Sector

Table 3-10 provides an overview of the CO_2, CH_4, and N_2O emissions from fossil fuel combustion by sector, including transportation, electric power, industrial, residential, commercial, and U.S. Territories.

Table 3-10: CO_2, CH_4, and N_2O Emissions from Fossil Fuel Combustion by Sector (MMT CO_2 Eq.)

End-Use Sector	1990	2005	2018	2019	2020	2021	2022
Transportation	**1,514.6**	**1,899.9**	**1,833.6**	**1,838.6**	**1,591.5**	**1,772.9**	**1,770.6**
CO_2	1,468.9	1,858.6	1,813.1	1,816.6	1,572.8	1,753.5	1,751.3
CH_4	7.2	4.3	2.8	2.9	2.5	2.6	2.6
N_2O	38.4	37.0	17.7	19.1	16.1	16.8	16.7
Electric Power	**1,838.7**	**2,427.8**	**1,776.5**	**1,626.9**	**1,458.5**	**1,561.3**	**1,554.5**
CO_2	1,820.0	2,400.1	1,753.4	1,606.7	1,439.6	1,540.9	1,531.7
CH_4	0.5	1.0	1.4	1.4	1.4	1.4	1.3
N_2O	18.2	26.7	21.7	18.8	17.5	19.0	21.6
Industrial	**881.3**	**852.2**	**814.4**	**813.7**	**765.6**	**784.1**	**804.7**
CO_2	876.5	847.6	810.5	809.8	762.0	780.5	801.1
CH_4	2.1	1.9	1.7	1.7	1.6	1.6	1.6
N_2O	2.8	2.6	2.2	2.2	2.0	2.1	2.0
Residential	**345.4**	**364.2**	**344.9**	**349.1**	**319.0**	**322.3**	**339.1**
CO_2	338.6	358.9	338.9	342.9	314.8	318.0	334.1
CH_4	5.9	4.5	5.1	5.3	3.6	3.6	4.3
N_2O	0.9	0.8	0.8	0.8	0.6	0.6	0.7
Commercial	**229.8**	**228.6**	**248.0**	**253.5**	**230.9**	**239.2**	**260.5**
CO_2	228.3	227.1	246.3	251.7	229.3	237.5	258.7
CH_4	1.2	1.2	1.4	1.4	1.3	1.3	1.4
N_2O	0.3	0.3	0.3	0.3	0.3	0.3	0.3
U.S. Territories[a]	**20.1**	**52.1**	**26.0**	**24.9**	**23.4**	**23.9**	**22.7**
Total	**4,829.9**	**5,824.8**	**5,043.4**	**4,906.6**	**4,388.9**	**4,703.7**	**4,752.0**

[a] U.S. Territories are not apportioned by sector, and emissions shown in the table are total greenhouse gas emissions from all fuel combustion sources.
Note: Totals may not sum due to independent rounding.

Other than the greenhouse gases CO_2, CH_4, and N_2O, gases emitted from stationary combustion include the greenhouse gas precursors nitrogen oxides (NO_x), CO, NMVOCs, and sulfur dioxide (SO_2). Methane and N_2O emissions from stationary combustion sources depend upon fuel characteristics and the size and vintage of combustion device, along with combustion technology, pollution control equipment, ambient environmental conditions, and operation and maintenance practices. Nitrous oxide emissions from stationary combustion are closely related to air-fuel mixes and combustion temperatures, as well as the characteristics of any pollution control equipment that is employed. Methane emissions from stationary combustion are primarily a function of the CH_4 content of the fuel and combustion efficiency.

Mobile combustion also produces emissions of CH_4, N_2O, and greenhouse gas precursors including NO_x, CO, and NMVOCs. As with stationary combustion, N_2O and NO_x emissions from mobile combustion are closely related to fuel characteristics, air-fuel mixes, combustion temperatures, and the use of pollution control equipment. Nitrous oxide from mobile sources, in particular, can be formed by the catalytic processes used to control NO_x, CO, and hydrocarbon emissions. Carbon monoxide emissions from mobile combustion are significantly affected by combustion efficiency and the presence of post-combustion emission controls. Carbon monoxide emissions are highest when air-fuel mixtures have less oxygen than required for complete combustion. These emissions occur especially in vehicle idle, low speed, and cold start conditions. Methane and NMVOC emissions from motor vehicles are a function of the CH_4 content of the motor fuel, the amount of hydrocarbons passing uncombusted through the engine, and any post-combustion control of hydrocarbon emissions (such as catalytic converters).

An alternative method of presenting combustion emissions is to allocate emissions associated with electric power to the sectors in which it is used. Four end-use sectors are defined: transportation, industrial, residential, and commercial. In Table 3-11 below, electric power emissions have been distributed to each end-use sector based upon the sector's share of national electricity use, with the exception of CH_4 and N_2O from transportation electricity use.[13] Emissions from U.S. Territories are also calculated separately due to a lack of end-use-specific consumption data.[14] This method assumes that emissions from combustion sources are distributed across the four end-use sectors based on the ratio of electricity use in that sector. The results of this alternative method are presented in Table 3-11.

Table 3-11: CO_2, CH_4, and N_2O Emissions from Fossil Fuel Combustion by End-Use Sector with Electricity Emissions Distributed (MMT CO_2 Eq.)

End-Use Sector	1990	2005	2018	2019	2020	2021	2022
Transportation	**1,517.6**	**1,904.6**	**1,838.4**	**1,843.4**	**1,595.6**	**1,778.0**	**1,776.7**
CO_2	1,472.0	1,863.3	1,817.9	1,821.4	1,576.9	1,758.6	1,757.4
CH_4	7.2	4.3	2.8	2.9	2.5	2.6	2.6
N_2O	38.4	37.0	17.7	19.1	16.1	16.8	16.7
Industrial	**1,574.8**	**1,597.0**	**1,322.4**	**1,285.0**	**1,180.8**	**1,235.2**	**1,248.2**
CO_2	1,562.9	1,584.0	1,311.8	1,275.3	1,171.8	1,225.6	1,238.0
CH_4	2.2	2.2	2.1	2.1	2.0	2.0	1.9
N_2O	9.7	10.8	8.5	7.6	7.1	7.6	8.2
Residential	**944.2**	**1,230.1**	**995.7**	**940.2**	**871.6**	**902.1**	**912.9**
CO_2	931.3	1,214.9	981.2	926.7	860.1	890.3	899.4
CH_4	6.0	4.9	5.6	5.8	4.2	4.2	4.8
N_2O	6.9	10.3	8.8	7.7	7.3	7.7	8.7
Commercial	**773.1**	**1,040.9**	**861.0**	**813.1**	**717.6**	**764.6**	**791.6**
CO_2	766.0	1,030.1	851.3	804.4	709.6	756.1	782.0
CH_4	1.3	1.5	1.8	1.9	1.8	1.8	1.8
N_2O	5.7	9.3	7.8	6.8	6.2	6.7	7.7
U.S. Territories[a]	**20.1**	**52.1**	**26.0**	**24.9**	**23.4**	**23.9**	**22.7**
Total	**4,829.9**	**5,824.8**	**5,043.4**	**4,906.6**	**4,388.9**	**4,703.7**	**4,752.0**

[a] U.S. Territories are not apportioned by sector, and emissions are total greenhouse gas emissions from all fuel combustion sources.

Notes: Totals may not sum due to independent rounding. Emissions from fossil fuel combustion by electric power are allocated based on aggregate national electricity use by each end-use sector.

[13] Separate calculations are performed for transportation-related CH_4 and N_2O. The methodology used to calculate these emissions is discussed in the Mobile Combustion section.

[14] U.S. Territories (including American Samoa, Guam, Puerto Rico, U.S. Virgin Islands, Wake Island, and other outlying U.S. Pacific Islands) consumption data obtained from EIA are only available at the aggregate level and cannot be broken out by end-use sector. The distribution of emissions to each end-use sector for the 50 states does not apply to territories data.

Electric Power Sector

The process of generating electricity is the largest stationary source of CO_2 emissions in the United States, representing 30.3 percent of total CO_2 emissions from all CO_2 emissions sources across the United States. Methane and N_2O accounted for a small portion of total greenhouse gas emissions from electric power, representing 0.1 percent and 1.4 percent, respectively. Electric power also accounted for 32.6 percent of CO_2 emissions from fossil fuel combustion in 2022. Methane and N_2O from electric power represented 11.4 and 52.2 percent of total CH_4 and N_2O emissions from fossil fuel combustion in 2022, respectively.

For the underlying energy data used in this chapter, the Energy Information Administration (EIA) places electric power generation into three functional categories: the electric power sector, the commercial sector, and the industrial sector. The energy use and emissions associated with the electric power sector are included here. The electric power sector consists of electric utilities and independent power producers whose primary business is the production of electricity. This includes both regulated utilities and non-utilities (e.g., independent power producers, qualifying co-generators, and other small power producers). Energy use and emissions associated with electric generation in the commercial and industrial sectors is reported in those other sectors where the producer of the power indicates that its primary business is something other than the production of electricity.[15]

Total greenhouse gas emissions from the electric power sector have decreased by 15.5 percent since 1990. From 1990 to 2007, electric power sector emissions increased by 33 percent, driven by a significant increase in electricity demand (39 percent) while the carbon intensity of electricity generated showed a modest decline (2.1 percent). From 2008 to 2022, as electricity demand increased by 5.2 percent, electric power sector emissions decreased by 35 percent, driven by a significant drop (25 percent) in the carbon intensity of electricity generated. Overall, the carbon intensity of the electric power sector, in terms of CO_2 Eq. per QBtu, decreased by 28 percent from 1990 to 2022 with additional trends detailed in Box 3-4. This decoupling of electric power generation and the resulting CO_2 emissions is shown in Figure 3-9. This recent decarbonization of the electric power sector is a result of several key drivers.

Coal-fired electric generation (in kilowatt-hours [kWh]) decreased from 54 percent of generation in 1990 to 20 percent in 2022.[16] This corresponded with an increase in natural gas generation and renewable energy generation, largely from wind and solar energy. Natural gas generation (in kWh) represented 11 percent of electric power generation in 1990 and increased over the 33-year period to represent 39 percent of electric power sector generation in 2022 (see Table 3-12). Natural gas has a much lower carbon content than coal and is generated in power plants that are generally more efficient in terms of kWh produced per Btu of fuel combusted, which has led to lower emissions as natural gas replaces coal-powered electricity generation. Natural gas and coal used in the United States in 2022 had an average carbon content of 14.43 MMT C/Qbtu and 26.13 MMT C/Qbtu respectively.

[15] Utilities primarily generate power for the U.S. electric grid for sale to retail customers. Non-utilities typically generate electricity for sale on the wholesale electricity market (e.g., to utilities for distribution and resale to retail customers). Where electricity generation occurs outside the EIA-defined electric power sector, it is typically for the entity's own use.

[16] Values represent electricity *net* generation from the electric power sector (EIA 2024a).

Table 3-12: Electric Power Generation by Fuel Type (Percent)

Fuel Type	1990	2005	2018	2019	2020	2021	2022
Coal	54.1%	51.1%	28.4%	24.2%	19.9%	22.6%	20.3%
Natural Gas	10.7%	17.5%	34.0%	37.3%	39.5%	37.3%	38.8%
Nuclear	19.9%	20.0%	20.1%	20.4%	20.5%	19.7%	18.9%
Renewables	11.3%	8.3%	16.8%	17.6%	19.5%	19.8%	21.4%
Petroleum	4.1%	3.0%	0.6%	0.4%	0.4%	0.5%	0.5%
Other Gases[a]	+	0.1%	0.1%	0.1%	0.1%	0.1%	0.1%
Net Electricity Generation (Billion kWh)[b]	2,905	3,902	4,020	3,966	3,851	3,955	4,076

+ Does not exceed 0.05 percent.

[a] Other gases include blast furnace gas, propane gas, and other manufactured and waste gases derived from fossil fuels.

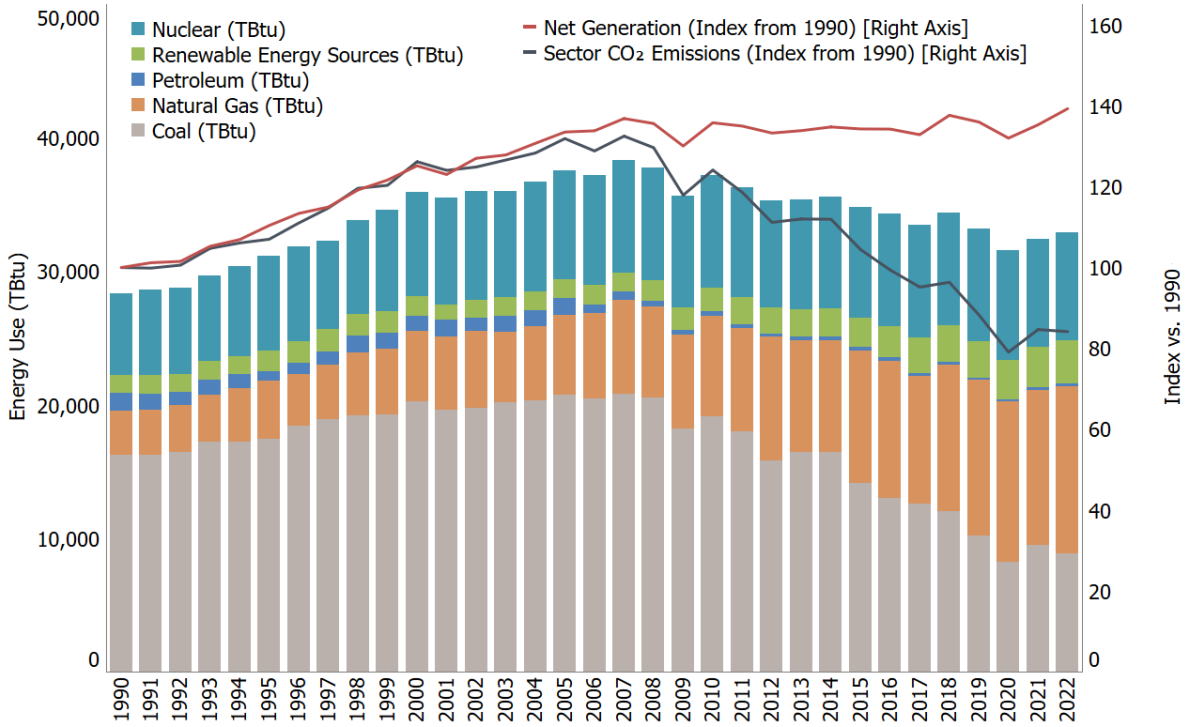
[b] Represents net electricity generation from the electric power sector. Excludes net electricity generation from commercial and industrial combined-heat-and-power and electricity-only plants. Does not include electricity generation from purchased steam as the fuel used to generate the steam cannot be determined.

In 2022, CO_2 emissions from the electric power sector decreased by 0.6 percent relative to 2021. This decrease in CO_2 emissions was primarily driven by a decrease in coal consumed to produce electricity in the electric power sector. Consumption of coal for electric power decreased by 6.4 percent while consumption of natural gas increased 7.6 percent from 2021 to 2022, leading to an overall decrease in emissions. There has also been a rapid increase in renewable energy electricity generation in the electric power sector in recent years. Electricity generation from renewable sources increased by 11 percent from 2021 to 2022 (see Table 3-12). A decrease in coal-fired electricity generation and increases in natural gas and renewable energy sources for electricity generation contributed to a decoupling of emissions trends from electric power generation trends over the recent time series (see Figure 3-9).

Decreases in natural gas prices and the associated increase in natural gas generation, particularly between 2005 and 2019, was a primary driver of the fuel switching from using coal to using natural gas for electricity generation, which led to a significant decrease in CO_2 emissions from electricity generation. During this time period, the cost of natural gas (in $/MMBtu) decreased by 56 percent while the cost of coal (in $/MMBtu) increased by 74 percent (EIA 2024a). However, from 2020 to 2022, natural gas prices increased 200 percent and are now 9 percent higher than 2005 levels due to the COVID-19 pandemic and other factors disrupting the domestic and global natural gas markets. While the increase in natural gas prices led to a temporary trend reversal, with coal consumption increasing and natural gas consumption decreasing from 2020 to 2021, the broader trend of declining coal consumption for electricity generation continues. From 2021 to 2022, coal consumption decreased 6 percent while natural gas consumption increased 8 percent.

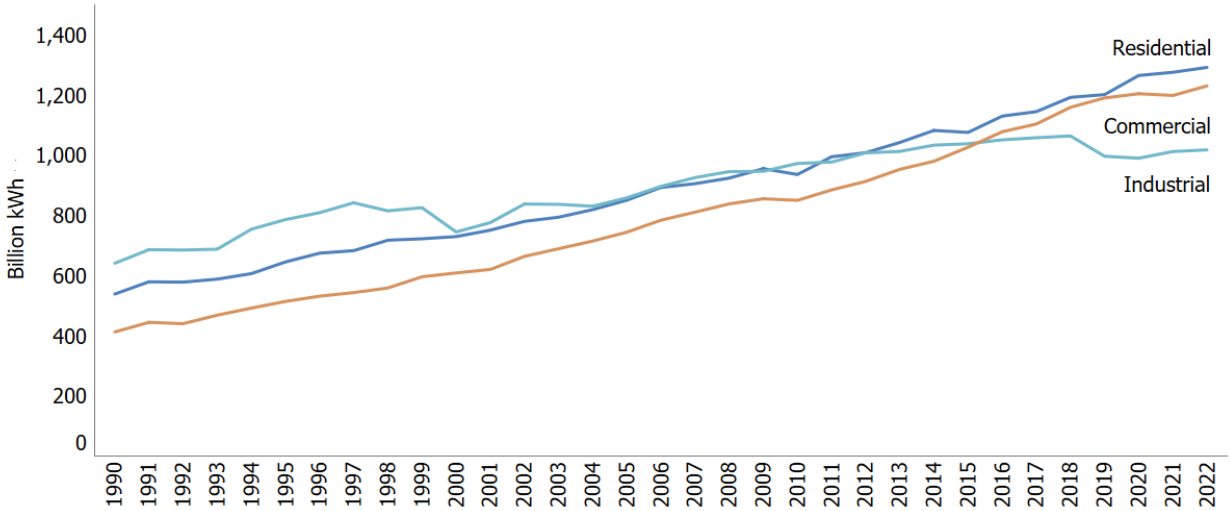
Moving forward, the shift away from coal—and increasingly towards renewable energy sources in addition to natural gas—for electricity generation will further contribute to reductions in power sector emissions. Renewable energy generation (in kWh) from wind and solar energy increased from 0.1 percent of total generation in 1990 to 5 percent in 2015 and increased at a faster pace to 14 percent of total generation in 2022. The decrease in carbon intensity occurred even as total electricity retail sales increased 45 percent, from 2,713 billion kWh in 1990 to 3,927 billion kWh in 2022.

Figure 3-9: Fuels Used in Electric Power Generation and Total Electric Power Sector CO_2 Emissions



Electricity was used primarily in the residential, commercial, and industrial end-use sectors for lighting, heating, electric motors, appliances, electronics, and air conditioning (see Figure 3-10). Note that transportation is an end-use sector as well but is not shown in Figure 3-10 due to the sector's relatively low percentage of electricity use. The Transportation Sector and Mobile Combustion section provides a break-out of CO_2 emissions from electricity use in the transportation end-use sector.

Figure 3-10: Electric Power Retail Sales by End-Use Sector



In 2022, electricity sales to the residential and commercial end-use sectors, as presented in Figure 3-10, increased by 2.6 percent and 4.7 percent relative to 2021, respectively. Electricity sales to the industrial sector in 2022

increased by approximately 2.0 percent relative to 2021. The sections below describe end-use sector energy use in more detail. Overall, in 2022, the amount of electricity retail sales (in kWh) increased by 3.2 percent relative to 2021.

Industrial Sector

Industrial sector CO_2, CH_4, and N_2O emissions accounted for 17, 14, and 5 percent of CO_2, CH_4, and N_2O emissions from fossil fuel combustion, respectively, in 2022. Carbon dioxide, CH_4, and N_2O emissions resulted from the direct consumption of fossil fuels for steam and process heat production.

The industrial end-use sector, per the underlying energy use data from EIA, includes activities such as manufacturing, construction, mining, and agriculture. The largest of these activities in terms of energy use is manufacturing, of which six industries—petroleum refineries, chemicals, paper, primary metals, food, and nonmetallic mineral products—represent the majority of the energy use (EIA 2024a; EIA 2009b).

There are many dynamics that impact emissions from the industrial sector including economic activity, changes in the make-up of the industrial sector, changes in the emissions intensity of industrial processes, and weather-related impacts on heating and cooling of industrial buildings.[17] Structural changes within the U.S. economy that lead to shifts in industrial output away from energy-intensive manufacturing products to less energy-intensive products (e.g., from steel to computer equipment) have had a significant effect on industrial emissions.

From 2021 to 2022, total industrial production and manufacturing output increased by 3.4 percent (FRB 2022). Over this period, output increased slightly across production indices for Food, Nonmetallic Mineral Products, Paper, Petroleum Refineries, and Primary Metals. Production of chemicals declined slightly between 2021 and 2022 (see Figure 3-11). From 2021 to 2022, total energy use in the industrial sector increased by 2.0 percent, driven mainly by a 2.6 percent increase in fossil fuel consumption in the industrial sector. Consumption of renewables decreased 1.6 percent from 2021 to 2022. Due to the relative increases and decreases of individual indices there was an increase in natural gas and an increase in electricity used by this sector (see Figure 3-12). In 2022, CO_2, CH_4, and N_2O emissions from fossil fuel combustion and electricity use within the industrial end-use sector totaled 1,248.2 MMT CO_2 Eq., a 1.1 percent increase from 2021 emissions.

Through EPA's Greenhouse Gas Reporting Program (GHGRP), specific industrial sector trends can be discerned from the overall total EIA industrial fuel consumption data used for these calculations. For example, from 2021 to 2022, the underlying EIA data showed increased consumption of natural gas and petroleum and decreased consumption of coal in the industrial sector. The GHGRP data highlights that several industries contributed to these trends, including chemical manufacturing; pulp, paper and print; food processing, beverages and tobacco; minerals manufacturing; and agriculture-forest-fisheries.[18]

[17] Some commercial customers are large enough to obtain an industrial price for natural gas and/or electricity and are consequently grouped with the industrial end-use sector in U.S. energy statistics. These misclassifications of large commercial customers likely cause the industrial end-use sector to appear to be more sensitive to weather conditions.

[18] Further details on industrial sector combustion emissions are provided by EPA's GHGRP. See http://ghgdata.epa.gov/ghgp/main.do.

Figure 3-11: Industrial Production Indices (Index 2017=100)

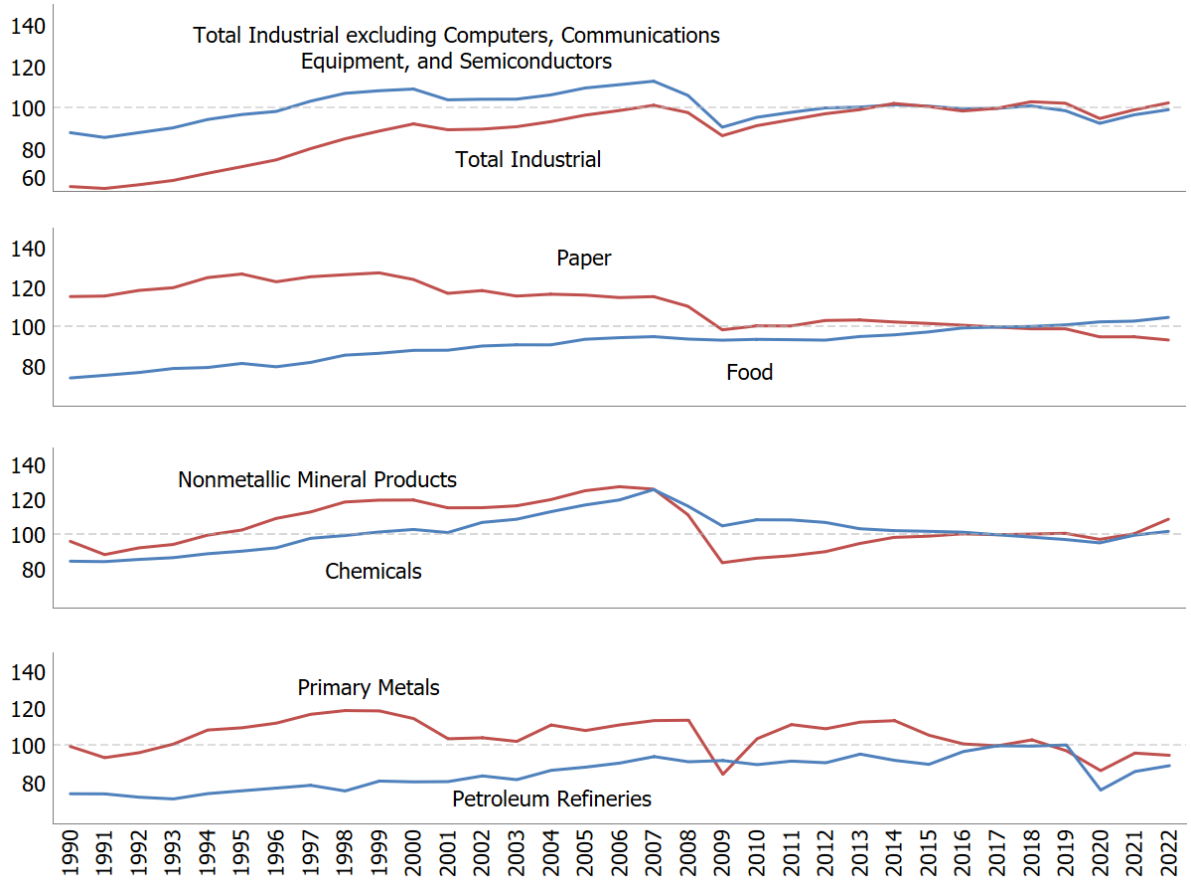
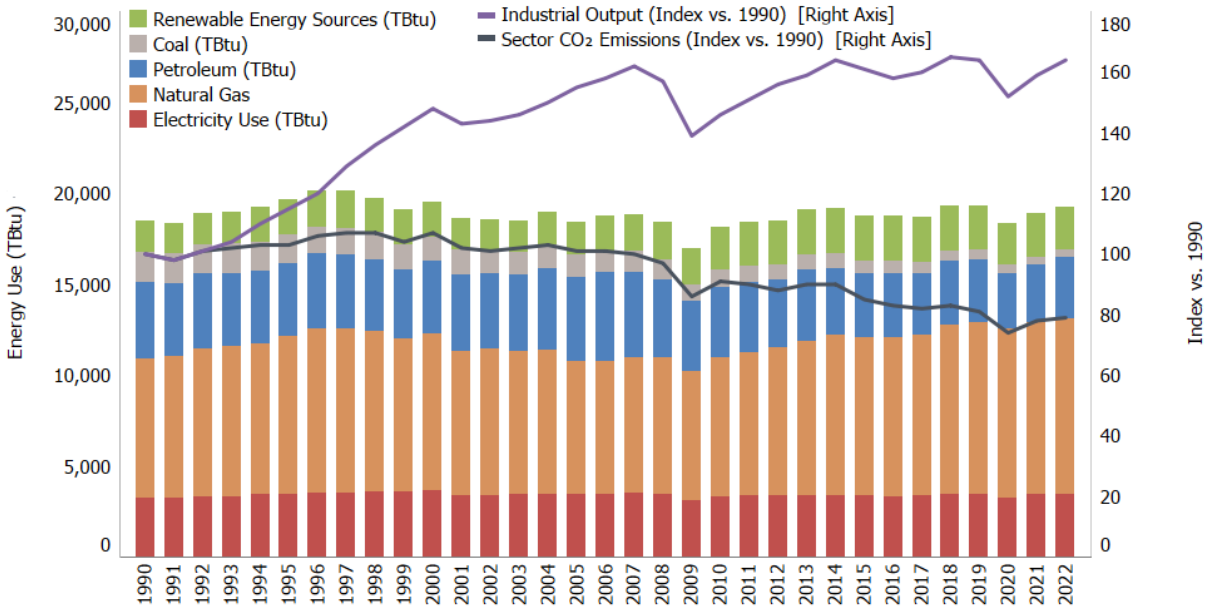


Figure 3-12: Fuels and Electricity Used in Industrial Sector, Industrial Output, and Total Sector CO_2 Emissions (Including Electricity)



Despite the growth in industrial output (65 percent) and the overall U.S. economy (114 percent) from 1990 to 2022, direct CO_2 emissions from fossil fuel combustion in the industrial sector decreased by 8.6 percent over the same time series. A number of factors are assumed to result in decoupling of growth in industrial output from industrial greenhouse gas emissions, for example: (1) more rapid growth in output from less energy-intensive industries relative to traditional manufacturing industries, and (2) energy-intensive industries such as steel are employing new methods, such as electric arc furnaces, that are less carbon-intensive than the older methods.

Box 3-3: Uses of Greenhouse Gas Reporting Program Data and Improvements in Reporting Emissions from Industrial Sector Fossil Fuel Combustion

As described in the calculation methodology, total fossil fuel consumption for each year is based on aggregated end-use sector consumption published by the EIA. The availability of facility-level combustion emissions through EPA's GHGRP has provided an opportunity to better characterize the industrial sector's energy consumption and emissions in the United States, through a disaggregation of EIA's industrial sector fuel consumption data from select industries.

For GHGRP 2010 through 2022 reporting years, facility-level fossil fuel combustion emissions reported through EPA's GHGRP were categorized and distributed to specific industry types by utilizing facility-reported NAICS codes (as published by the U.S. Census Bureau). As noted previously in this report, the definitions and provisions for reporting fuel types in EPA's GHGRP include some differences from the *Inventory's* use of EIA national fuel statistics to meet Paris Agreement and UNFCCC reporting guidelines. The IPCC has provided guidance on aligning facility-level reported fuels and fuel types published in national energy statistics, which guided this exercise.[19]

As with previous *Inventory* reports, the current effort represents an attempt to align, reconcile, and coordinate the facility-level reporting of fossil fuel combustion emissions under EPA's GHGRP with the national-level approach presented in this report. Consistent with recommendations for reporting the *Inventory* to the UNFCCC, progress was made on certain fuel types for specific industries and has been included in the Common Reporting Tables (CRTs) that are submitted to the UNFCCC along with this report.[20] The efforts in reconciling fuels focus on standard, common fuel types (e.g., natural gas, distillate fuel oil) where the fuels in EIA's national statistics aligned well with facility-level GHGRP data. For these reasons, the current information presented in the CRTs should be viewed as an initial attempt at this exercise. Additional efforts will be made for future *Inventory* reports to improve the mapping of fuel types and examine ways to reconcile and coordinate any differences between facility-level data and national statistics. The current analysis includes the full time series presented in the CRTs. Analyses were conducted linking GHGRP facility-level reporting with the information published by EIA in its MECS data in order to disaggregate the full 1990 through 2022 time period in the CRTs. It is believed that the current analysis has led to improvements in the presentation of data in the *Inventory*, but further work will be conducted, and future improvements will be realized in subsequent *Inventory* reports. This includes incorporating the latest MECS data as it becomes available.

Residential and Commercial Sectors

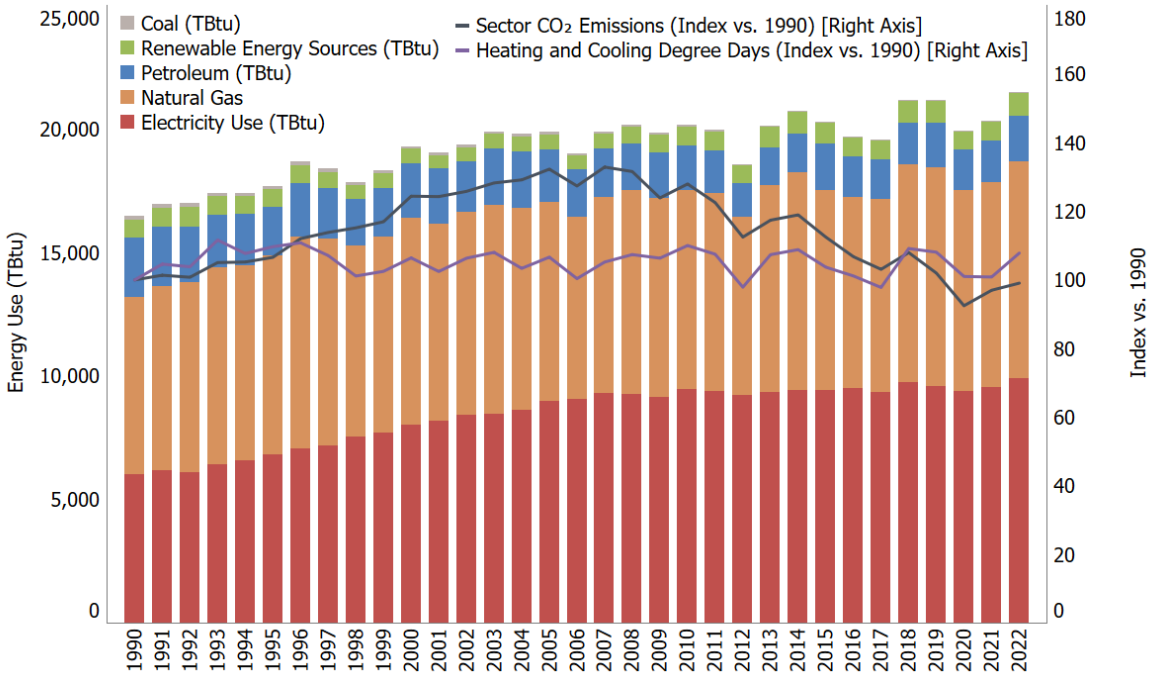
Emissions from the residential and commercial sectors have generally decreased since 2005. Short-term trends are often correlated with seasonal fluctuations in energy use caused by weather conditions, rather than prevailing economic conditions. Population growth and a trend towards larger houses has led to increasing energy use over

[19] See Section 4 "Use of Facility-Level Data in Good Practice National Greenhouse Gas Inventories" of the IPCC meeting report, and specifically the section on using facility-level data in conjunction with energy data, at http://www.ipcc-nggip.iges.or.jp/public/tb/TFI_Technical_Bulletin_1.pdf.

[20] See https://www.epa.gov/ghgemissions/inventory-us-greenhouse-gas-emissions-and-sinks.

the time series, while population migration to warmer areas and improved energy efficiency and building insulation have slowed the increase in energy use in recent years. Starting in around 2014, energy use and emissions begin to decouple due to decarbonization of the electric power sector (see Figure 3-13).

Figure 3-13: Fuels and Electricity Used in Residential and Commercial Sectors, Heating and Cooling Degree Days, and Total Sector CO_2 Emissions (Including Electricity)



In 2022, excluding indirect emissions from electricity use, the residential and commercial sectors accounted for 7 and 6 percent of CO_2 emissions from fossil fuel combustion, respectively; 39 and 13 percent of CH_4 emissions from fossil fuel combustion, respectively; and 2 and 1 percent of N_2O emissions from fossil fuel combustion, respectively. Emissions from these sectors are primarily attributable to building -related activities such as the direct consumption of natural gas and petroleum products, primarily for heating and cooking needs. Coal consumption was a minor component of energy use in the commercial sector and did not contribute to any energy use in the residential sector. Greenhouse gas emissions from commercial and residential buildings also increase substantially when emissions from electricity end-use are included, because the building sector uses 75 percent of the electricity generated in the United States (e.g., for heating, ventilation, and air conditioning; lighting; and appliances) (NREL 2023). In 2022, total emissions (CO_2, CH_4, and N_2O) from fossil fuel combustion and electricity use within the residential and commercial end-use sectors were 912.9 MMT CO_2 Eq. and 791.6 MMT CO_2 Eq., respectively. Total CO_2, CH_4, and N_2O emissions from combined fossil fuel combustion and electricity use within the residential and commercial end-use sectors increased by 1.2 and 3.5 percent from 2021 to 2022, respectively. An increase in heating degree days (7.9 percent) and cooling degree days (4.3 percent) increased energy demand for heating and cooling in the residential and commercial sectors. This resulted in a 2.6 percent increase in residential sector electricity use. From 2021 to 2022 there was a 8.4 percent higher direct energy use in the commercial sector. In addition, a shift toward energy efficient products and more stringent energy efficiency standards for household equipment has contributed to a decrease in energy demand in households (EIA 2022), resulting in a decrease in energy-related emissions in the residential sector since 1990. In the long term, the residential sector is also affected by population growth, migration trends toward warmer areas, and changes in total housing units and building attributes (e.g., larger sizes and improved insulation).

In 2022, combustion emissions from natural gas consumption represented 81 and 74 percent of the direct fossil fuel CO_2 emissions from the residential and commercial sectors, respectively. Carbon dioxide emissions from natural gas combustion in the residential and commercial sectors in 2022 increased by 5.2 percent and 6.6 percent from 2021, respectively.

U.S. Territories

Emissions from U.S. Territories are based on the fuel consumption in American Samoa, Guam, Puerto Rico, U.S. Virgin Islands, Wake Island, and other outlying U.S. Pacific Islands. As described in the Methodology section of CO_2 from Fossil Fuel Combustion, this data is collected separately from the sectoral-level data available for the general calculations. As sectoral information is not available for U.S. Territories, CO_2, CH_4, and N_2O emissions are not presented for U.S. Territories in the tables above by sector, though the emissions will occur across all sectors and sources including stationary, transportation and mobile combustion sources.

Transportation Sector and Mobile Combustion

This discussion of transportation emissions follows the alternative method of presenting combustion emissions by allocating emissions associated with electricity generation to the transportation end-use sector, as presented in Table 1-9. Table 1-8 presents direct CO_2, CH_4, and N_2O emissions from all transportation sources (i.e., excluding emissions allocated to electricity consumption in the transportation end-use sector).

The transportation end-use sector and other mobile combustion accounted for 1,776.7 MMT CO_2 Eq. in 2022, which represented 37 percent of CO_2 emissions, 23 percent of CH_4 emissions, and 41 percent of N_2O emissions from fossil fuel combustion, respectively.[21] Fuel purchased in the U.S. for international aircraft and marine travel accounted for an additional 98.9 MMT CO_2 Eq. in 2022; these emissions are recorded as international bunkers and are not included in U.S. totals according to Paris Agreement and UNFCCC reporting protocols.

Transportation End-Use Sector

From 1990 to 2019, transportation emissions from fossil fuel combustion rose by 21 percent, followed by a reduction of 13 percent from 2019 to 2020, followed by an increase of 12 percent from 2020 to 2022. Overall, from 1990 to 2022, transportation emissions from fossil fuel combustion increased by 17 percent. The increase in transportation emissions from fossil fuel combustion from 1990 to 2022 was due, in large part, to increased demand for travel (see Figure 3-14). The number of vehicle miles traveled by light-duty motor vehicles (passenger cars and light-duty trucks) increased 47 percent from 1990 to 2022, as a result of a confluence of factors including population growth, economic growth, urban sprawl, and low fuel prices over much of this period. Between 2019 and 2020, emissions from light-duty vehicles fell by 11 percent, primarily the result of the COVID-19 pandemic and associated restrictions, such as people working from home and traveling less. Light-duty vehicle VMT rebounded in 2022 but is still estimated to be 2 percent below 2019 levels.

Commercial aircraft emissions decreased by 5 percent between 2019 and 2022 but have decreased 7 percent since 2007 (FAA 2024 and DOT 1991 through 2023).[22] Decreases in jet fuel emissions (excluding bunkers) started in 2007 due in part to improved operational efficiency that results in more direct flight routing, improvements in aircraft and engine technologies to reduce fuel burn and emissions, and the accelerated retirement of older, less fuel-efficient aircraft; however, the sharp decline in commercial aircraft emissions from 2019 to 2020 and their gradual recovery since is primarily due to COVID-19 impacts on scheduled passenger air travel.

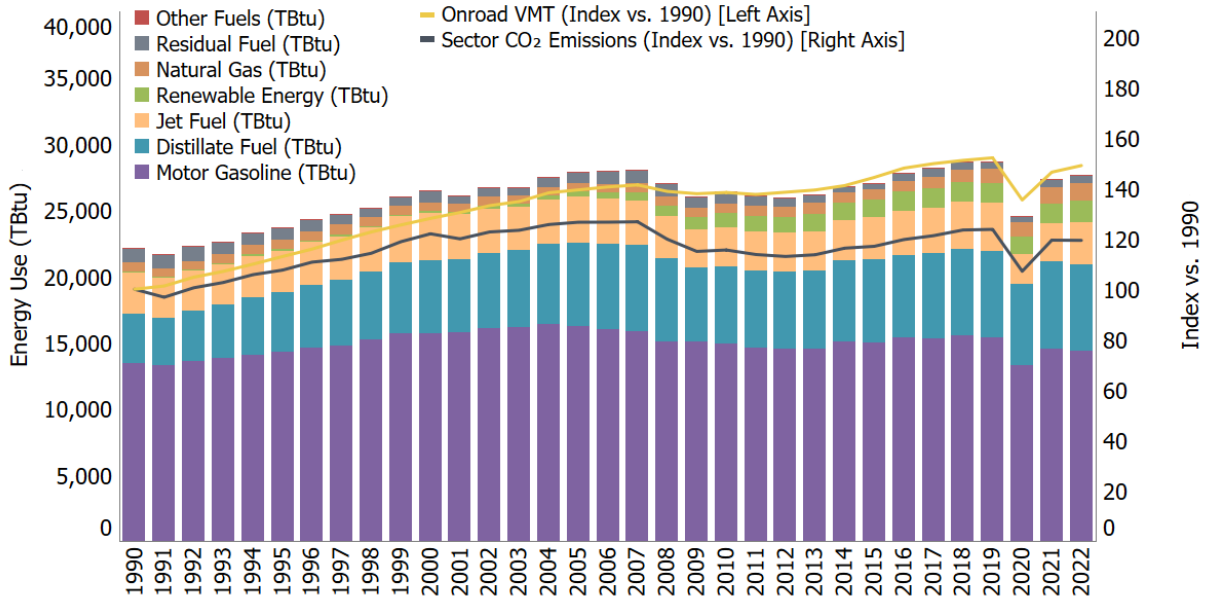
Almost all of the energy consumed for transportation was supplied by petroleum-based products, with more than half being related to gasoline consumption in automobiles and other highway vehicles. Other fuel uses, especially

[21] Note that these totals include CO_2, CH_4 and N_2O emissions from some sources in the U.S. Territories (ships and boats, recreational boats, non-transportation mobile sources) and CH_4 and N_2O emissions from transportation rail electricity.

[22] Commercial aircraft consists of passenger aircraft, cargo, and other chartered flights.

diesel fuel for freight trucks and jet fuel for aircraft, accounted for the remainder. The primary driver of transportation-related emissions was CO_2 from fossil fuel combustion, which increased by 19 percent from 1990 to 2022. Annex 3.2 presents the total emissions from all transportation and mobile sources, including CO_2, N_2O, CH_4, and HFCs.

Figure 3-14: Fuels Used in Transportation Sector, On-road VMT, and Total Sector CO_2 Emissions



Notes: Distillate fuel, residual fuel, and jet fuel include adjustments for international bunker fuels. Distillate fuel and motor gasoline include adjustments for the sectoral allocation of these fuels. Other Fuels includes aviation gasoline and propane.

Source: Information on fuel consumption was obtained from EIA (2022).

Transportation Fossil Fuel Combustion CO_2 Emissions

Domestic transportation CO_2 emissions increased by 19 percent (285.4 MMT CO_2 Eq.) between 1990 and 2022, an annualized increase of 0.6 percent. This includes a 24 percent increase in CO_2 emissions between 1990 and 2019, followed by a 13 percent decrease in 2020. Carbon dioxide emissions then increased by 11 percent between 2020 and 2022. Among domestic transportation sources, light-duty vehicles (including passenger cars and light-duty trucks) represented 57 percent of CO_2 emissions, medium- and heavy-duty trucks and buses 24 percent, commercial aircraft 7 percent, and other sources 11 percent. See Table 3-13 for a detailed breakdown of transportation CO_2 emissions by mode and fuel type.

Almost all of the energy consumed by the transportation sector is petroleum-based, including motor gasoline, diesel fuel, jet fuel, and residual oil. Carbon dioxide emissions from the combustion of ethanol and biodiesel for transportation purposes, along with the emissions associated with the agricultural and industrial processes involved in the production of biofuel, are captured in other *Inventory* sectors.[23] Ethanol consumption from the transportation sector has increased from 0.7 billion gallons in 1990 to 12.9 billion gallons in 2022, while biodiesel

[23] Biofuel estimates are presented in the Energy chapter for informational purposes only, in line with IPCC methodological guidance and UNFCCC reporting obligations. Net carbon fluxes from changes in biogenic carbon reservoirs in croplands are accounted for in the estimates for Land Use, Land-Use Change, and Forestry (see Chapter 6). More information and additional analyses on biofuels are available at EPA's Renewable Fuels Standards website. See https://www.epa.gov/renewable-fuel-standard-program.

consumption has increased from 0.01 billion gallons in 2001 to 1.6 billion gallons in 2022." For additional information, see Section 3.10 on biofuel consumption at the end of this chapter and Table A-74 in Annex 3.2.

Carbon dioxide emissions from passenger cars and light-duty trucks totaled 1,005.5 MMT CO_2 in 2022, an increase of 10 percent (91.2 MMT CO_2) from 1990. The increase in CO_2 emissions from passenger cars and light-duty trucks from 1990 to 2022 was due, in large part, to increased demand for travel as fleet-wide light-duty vehicle fuel economy was relatively stable (average new vehicle fuel economy declined slowly from 1990 through 2004 and then increased more rapidly from 2005 through 2022). Carbon dioxide emissions from passenger cars and light-duty trucks peaked at 1,145.5 MMT in 2004, and since then have declined about 12 percent. The decline in new light-duty vehicle fuel economy between 1990 and 2004 (see Figure 3-15) reflects the increasing market share of light-duty trucks, which grew from about 30 percent of new vehicle sales in 1990 to 48 percent in 2004. Starting in 2005, average new vehicle fuel economy began to increase while light-duty vehicle VMT grew only modestly for much of the period. Light-duty vehicle VMT grew by less than one percent or declined each year between 2005 and 2013, and again between 2017 and 2019. VMT grew at faster rates of 1.6 percent from 2014 to 2015, and 1.6 percent from 2015-2016. From 2019 to 2020, light-duty vehicle VMT declined by 11.0 percent due to COVID-19 pandemic; from 2020 to 2022 light-duty vehicle VMT rebounded as a part of the ongoing recovery from the pandemic, increasing by 9.8 percent.

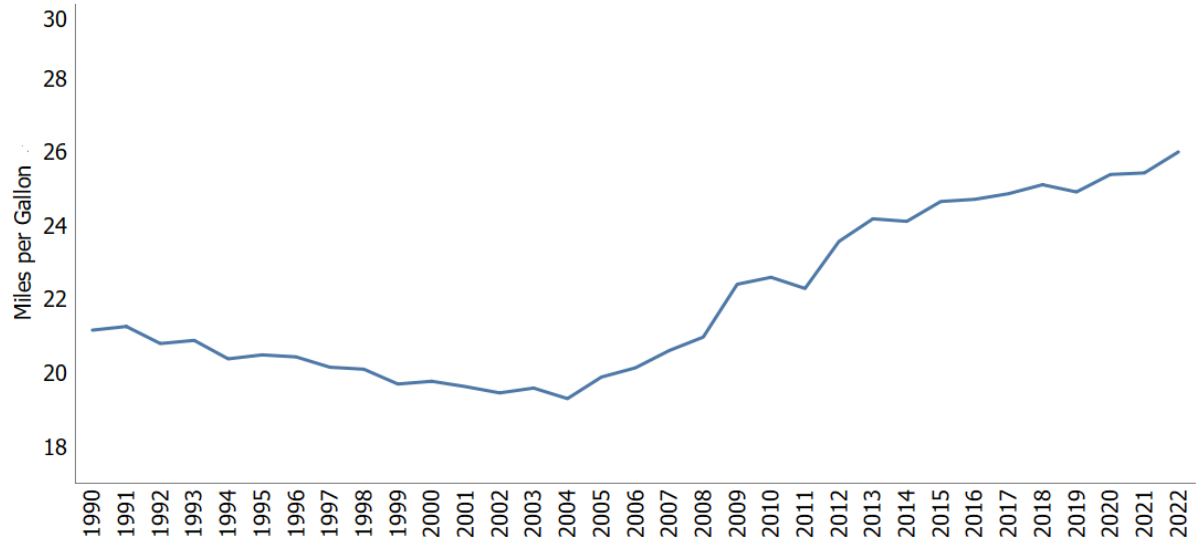
Average new vehicle fuel economy has improved almost every year since 2005 while the light-duty truck share of new vehicle sales decreased to about 33 percent of new vehicles in 2009 and has since varied from year to year between 36 and 63 percent. Since 2014, the light-duty truck share has steadily increased, reaching 62 percent of new vehicle sales in model year 2022. See Annex 3.2 for data by vehicle mode and information on VMT and the share of new vehicles (in VMT).

Medium- and heavy-duty truck CO_2 emissions increased by 73 percent from 1990 to 2022. This increase was largely due to a substantial growth in medium- and heavy-duty truck VMT, which increased by 72 percent between 1990 and 2022.

Carbon dioxide from the domestic operation of commercial aircraft increased by 18 percent (19.8 MMT CO_2) from 1990 to 2022. Across all categories of aviation, excluding international bunkers, CO_2 emissions decreased by 11 percent (20.8 MMT CO_2) between 1990 and 2022.[24] Carbon dioxide emissions from military aircraft decreased 65 percent between 1990 and 2022. Commercial aircraft CO_2 emissions increased 27 percent between 1990 and 2007, dropped 2 percent from 2007 to 2019, dropped another 33 percent from 2019 to 2020, then increased by 30 percent from 2020 to 2022. Overall, this represents a change of approximately 18 percent between 1990 and 2022. Transportation sources also produce CH_4 and N_2O; these emissions are included in Figure 3-14 and Table 3-15 and in the CH_4 and N_2O from Mobile Combustion section. Annex 3.2 presents total emissions from all transportation and mobile sources, including CO_2, CH_4, N_2O, and HFCs.

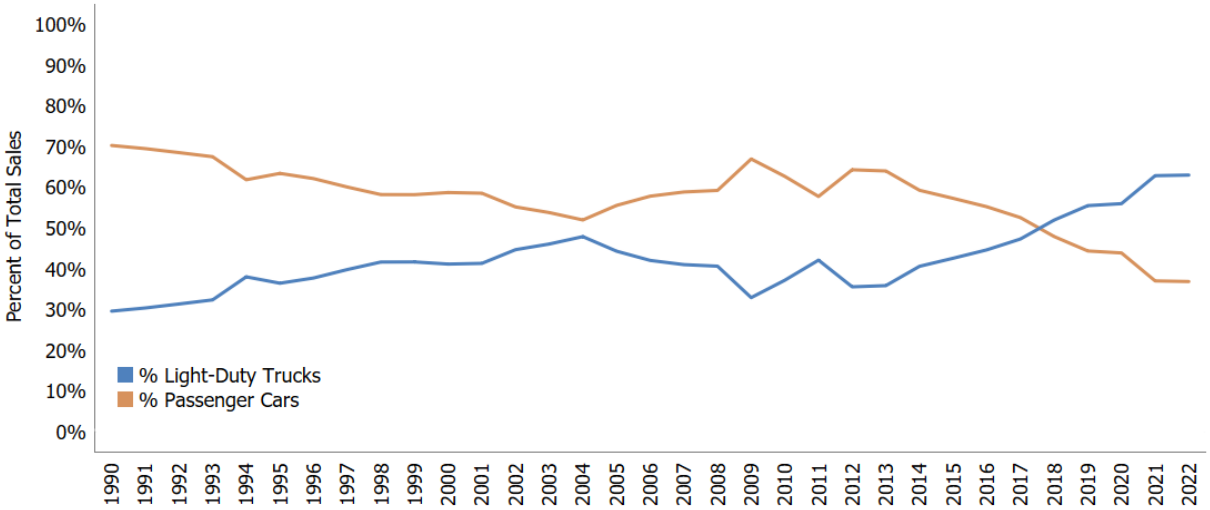
[24] Includes consumption of jet fuel and aviation gasoline. Does not include aircraft bunkers, which are not included in national emission totals, in line with IPCC methodological guidance and UNFCCC reporting obligations.

Figure 3-15: Sales-Weighted Fuel Economy of New Passenger Cars and Light-Duty Trucks, 1990–2022



Source: EPA (2023).

Figure 3-16: Sales of New Passenger Cars and Light-Duty Trucks, 1990–2022



Source: EPA (2023).

Table 3-13: CO_2 Emissions from Fossil Fuel Combustion in Transportation End-Use Sector (MMT CO_2 Eq.)

Fuel/Vehicle Type	1990	2005	2018	2019	2020	2021	2022
Gasoline[a]	**958.9**	**1,150.1**	**1,097.0**	**1,086.5**	**936.9**	**1,028.7**	**1,014.5**
Passenger Cars	612.8	518.9	382.5	380.0	328.0	360.5	356.0
Light-Duty Trucks	283.6	583.4	667.6	658.6	565.7	619.9	609.5
Medium- and Heavy-Duty Trucks[b]	42.8	28.1	26.2	27.0	24.1	27.4	27.9
Buses	2.1	1.1	2.7	2.8	2.5	2.9	2.9
Motorcycles	3.4	4.9	7.3	7.4	6.6	7.4	7.4
Recreational Boats[c]	14.3	13.7	10.7	10.7	9.9	10.6	10.8

Distillate Fuel Oil (Diesel)[a]	**274.6**	**472.1**	**486.6**	**484.1**	**455.2**	**488.1**	**483.9**
Passenger Cars	9.4	2.2	2.8	2.7	2.5	2.7	2.7
Light-Duty Trucks	8.4	30.4	31.2	31.2	30.2	33.3	33.8
Medium- and Heavy-Duty Trucks[b]	189.0	357.2	371.5	373.0	353.5	380.1	375.6
Buses	11.1	15.5	20.4	20.7	19.8	21.4	21.4
Rail	35.5	46.1	38.5	36.0	31.2	32.5	32.5
Recreational Boats[c]	2.7	2.9	2.8	2.9	2.6	2.8	3.0
Ships and Non-Recreational Boats[d]	6.8	8.4	9.3	7.5	7.6	7.8	7.8
International Bunker Fuels[e]	*11.7*	*9.5*	*10.0*	*10.1*	*7.8*	*7.4*	*7.2*
Jet Fuel	**222.3**	**249.5**	**255.2**	**258.5**	**160.4**	**203.5**	**231.5**
Commercial Aircraft[f]	109.9	132.7	129.6	136.7	91.3	119	129.7
Military Aircraft	35.7	19.8	12.1	12.2	11.7	12.5	12.4
General Aviation Aircraft	38.5	36.8	30.6	31.4	17.6	21.1	22.7
International Bunker Fuels[e]	*38.2*	*60.2*	*83.0*	*78.3*	*39.8*	*50.8*	*66.6*
International Bunker Fuels from Commercial Aviation	*30.0*	*55.6*	*79.8*	*75.1*	*36.7*	*47.6*	*63.5*
Aviation Gasoline	**3.1**	**2.4**	**1.5**	**1.6**	**1.4**	**1.5**	**1.5**
General Aviation Aircraft	3.1	2.4	1.5	1.6	1.4	1.5	1.5
Residual Fuel Oil	**76.3**	**62.9**	**45.4**	**39.7**	**29.4**	**46.2**	**47.3**
Ships and Non-Recreational Boats[e]	22.6	19.3	14.0	14.5	7.3	24.2	22.9
International Bunker Fuels[e]	*53.7*	*43.6*	*31.4*	*25.2*	*22.1*	*21.9*	*24.4*
Natural Gas[i]	**36.0**	**33.1**	**50.9**	**58.9**	**58.7**	**65.2**	**70.2**
Passenger Cars	+	+	+	+	+	+	+
Light-Duty Trucks	+	+	+	+	+	+	+
Medium- and Heavy-Duty Trucks	+	+	0.1	0.1	0.1	0.1	0.1
Buses	+	0.2	0.5	0.5	0.6	0.6	0.7
Pipeline[g]	36.0	32.8	50.3	58.3	58.0	64.4	69.3
LPG[i]	**1.4**	**1.8**	**0.8**	**0.8**	**0.5**	**0.6**	**0.6**
Passenger Cars	+	+	+	+	+	+	+
Light-Duty Trucks	0.1	0.1	+	+	+	+	+
Medium- and Heavy-Duty Trucks[b]	1.3	0.9	0.1	0.1	0.1	+	+
Buses	+	0.7	0.7	0.7	0.5	0.6	0.6
Electricity[k]	**3.0**	**4.7**	**4.8**	**4.8**	**4.1**	**5.0**	**6.1**
Passenger Cars	+	+	1.2	1.4	1.3	1.8	2.4
Light-Duty Trucks	+	+	0.2	0.2	0.3	0.7	1.1
Buses	+	+	+	+	0.1	0.1	0.1
Rail	3.0	4.7	3.4	3.1	2.4	2.5	2.5
Total [e,j]	**1,472.0**	**1,863.3**	**1,817.9**	**1,821.4**	**1,576.9**	**1758.6**	**1,757.4**
International Bunker Fuels	*103.6*	*113.3*	*124.3*	*113.6*	*69.6*	*80.2*	*98.2*
Biofuels-Ethanol[h]	*4.1*	*21.6*	*78.6*	*78.7*	*68.1*	*75.4*	*75.0*
Biofuels-Biodiesel[h]	*0.0*	*0.9*	*17.9*	*17.1*	*17.7*	*16.1*	*15.6*

+ Does not exceed 0.05 MMT CO_2 Eq.

[a] On-road fuel consumption data from FHWA Table MF-21 and MF-27 were used to determine total on-road use of motor gasoline and diesel fuel (FHWA 1996 through 2023). Ratios developed from MOVES3 output are used to apportion FHWA fuel consumption data to vehicle type and fuel type (see Annex 3.2 for information about the MOVES model).

[b] Includes medium- and heavy-duty trucks over 8,500 lbs.

[c] In 2014, EPA incorporated the NONROAD2008 model into the MOVES model framework. The current *Inventory* uses the Nonroad component of MOVES3 for years 1999 through 2022. See Annex 3.2 for information about the MOVES model.

[d] Note that large year over year fluctuations in emission estimates partially reflect nature of data collection for these sources.

[e] Official estimates exclude emissions from the combustion of both aviation and marine international bunker fuels; however, estimates of international bunker fuel-related emissions are presented for informational purposes.

[f] Commercial aircraft, as modeled in FAA's Aviation Environmental Design Tool (AEDT), consists of passenger aircraft, cargo, and other chartered flights.

[g] Pipelines reflect CO_2 emissions from natural gas-powered pipelines transporting natural gas.

[h] Ethanol and biodiesel estimates are presented for informational purposes only. See Section 3.10 of this chapter and the estimates in Land Use, Land-Use Change, and Forestry (see Chapter 6), in line with IPCC methodological guidance and Paris Agreement and UNFCCC reporting obligations, for more information on ethanol and biodiesel.

[i] Transportation sector natural gas and LPG consumption are based on data from EIA (2023b). Prior to the 1990 to 2015 *Inventory*, data from DOE TEDB were used to estimate each vehicle class's share of the total natural gas and LPG consumption. Since TEDB does not include estimates for natural gas use by medium and heavy-duty trucks or LPG use by passenger cars, EIA Alternative Fuel Vehicle Data (Browning 2017) is now used to determine each vehicle class's share of the total natural gas and LPG consumption. These changes were first incorporated in the 1990 to 2016 *Inventory* and apply to the 1990 to 2022 time period.

[j] Includes emissions from rail electricity.

[k] Electricity consumption by passenger cars, light-duty trucks (SUVs), and buses is based on plug-in electric vehicle sales and engine efficiency data, as outlined in Browning (2018). In prior *Inventory* years, CO_2 emissions from electric vehicle charging were allocated to the residential and commercial sectors. They are now allocated to the transportation sector. These changes apply to the 2010 through 2022 time period.

Notes: This table does not include emissions from non-transportation mobile sources, such as agricultural equipment and construction/mining equipment; it also does not include emissions associated with electricity consumption by pipelines or lubricants used in transportation. In addition, this table does not include CO_2 emissions from U.S. Territories, since these are covered in a separate chapter of the *Inventory*. Totals may not sum due to independent rounding.

Mobile Fossil Fuel Combustion CH_4 and N_2O Emissions

Mobile combustion includes emissions of CH_4 and N_2O from all transportation sources identified in the U.S. *Inventory* with the exception of pipelines and electric locomotives;[25] mobile sources also include non-transportation sources such as construction/mining equipment, agricultural equipment, vehicles used off-road, and other sources (e.g., snowmobiles, lawnmowers, etc.).[26] Annex 3.2 includes a summary of all emissions from both transportation and mobile sources. Table 3-14 and Table 3-15 provide mobile fossil fuel CH_4 and N_2O emission estimates in MMT CO_2 Eq.[27]

Mobile combustion was responsible for a small portion of national CH_4 emissions (0.4 percent) and was the fifth largest source of national N_2O emissions (4.3 percent) in 2022. From 1990 to 2022, mobile source CH_4 emissions declined by 64 percent, to 2.6 MMT CO_2 Eq. (93 kt), due largely to emissions control technologies employed in on-road vehicles since the mid-1990s to reduce CO, NO_x, NMVOC, and CH_4 emissions. Mobile source emissions of N_2O decreased by 57 percent, to 16.7 MMT CO_2 Eq. (63 kt) in 2022. Earlier generation control technologies initially resulted in elevated N_2O emissions, causing a 31 percent increase in N_2O emissions from mobile sources between 1990 and 1997. Improvements in later-generation emission control technologies have reduced N_2O output, resulting in a 67 percent decrease in mobile source N_2O emissions from 1997 to 2022 (see Figure 3-17). Overall, CH_4 and N_2O emissions were predominantly from gasoline-fueled passenger cars, light-duty trucks, and non-highway sources. See Annex 3.2 for data by vehicle mode and information on VMT and the share of new vehicles.

[25] Emissions of CH_4 from natural gas systems are reported separately. More information on the methodology used to calculate these emissions are included in this chapter and Annex 3.4.

[26] See the methodology sub-sections of the CO_2 from Fossil Fuel Combustion and CH_4 and N_2O from Mobile Combustion sections of this chapter. Note that N_2O and CH_4 emissions are reported using different categories than CO_2. CO_2 emissions are reported by end-use sector (transportation, industrial, commercial, residential, U.S. Territories), and generally adhere to a top-down approach to estimating emissions. CO_2 emissions from non-transportation mobile sources (e.g., lawn and garden equipment, farm equipment, construction equipment) are allocated to their respective end-use sector (i.e., construction equipment CO_2 emissions are included in the Industrial end-use sector instead of the transportation end-use sector). CH_4 and N_2O emissions are reported using the "mobile combustion" category, which includes non-transportation mobile sources. CH_4 and N_2O emission estimates are bottom-up estimates, based on total activity (fuel use, VMT) and emissions factors by source and technology type. These reporting schemes are in accordance with IPCC guidance. For informational purposes only, CO_2 emissions from non-transportation mobile sources are presented separately from their overall end-use sector in Annex 3.2.

[27] See Annex 3.2 for a complete time series of emission estimates for 1990 through 2022.

Figure 3-17: Mobile Source CH_4 and N_2O Emissions

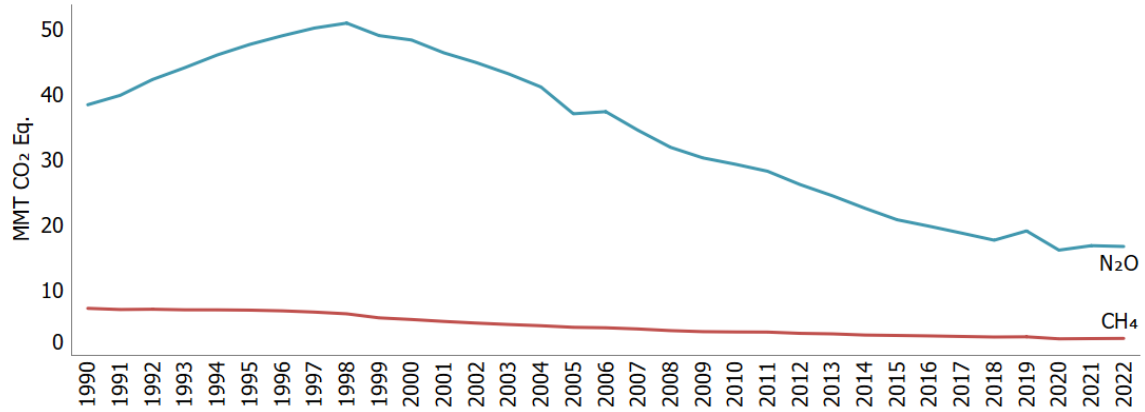


Table 3-14: CH_4 Emissions from Mobile Combustion (MMT CO_2 Eq.)

Fuel Type/Vehicle Type[a]	1990	2005	2018	2019	2020	2021	2022
Gasoline On-Road[b]	**5.8**	**2.4**	**0.9**	**1.0**	**0.8**	**0.8**	**0.7**
Passenger Cars	3.8	1.2	0.3	0.3	0.2	0.2	0.2
Light-Duty Trucks	1.5	1.0	0.5	0.6	0.5	0.5	0.5
Medium- and Heavy-Duty Trucks and Buses	0.5	0.1	+	+	+	+	+
Motorcycles	+	+	+	+	+	+	+
Diesel On-Road[b]	**+**	**+**	**0.1**	**0.1**	**0.1**	**0.1**	**0.1**
Passenger Cars	+	+	+	+	+	+	+
Light-Duty Trucks	+	+	+	+	+	+	+
Medium- and Heavy-Duty Trucks	+	+	0.1	0.1	0.1	0.1	0.1
Medium- and Heavy-Duty Buses	+	+	+	+	+	+	+
Alternative Fuel On-Road	**+**	**+**	**0.1**	**+**	**+**	**+**	**+**
Non-Road[c]	**1.4**	**1.8**	**1.7**	**1.7**	**1.6**	**1.6**	**1.7**
Ships and Boats	0.4	0.5	0.5	0.4	0.4	0.5	0.5
Rail[d]	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Aircraft	0.1	0.1	+	+	+	+	+
Agricultural Equipment[e]	0.2	0.2	0.1	0.1	0.1	0.1	0.1
Construction/Mining Equipment[f]	0.2	0.3	0.2	0.2	0.2	0.2	0.2
Other[g]	0.5	0.7	0.8	0.8	0.8	0.7	0.8
Total	**7.2**	**4.3**	**2.8**	**2.9**	**2.5**	**2.6**	**2.6**

+ Does not exceed 0.05 MMT CO_2 Eq.

[a] See Annex 3.2 for definitions of on-road vehicle types.

[b] Gasoline and diesel highway vehicle mileage estimates are based on data from FHWA Highway Statistics Table VM-1. VMT estimates from FHWA are allocated to vehicle type using ratios of VMT per vehicle type to total VMT, derived from EPA's MOVES3 model (see Annex 3.2 for information about the MOVES model).

[c] Nonroad fuel consumption estimates for 2020 are adjusted to account for the COVID-19 pandemic and associated restrictions. For agricultural equipment and airport equipment, sector specific adjustment factors were applied to the 2019 data. For all other sectors, a 7.7 percent reduction factor is used, based on transportation diesel use (EIA 2023b).

[d] Rail emissions do not include emissions from electric powered locomotives. Class II and Class III diesel consumption data for 2014 to 2021 is estimated by applying the historical average fuel usage per carload factor to the annual number of carloads.

[e] Includes equipment, such as tractors and combines, as well as fuel consumption from trucks that are used off-road in agriculture.

[f] Includes equipment, such as cranes, dumpers, and excavators, as well as fuel consumption from trucks that are used off-road in construction.

[g] "Other" includes snowmobiles and other recreational equipment, logging equipment, lawn and garden equipment, railroad equipment, airport equipment, commercial equipment, and industrial equipment, as well as fuel consumption from trucks that are used off-road for commercial/industrial purposes.

Table 3-15: N_2O Emissions from Mobile Combustion (MMT CO_2 Eq.)

Fuel Type/Vehicle Type[a]	1990	2005	2018	2019	2020	2021	2022
Gasoline On-Road[b]	**32.0**	**28.5**	**7.0**	**8.1**	**6.3**	**6.0**	**5.3**
Passenger Cars	22.4	13.3	2.5	2.5	2.0	1.9	1.6
Light-Duty Trucks	8.7	14.0	4.3	5.4	4.2	3.9	3.5
Medium- and Heavy-Duty Trucks and Buses	0.8	1.2	0.2	0.2	0.1	0.1	0.1
Motorcycles	+	+	0.1	0.1	0.1	0.1	0.1
Diesel On-Road[b]	**0.2**	**0.4**	**3.0**	**3.2**	**3.0**	**3.3**	**3.5**
Passenger Cars	+	+	+	+	+	+	+
Light-Duty Trucks	+	+	0.3	0.2	0.2	0.3	0.3
Medium- and Heavy-Duty Trucks	0.2	0.3	2.4	2.7	2.5	2.7	2.9
Medium- and Heavy-Duty Buses	+	+	0.3	0.3	0.2	0.3	0.3
Alternative Fuel On-Road	**+**	**+**	**0.2**	**0.1**	**0.1**	**0.1**	**0.1**
Non-Road[c]	**6.2**	**8.1**	**7.5**	**7.6**	**6.7**	**7.4**	**7.8**
Ships and Boats	0.2	0.2	0.2	0.2	0.1	0.3	0.3
Rail[d]	0.2	0.3	0.3	0.2	0.2	0.2	0.2
Aircraft	1.5	1.6	1.4	1.5	1.0	1.3	1.4
Agricultural Equipment[e]	1.2	1.4	1.1	1.1	1.1	1.1	1.1
Construction/Mining Equipment[f]	1.2	1.9	1.6	1.7	1.6	1.7	1.7
Other[g]	1.8	2.8	2.9	2.9	2.7	2.9	3.2
Total	**38.4**	**37.0**	**17.7**	**19.1**	**16.1**	**16.8**	**16.7**

+ Does not exceed 0.05 MMT CO_2 Eq.

[a] See Annex 3.2 for definitions of on-road vehicle types.

[b] Gasoline and diesel highway vehicle mileage estimates are based on data from FHWA Highway Statistics Table VM-1. VMT estimates from FHWA are allocated to vehicle type using ratios of VMT per vehicle type to total VMT, derived from EPA's MOVES3 model (see Annex 3.2 for information about the MOVES model).

[c] Nonroad fuel consumption estimates for 2020 are adjusted to account for the COVID-19 pandemic and associated restrictions. For agricultural equipment and airport equipment, sector specific adjustment factors were applied to the 2019 data. For all other sectors, a 7.7 percent reduction factor is used, based on transportation diesel use (EIA 2023a).

[d] Rail emissions do not include emissions from electric powered locomotives. Class II and Class III diesel consumption data for 2014 through 2021 is estimated by applying the historical average fuel usage per carload factor to the annual number of carloads.

[e] Includes equipment, such as tractors and combines, as well as fuel consumption from trucks that are used off-road in agriculture.

[f] Includes equipment, such as cranes, dumpers, and excavators, as well as fuel consumption from trucks that are used off-road in construction.

[g] "Other" includes snowmobiles and other recreational equipment, logging equipment, lawn and garden equipment, railroad equipment, airport equipment, commercial equipment, and industrial equipment, as well as fuel consumption from trucks that are used off-road for commercial/industrial purposes.

Note: Totals may not sum due to independent rounding.

CO_2 from Fossil Fuel Combustion

Methodology and Time-Series Consistency

CO_2 emissions from fossil fuel combustion are estimated in line with a Tier 2 method described by the IPCC in the *2006 IPCC Guidelines for National Greenhouse Gas Inventories* (IPCC 2006) Chapter 2, Figure 2.1 decision tree and

available data on energy use and country specific fuel carbon contents with some exceptions as discussed below.[28] A detailed description of the U.S. methodology is presented in Annex 2.1, and is characterized by the following steps:

1. *Determine total fuel consumption by fuel type and sector*. Total fossil fuel consumption for each year is estimated by aggregating consumption data by end-use sector (e.g., commercial, industrial), primary fuel type (e.g., coal, petroleum, gas), and secondary fuel category (e.g., motor gasoline, distillate fuel oil). Fuel consumption data for the United States were obtained directly from the EIA of the U.S. Department of Energy (DOE), primarily from the *Monthly Energy Review* (EIA 2024a). EIA data include fuel consumption statistics from the 50 U.S. states and the District of Columbia, including tribal lands. The EIA does not include territories in its national energy statistics, so fuel consumption data for territories were collected separately from EIA's International Energy Statistics (EIA 2024b).[29]

   For consistency of reporting, the IPCC has recommended that countries report energy data using the International Energy Agency (IEA) reporting convention and/or IEA data. Data in the IEA format are presented "top down"—that is, energy consumption for fuel types and categories are estimated from energy production data (accounting for imports, exports, stock changes, and losses). The resulting quantities are referred to as "apparent consumption." The data collected in the United States by EIA on an annual basis and used in this *Inventory* are predominantly from mid-stream or conversion energy consumers such as refiners and electric power generators. These annual surveys are supplemented with end-use energy consumption surveys, such as the Manufacturing Energy Consumption Survey, that are conducted on a periodic basis (every four years). These consumption datasets help inform the annual surveys to arrive at the national total and sectoral breakdowns for that total.[30]

   Also, note that U.S. fossil fuel energy statistics are generally presented using gross calorific values (GCV) (i.e., higher heating values). Fuel consumption activity data presented here have not been adjusted to correspond to international standards, which are to report energy statistics in terms of net calorific values (NCV) (i.e., lower heating values).[31]

2. *Subtract uses accounted for in the Industrial Processes and Product Use chapter*. Portions of the fuel consumption data for seven fuel categories—coking coal, distillate fuel, industrial other coal, petroleum coke, natural gas, residual fuel oil, and other oil—were reallocated to the Industrial Processes and Product Use chapter, as they were consumed during non-energy-related industrial activity. To make these adjustments, additional data were collected from AISI (2004 through 2021), Coffeyville (2012), U.S. Census Bureau (2001 through 2011), EIA (2024a, 2023c, 2023d), USAA (2008 through 2021), USGS (1991 through 2020), (USGS 2019), USGS (2014 through 2021a), USGS (2014 through 2021b), USGS (1995 through 2013), USGS (1995, 1998, 2000, 2001, 2002, 2007), USGS (2021a), USGS (1991 through 2015a), USGS (1991 through 2020), USGS (2014 through 2021a), USGS (1991 through 2015b), USGS (2021b), USGS (1991 through 2020).[32]

3. *Adjust for biofuels and petroleum denaturant*. Fossil fuel consumption estimates are adjusted downward to exclude fuels with biogenic origins and avoid double counting in petroleum data statistics. Carbon

[28] The IPCC Tier 3B methodology is used for estimating emissions from commercial aircraft.

[29] Fuel consumption by U.S. Territories (i.e., American Samoa, Guam, Puerto Rico, U.S. Virgin Islands, Wake Island, and other U.S. Pacific Islands) is included in this report and contributed total emissions of 22.6 MMT CO_2 Eq. in 2022.

[30] See IPCC Reference Approach for Estimating CO_2 Emissions from Fossil Fuel Combustion in Annex 4 for a comparison of U.S. estimates using top-down and bottom-up approaches.

[31] A crude convention to convert between gross and net calorific values is to multiply the heat content of solid and liquid fossil fuels by 0.95 and gaseous fuels by 0.9 to account for the water content of the fuels. Biomass-based fuels in U.S. energy statistics, however, are generally presented using net calorific values.

[32] See sections on Iron and Steel Production and Metallurgical Coke Production, Ammonia Production and Urea Consumption, Petrochemical Production, Titanium Dioxide Production, Ferroalloy Production, Aluminum Production, and Silicon Carbide Production and Consumption in the Industrial Processes and Product Use chapter.

dioxide emissions from ethanol added to motor gasoline and biodiesel added to diesel fuel are not included specifically in summing energy sector totals. Net carbon fluxes from changes in biogenic carbon reservoirs are accounted for in the estimates for LULUCF, therefore, fuel consumption estimates are adjusted to remove ethanol and biodiesel.[33] For the years 1993 through 2008, petroleum denaturant is currently included in EIA statistics for both natural gasoline and finished motor gasoline. To avoid double counting, petroleum denaturant is subtracted from finished motor gasoline for these years.[34]

4. *Adjust for exports of CO_2.* Since October 2000, the Dakota Gasification Plant has been exporting CO_2 produced in the coal gasification process to Canada by pipeline. Because this CO_2 is not emitted to the atmosphere in the United States, the associated fossil fuel (lignite coal) that is gasified to create the exported CO_2 is subtracted from EIA (2023d) coal consumption statistics that are used to calculate greenhouse gas emissions from the Energy Sector. The associated fossil fuel is the total fossil fuel burned at the plant with the CO_2 capture system multiplied by the fraction of the plant's total site-generated CO_2 that is recovered by the capture system. To make these adjustments, data for CO_2 exports were collected from Environment and Climate Change Canada (2022). A discussion of the methodology used to estimate the amount of CO_2 captured and exported by pipeline is presented in Annex 2.1.

5. *Adjust sectoral allocation of distillate fuel oil and motor gasoline.* EPA conducted a separate bottom-up analysis of transportation fuel consumption based on data from the Federal Highway Administration that indicated that the amount of distillate and motor gasoline consumption allocated to the transportation sector in the EIA statistics should be adjusted. Therefore, for these estimates, the transportation sector's distillate fuel and motor gasoline consumption were adjusted to match the value obtained from the bottom-up analysis. As the total distillate and motor gasoline consumption estimate from EIA are considered to be accurate at the national level, the distillate and motor gasoline consumption totals for the residential, commercial, and industrial sectors were adjusted proportionately. The data sources used in the bottom-up analysis of transportation fuel consumption include AAR (2008 through 2022), Benson (2002 through 2004), DOE (1993 through 2020), EIA (2007), EIA (2024a), EPA (2022), and FHWA (1996 through 2023).[35]

6. *Adjust for fuels consumed for non-energy uses*. U.S. aggregate energy statistics include consumption of fossil fuels for non-energy purposes. These are fossil fuels that are manufactured into plastics, asphalt, lubricants, or other products. Depending on the end-use, this can result in storage of some or all of the carbon contained in the fuel for a period of time. As the emission pathways of carbon used for non-energy purposes are vastly different than fuel combustion (since the carbon in these fuels ends up in products instead of being combusted), these emissions are estimated separately in Section3.2. Therefore, the amount of fuels used for non-energy purposes was subtracted from total fuel consumption. Data on non-fuel consumption were provided by EIA (2023c).

7. *Subtract consumption of international bunker fuels.* According to the Paris Agreement and UNFCCC reporting guidelines emissions from international transport activities, or bunker fuels, should not be included in national totals. U.S. energy consumption statistics include these bunker fuels (e.g., distillate fuel oil, residual fuel oil, and jet fuel) as part of consumption by the transportation end-use sector, however, so emissions from international transport activities were calculated separately following the same procedures used to calculate emissions from consumption of all fossil fuels (i.e., estimation of consumption, and determination of carbon content).[36] The Office of the Under Secretary of Defense (Installations and Environment) and the Defense Logistics Agency Energy (DLA Energy) of the U.S. Department of Defense (DoD) (DLA Energy 2022) supplied data on military jet fuel and marine fuel use.

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[33] Natural gas energy statistics from EIA (2023a) are already adjusted downward to account for biogas in natural gas.

[34] These adjustments are explained in greater detail in Annex 2.1.

[35] Bottom-up gasoline and diesel highway vehicle fuel consumption estimates are based on data from FHWA Highway Statistics Table MF-21, MF-27, and VM-1 (FHWA 1996 through 2021).

[36] See International Bunker Fuels section in this chapter for a more detailed discussion.

Commercial jet fuel use was estimated based on data from FAA (2024) and DOT (1991 through 2022); residual and distillate fuel use for civilian marine bunkers was obtained from DOC (1991 through 2022) for 1990 through 2001 and 2007 through 2020, and DHS (2008) for 2003 through 2006.[37] Consumption of these fuels was subtracted from the corresponding fuels totals in the transportation end-use sector. Estimates of international bunker fuel emissions for the United States are discussed in detail in Section 3.9.

8. *Determine the total carbon content of fuels consumed.* Total carbon was estimated by multiplying the amount of fuel consumed by the amount of carbon in each fuel. This total carbon estimate defines the maximum amount of carbon that could potentially be released to the atmosphere if all of the carbon in each fuel was converted to CO_2. A discussion of the methodology and sources used to develop the carbon content coefficients are presented in Annexes 2.1 and 2.2.

9. *Estimate CO_2 Emissions.* Total CO_2 emissions are the product of the adjusted energy consumption (from the previous methodology steps 1 through 7), the carbon content of the fuels consumed, and the fraction of carbon that is oxidized. The fraction oxidized was assumed to be 100 percent for petroleum, coal, and natural gas based on guidance in IPCC (2006) (see Annex 2.1). Carbon emissions were multiplied by the molecular-to-atomic weight ratio of CO_2 to carbon (44/12) to obtain total CO_2 emitted from fossil fuel combustion in million metric tons (MMT).

10. *Allocate transportation emissions by vehicle type.* This report provides a more detailed accounting of emissions from transportation because it is such a large consumer of fossil fuels in the United States. For fuel types other than jet fuel, fuel consumption data by vehicle type and transportation mode were used to allocate emissions by fuel type calculated for the transportation end-use sector. Heat contents and densities were obtained from EIA (2023c) and USAF (1998).[38]

    - For on-road vehicles, annual estimates of combined motor gasoline and diesel fuel consumption by vehicle category were obtained from FHWA (1996 through 2023); for each vehicle category, the percent gasoline, diesel, and other (e.g., CNG, LPG) fuel consumption are estimated using data from EPA's MOVES model and DOE (1993 through 2022).[39,40]

    - For non-road vehicles, activity data were obtained from AAR (2008 through 2022), APTA (2007 through 2022), APTA (2006), BEA (1991 through 2015), Benson (2002 through 2004), BTS (2019 through 2022), DLA Energy (2022), DOC (1991 through 2022), DOE (1993 through 2022), DOT (1991 through 2022), EIA (2009a), EIA (2023a), EIA (2002), EIA (1991 through 2022), EPA (2022),[41] and Gaffney (2007).

[37] Data for 2002 were interpolated due to inconsistencies in reported fuel consumption data.

[38] For a more detailed description of the data sources used for the analysis of the transportation end use sector see the Mobile Combustion (excluding CO_2) and International Bunker Fuels sections of the Energy chapter, Annex 3.2, and Annex 3.8, respectively.

[39] On-road fuel consumption data from FHWA Table MF-21 and MF-27 were used to determine total on-road use of motor gasoline and diesel fuel (FHWA 1996 through 2020). Data for 2021 is proxied using FHWA Traffic Volume Travel Trends. Ratios developed from MOVES3 output are used to apportion FHWA fuel consumption data to vehicle type and fuel type (see Annex 3.2 for information about the MOVES model).

[40] Transportation sector natural gas and LPG consumption are based on data from EIA (2024a). In previous Inventory years, data from DOE (1993 through 2022) TEDB was used to estimate each vehicle class's share of the total natural gas and LPG consumption. Since TEDB does not include estimates for natural gas use by medium- and heavy-duty trucks or LPG use by passenger cars, EIA Alternative Fuel Vehicle Data (Browning 2017) is now used to determine each vehicle class's share of the total natural gas and LPG consumption. These changes were first incorporated in the 1990 through 2015 Inventory and apply to the time period from 1990 to 2015.

[41] In 2014, EPA incorporated the NONROAD2008 model into the MOVES model framework (EPA 2022b). The current *Inventory* uses the Nonroad component of MOVES3 for years 1999 through 2022.

- For jet fuel used by aircraft, CO_2 emissions from commercial aircraft were developed by the U.S. Federal Aviation Administration (FAA) using a Tier 3B methodology, consistent IPCC (2006) (see Annex 3.3). Carbon dioxide emissions from other aircraft were calculated directly based on reported consumption of fuel as reported by EIA. Allocation to domestic military uses was made using DoD data (see Annex 3.8). General aviation jet fuel consumption is calculated as the remainder of total jet fuel use (as determined by EIA) nets all other jet fuel use as determined by FAA and DoD. For more information, see Annex 3.2.

Methodological recalculations were applied to the entire time series to ensure time-series consistency from 1990 through 2022. Due to data availability and sources, some adjustments outlined in the methodology above are not applied consistently across the full 1990 to 2022 time series. As described in greater detail in Annex 2.1, to align with EIA's methodology for calculating motor gasoline consumption, petroleum denaturant adjustments are applied to motor gasoline consumption only for the period 1993 through 2008. In addition to ensuring time-series consistency, to ensure consistency in reporting between the *Inventory* and the Canadian National Greenhouse Gas Inventory, the amount of associated fossil fuel (lignite coal) that is gasified to create the exported CO_2 from the Dakota Gasification Plant is adjusted to align with the Canadian National Greenhouse Gas Inventory (Environment and Climate Change Canada 2022). This adjustment is explained in greater detail in Annex 2.1. As discussed in Annex 5, data are unavailable to include estimates of CO_2 emissions from any liquid fuel used in pipeline transport or non-hazardous industrial waste incineration, but those emissions are assumed to be insignificant.

Box 3-4: Carbon Intensity of U.S. Energy Consumption

The amount of carbon emitted from the combustion of fossil fuels is dependent upon the carbon content of the fuel and the fraction of that carbon that is oxidized. Fossil fuels vary in their average carbon content, ranging from about 53 MMT CO_2 Eq./QBtu for natural gas to upwards of 95 MMT CO_2 Eq./QBtu for coal and petroleum coke (see Tables A-42 and A-43 in Annex 2.1 for carbon contents of all fuels). In general, the carbon content per unit of energy of fossil fuels is the highest for coal products, followed by petroleum, and then natural gas. The overall carbon intensity of the U.S. economy is thus dependent upon the quantity and combination of fuels and other energy sources employed to meet demand.

Table 3-16 provides a time series of the carbon intensity of direct emissions for each sector of the U.S. economy. The time series incorporates only the energy from the direct combustion of fossil fuels in each sector. For example, the carbon intensity for the residential sector does not include the energy from or emissions related to the use of electricity for lighting, as it is instead allocated to the electric power sector. For the purposes of maintaining the focus of this section, renewable energy and nuclear energy are not included in the energy totals used in Table 3-16 in order to focus attention on fossil fuel combustion as detailed in this chapter. Looking only at this direct consumption of fossil fuels, the residential sector exhibited the lowest carbon intensity, which is related to the large percentage of its energy derived from natural gas for heating. The carbon intensity of the commercial sector has predominantly declined since 1990 as commercial businesses shift away from petroleum to natural gas. The industrial sector was more dependent on petroleum and coal than either the residential or commercial sectors, and thus had higher carbon intensities over this period. The carbon intensity of the transportation sector was closely related to the carbon content of petroleum products (e.g., motor gasoline and jet fuel, both around 70 MMT CO_2 Eq./QBtu), which were the primary sources of energy. Lastly, the electric power sector had the highest carbon intensity due to its heavy reliance on coal for generating electricity.

Table 3-16: Carbon Intensity from Direct Fossil Fuel Combustion by Sector (MMT CO_2 Eq./QBtu)

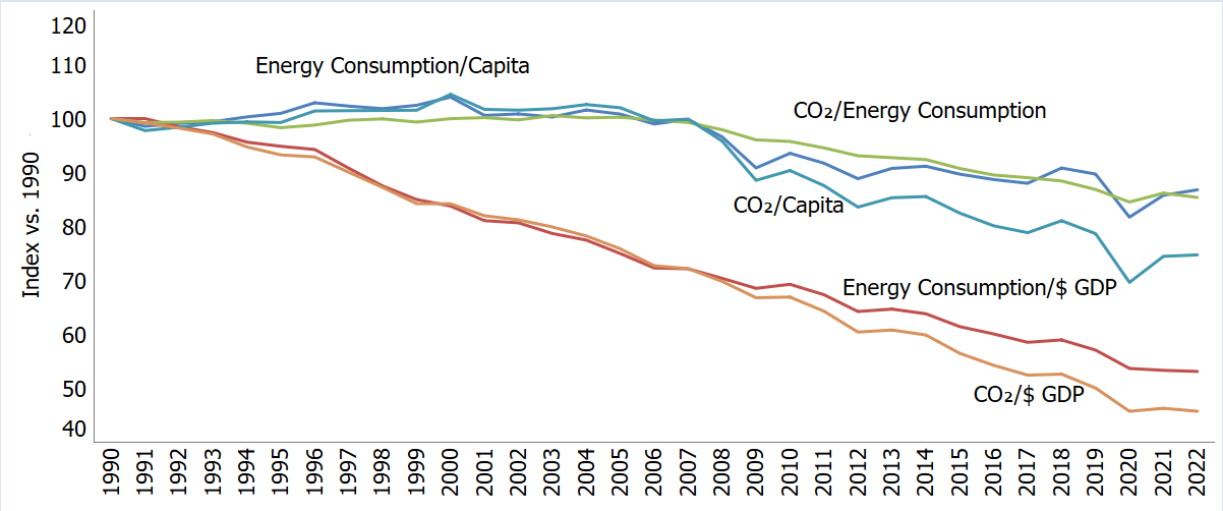
Sector	1990	2005	2018	2019	2020	2021	2022
Residential[a]	57.4	56.8	55.3	55.3	55.1	55.2	55.2
Commercial[a]	59.7	57.8	56.0	56.2	56.3	56.2	56.5
Industrial[a]	64.8	64.6	60.5	60.2	59.6	59.6	59.6
Transportation[a]	71.1	71.5	71.0	70.9	70.8	70.9	70.8
Electric Power[b]	87.3	85.8	75.5	72.9	70.5	72.4	70.9

U.S. Territories[c]	73.1	73.4	70.4	70.8	71.7	70.1	71.3
All Sectors[c]	**73.1**	**73.6**	**68.3**	**67.3**	**66.3**	**67.0**	**66.5**

[a] Does not include electricity or renewable energy consumption.
[b] Does not include electricity produced using nuclear or renewable energy.
[c] Does not include nuclear or renewable energy consumption.
Note: Excludes non-energy fuel use emissions and consumption. Totals may not sum due to independent rounding.

For the time period of 1990 through about 2008, the carbon intensity of U.S. energy consumption was fairly constant, as the proportion of fossil fuels used by the individual sectors did not change significantly over that time. Starting in 2008 the carbon intensity of U.S. energy consumption has decreased, reflecting the shift from coal to natural gas in the electric power sector during that time period. Per capita energy consumption fluctuated little from 1990 to 2007, but then started decreasing after 2007 and, in 2022, was approximately 13.2 percent below levels in 1990 (see Figure 3-18). To differentiate these estimates from those of Table 3-16, the carbon intensity trend shown in Figure 3-18 and described below includes nuclear and renewable energy EIA data to provide a comprehensive economy-wide picture of energy consumption. Due to a general shift from a manufacturing-based economy to a service-based economy, as well as overall increases in efficiency, energy consumption and energy-related CO_2 emissions per dollar of gross domestic product (GDP) have both declined since 1990 (BEA 2024).

Figure 3-18: U.S. Energy Consumption and Energy-Related CO_2 Emissions Per Capita and Per Dollar GDP



Carbon intensity estimates were developed using nuclear and renewable energy data from EIA (2023c), EPA (2010), and fossil fuel consumption data as discussed above and presented in Annex 2.1.

Uncertainty

For estimates of CO_2 from fossil fuel combustion, the amount of CO_2 emitted is directly related to the amount of fuel consumed, the fraction of the fuel that is oxidized, and the carbon content of the fuel. Therefore, a careful accounting of fossil fuel consumption by fuel type, average carbon contents of fossil fuels consumed, and production of fossil fuel-based products with long-term carbon storage should yield an accurate estimate of CO_2 emissions.

Nevertheless, there are uncertainties in the consumption data, carbon content of fuels and products, and carbon oxidation efficiencies. For example, given the same primary fuel type (e.g., coal, petroleum, or natural gas), the

amount of carbon contained in the fuel per unit of useful energy can vary. For the United States, however, the impact of these uncertainties on overall CO_2 emission estimates is believed to be relatively small. See, for example, Marland and Pippin (1990). See also Annex 2.2 for a discussion of uncertainties associated with fuel carbon contents. Recent updates to carbon factors for natural gas and coal utilized the same approach as previous Inventories with updated recent data, therefore, the uncertainty estimates around carbon contents of the different fuels as outlined in Annex 2.2 were not impacted and the historic uncertainty ranges still apply.

Although national statistics of total fossil fuel and other energy consumption are relatively accurate, the allocation of this consumption to individual end-use sectors (i.e., residential, commercial, industrial, and transportation) is less certain. For example, for some fuels the sectoral allocations are based on price rates (i.e., tariffs), but a commercial establishment may be able to negotiate an industrial rate or a small industrial establishment may end up paying an industrial rate, leading to a misallocation of emissions. Also, the deregulation of the natural gas industry and the more recent deregulation of the electric power industry have likely led to some minor challenges in collecting accurate energy statistics as firms in these industries have undergone significant restructuring.

To calculate the total CO_2 emission estimate from energy-related fossil fuel combustion, the amount of fuel used in non-energy production processes were subtracted from the total fossil fuel consumption. The amount of CO_2 emissions resulting from non-energy related fossil fuel use has been calculated separately and reported in the Carbon Emitted from Non-Energy Uses of Fossil Fuels section of this report (Section 3.2). These factors all contribute to the uncertainty in the CO_2 estimates. Detailed discussions on the uncertainties associated with carbon emitted from non-energy uses of fossil fuels can be found within that section of this chapter.

Various sources of uncertainty surround the estimation of emissions from international bunker fuels, which are subtracted from the U.S. totals (see the detailed discussions on these uncertainties provided in Section 3.9). Another source of uncertainty is fuel consumption by U.S. Territories. The United States does not collect energy statistics for its territories at the same level of detail as for the fifty states and the District of Columbia. Therefore, estimating both emissions and bunker fuel consumption by these territories is difficult.

Uncertainties in the emission estimates presented above also result from the data used to allocate CO_2 emissions from the transportation end-use sector to individual vehicle types and transport modes. In many cases, bottom-up estimates of fuel consumption by vehicle type do not match aggregate fuel-type estimates from EIA. Further research is planned to improve the allocation into detailed transportation end-use sector emissions.

The uncertainty analysis was performed by primary fuel type for each end-use sector, using the IPCC-recommended Approach 2 uncertainty estimation methodology, Monte Carlo stochastic simulation technique, with @RISK software. For this uncertainty estimation, the inventory estimation model for CO_2 from fossil fuel combustion was integrated with the relevant variables from the inventory estimation model for International Bunker Fuels, to realistically characterize the interaction (or endogenous correlation) between the variables of these two models. About 170 input variables were modeled for CO_2 from energy-related fossil fuel combustion (including about 20 for non-energy fuel consumption and about 20 for International Bunker Fuels).

In developing the uncertainty estimation model, uniform distributions were assumed for all activity-related input variables and emission factors, based on the SAIC/EIA (2001) report.[42] Triangular distributions were assigned for the oxidization factors (or combustion efficiencies). The uncertainty ranges were assigned to the input variables based on the data reported in SAIC/EIA (2001) and on conversations with various agency personnel.[43]

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[42] SAIC/EIA (2001) characterizes the underlying probability density function for the input variables as a combination of uniform and normal distributions (the former to represent the bias component and the latter to represent the random component). However, for purposes of the current uncertainty analysis, it was determined that uniform distribution was more appropriate to characterize the probability density function underlying each of these variables.

[43] In the SAIC/EIA (2001) report, the quantitative uncertainty estimates were developed for each of the three major fossil fuels used within each end-use sector; the variations within the sub-fuel types within each end-use sector were not modeled. However, for purposes of assigning uncertainty estimates to the sub-fuel type categories within each end-use sector in the current uncertainty analysis, SAIC/EIA (2001)-reported uncertainty estimates were extrapolated.

The uncertainty ranges for the activity-related input variables were typically asymmetric around their inventory estimates; the uncertainty ranges for the emissions factors were symmetric. Bias (or systematic uncertainties) associated with these variables accounted for much of the uncertainties associated with these variables (SAIC/EIA 2001).[44] For purposes of this uncertainty analysis, each input variable was simulated 10,000 times through Monte Carlo sampling.

The results of the Approach 2 quantitative uncertainty analysis are summarized in Table 3-17. Fossil fuel combustion CO_2 emissions in 2022 were estimated to be between 4,603.1 and 4,905.2 MMT CO_2 Eq. at a 95 percent confidence level. This indicates a range of 2 percent below to 4 percent above the 2022 emission estimate of 4,699.4 MMT CO_2 Eq.

Table 3-17: Approach 2 Quantitative Uncertainty Estimates for CO_2 Emissions from Energy-Related Fossil Fuel Combustion by Fuel Type and Sector (MMT CO_2 Eq. and Percent)

Fuel/Sector	2022 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (MMT CO_2 Eq.)		Uncertainty Range Relative to Emission Estimate[a] (%)	
		Lower Bound	Upper Bound	Lower Bound	Upper Bound
Coal[b]	**898.8**	**868.6**	**983.9**	**-3%**	**9%**
Residential	NO	NO	NO	NO	NO
Commercial	1.4	1.3	1.6	-5%	15%
Industrial	43.0	41.0	49.9	-5%	16%
Transportation	NO	NO	NO	NO	NO
Electric Power	851.5	818.9	933.8	-4%	10%
U.S. Territories	2.9	2.5	3.4	-12%	19%
Natural Gas[b]	**1,706.8**	**1,687.3**	**1,784.4**	**-1%**	**5%**
Residential	272.0	264.4	291.1	-3%	7%
Commercial	192.3	186.9	205.8	-3%	7%
Industrial	510.4	494.9	548.0	-3%	7%
Transportation	70.2	68.2	75.1	-3%	7%
Electric Power	659.3	640.1	693.0	-3%	5%
U.S. Territories	2.7	2.4	3.2	-12%	17%
Petroleum[b]	**2,093.4**	**1,966.4**	**2,215.9**	**-6%**	**6%**
Residential	62.1	58.6	65.4	-6%	5%
Commercial	65.1	61.5	68.5	-5%	5%
Industrial	247.6	193.3	302.0	-22%	22%
Transportation	1,681.1	1,573.2	1,785.6	-6%	6%
Electric Power	20.5	19.7	22.0	-4%	7%
U.S. Territories	17.0	15.7	18.7	-7%	10%
Geothermal	**0.4**	**0.2**	**1.0**	**-48%**	**173%**
Electric Power	0.4	0.2	1.0	-48%	173%
Total (including Geothermal)[b]	**4,699.4**	**4,603.1**	**4,905.2**	**-2%**	**4%**

NO (Not Occurring)

[a] Range of emission estimates predicted by Monte Carlo stochastic simulation for a 95 percent confidence interval.

[b] The low and high estimates for total emissions were calculated separately through simulations and, hence, the low and high emission estimates for the sub-source categories do not sum to total emissions.

Note: Totals may not sum due to independent rounding.

[44] Although, in general, random uncertainties are the main focus of statistical uncertainty analysis, when the uncertainty estimates are elicited from experts, their estimates include both random and systematic uncertainties. Hence, both these types of uncertainties are represented in this uncertainty analysis.

QA/QC and Verification

In order to ensure the quality of the CO_2 emission estimates from fossil fuel combustion, general (IPCC Tier 1) and category-specific (Tier 2) Quality Assurance/Quality Control (QA/QC) procedures were implemented consistent with the U.S. Inventory QA/QC plan outlined in Annex 8. The Tier 2 procedures that were implemented involved checks specifically focusing on the activity data and methodology used for estimating CO_2 emissions from fossil fuel combustion in the United States. Emission totals for the different sectors and fuels were compared and trends were investigated to determine whether any corrective actions were needed. Minor corrective actions were taken.

One area of QA/QC and verification is to compare the estimates and emission factors used in the *Inventory* with other sources of CO_2 emissions reporting. Two main areas and sources of data were considered. The first is a comparison with the EPA GHGRP combustion data (Subpart C) for stationary combustion sources excluding the electric power sector. This mainly focused on considering carbon factors for natural gas. The second comparison is with the EPA Air Markets Program data for electric power production. This considered carbon factors for coal and natural gas used in electric power production.

The EPA GHGRP collects greenhouse gas emissions data from large emitters including information on fuel combustion. This excludes emissions from mobile sources and smaller residential and commercial sources, those emissions are covered under supplier reporting (Subparts MM and NN) and are areas for further research. Fuel combustion CO_2 data reported in 2022 was 2,082.6 MMT CO_2. Of that, 1,577.7 MMT CO_2 was from electricity production. Therefore, the non-electric power production fuel combustion reporting was a fraction of the total covered by the *Inventory* under fossil fuel combustion. Furthermore, reporters under the GHGRP can use multiple methods of calculating emissions; one method is to use the default emission factors provided in the rule, while another is based on a tier 3 approach using their own defined emission factors. Based on data from reporters on approach used, it was determined that only about 10 percent of natural gas combustion emissions were based on a tier 3 approach. Given the small sample size compared to the overall *Inventory* calculations for natural gas combustion EPA determined it was not reasonable to consider the GHGRP tier 3 natural gas factors at this time. A more detailed analysis was done on upstream oil and gas natural gas combustion emissions using the GHGRP data as discussed in Annex 2.2.

EPA collects detailed sulfur dioxide (SO_2), nitrogen oxides (NO_X), and carbon dioxide (CO_2) emissions data and other information from power plants across the country as part of the Acid Rain Program (ARP), the Cross-State Air Pollution Rule (CSAPR), the CSAPR Update, and the Revised CSAPR Update (RCU). The CO_2 data from these Air Market Programs (AMP) can be compared to the electric power sector emissions calculated from the *Inventory* as shown in Table 3-18 for the three most recent years of data.

Table 3-18: Comparison of Electric Power Sector Emissions (MMT CO_2 Eq. and Percent)

Fuel/Sector	CO_2 Emissions (MMT CO_2 Eq.)			% Change	
	2020	2021	2022	20-21	21-22
Inventory Electric Power Sector	**1,439.6**	**1,540.9**	**1,531.7**	**7.0%**	**-0.6%**
Coal	788.2	910.1	851.5	15.5%	-6.4%
Natural Gas	634.8	612.8	659.3	-3.5%	7.6%
Petroleum	16.2	17.7	20.5	9.6%	15.9%
AMP Electric Power Sector	**1,430.8**	**1,531.7**	**1,520.1**	**7.1%**	**-0.8%**
Coal	792.7	913.4	858.5	15.2%	-6.0%
Natural Gas	629.4	609.6	652.7	-3.1%	7.1%
Petroleum	8.8	8.7	8.9	-0.8%	2.7%

Note: Totals may not sum due to independent rounding.

In general the emissions and trends from the two sources line up well. There are differences expected based on coverage and scope of each source. The *Inventory* covers all emissions from the electric power sector as defined above. The EPA AMP data covers emissions from electricity generating units of a certain size so in some respects it could cover more sources (like electric power units at industrial facilities that would be covered under the industrial sector in the *Inventory*) and not as many sources (since smaller units are excluded). The EPA AMP data also includes heat input for different fuel types. That data can be combined with emissions to calculate implied

emission factors.[45] The following Table 3-19 shows the implied emissions factors for coal and natural gas from the EPA AMP data compared to the factors used in the *Inventory* for the three most recent years of data.

Table 3-19: Comparison of Emissions Factors (MMT Carbon/QBtu)

Fuel Type	2020	2021	2022
EPA AMP			
Coal	25.67	25.66	25.53
Natural Gas	14.56	14.60	14.61
EPA Inventory			
Electric Power Coal	26.12	26.13	26.13
Natural Gas	14.43	14.43	14.43

The factors for natural gas line up reasonably well, the EPA factors are roughly 1 percent lower than those calculated from the EPA AMP data. For coal the EPA emissions factors are roughly 2 percent higher than those calculated from the EPA AMP data. One possible reason for the difference is that the EPA *Inventory* factors are based on all coal used in electric power production while the factors from the EPA AMP data are based on units where coal is the source of fuel used. There are units that use coal and other fuel sources but emissions for each fuel type could not be calculated. This is an area of further research but given current data available the approach to develop carbon factors as outlined in Annex 2 is still felt to be the most appropriate to represent total fuel combustion in the United States.

The Paris Agreement and the UNFCCC reporting guidelines also require countries to complete a "top-down" reference approach for estimating CO_2 emissions from fossil fuel combustion in addition to their "bottom-up" sectoral methodology. The reference approach (detailed in Annex 4) uses alternative methodologies and different data sources than those contained in this section of the report. The reference approach estimates fossil fuel consumption by adjusting national aggregate fuel production data for imports, exports, and stock changes rather than relying on end-user consumption surveys. The reference approach assumes that once carbon-based fuels are brought into a national economy, they are either saved in some way (e.g., stored in products, kept in fuel stocks, or left unoxidized in ash) or combusted, and therefore the carbon in them is oxidized and released into the atmosphere. In the reference approach, accounting for actual consumption of fuels at the sectoral or sub-national level is not required. One difference between the two approaches is that emissions from carbon that was not stored during non-energy use of fuels are subtracted from the sectoral approach and reported separately (see Section 3.2). These emissions, however, are not subtracted in the reference approach. As a result, the reference approach emission estimates are comparable to those of the sectoral approach, with the exception that the non-energy use (NEU) source category emissions are included in the reference approach (see Annex 4 for more details).

Recalculations Discussion

EIA (2024a) updated distillate fuel oil consumed by the transportation sector for 2010 and on. This caused transportation petroleum CO_2 emissions to increase by an average annual amount of 0.2 MMT CO_2 Eq. (less than half a percent) for the years 2010 through 2021.

EIA (2024a) updated propane consumed by the industrial sector for 2010 and on, which is used to calculate HGL (Energy Use) annually variable carbon content coefficients. In addition, EIA (2023b) shifted all 2022 product supplied of natural gasoline and unfinished oils to crude oil transfers. This change was made to reflect that natural gasoline and unfinished oils are used as feedstocks in crude oil production instead of directly consumed as an end-use fuel. EPA made the same adjustment across the timeseries. This change impacted industrial energy

[45] These emission factors can be converted from MMT Carbon/QBtu to MMT CO_2 Eq./QBtu by multiplying the emission factor by 44/12, the molecular-to-atomic weight ratio of CO_2 to C. This would assume the fraction oxidized to be 100 percent, which is the guidance in IPCC (2006) (see Annex 2.1).

consumption across the timeseries as well as non-energy use consumption, which impacts industrial energy consumption values. This change also impacted the HGL carbon content coefficient used to calculate emissions.

To better align with EIA methodology, the non-energy use consumption of HGLs is now calculated for the entire timeseries by assuming that 100 percent of ethane, ethylene, and propylene consumption is for non-combustion use and 85 percent of normal butane, butylene, isobutane, and isobutylene is for non-combustion use. Non-energy use consumption of propane is calculated by subtracting the non-energy consumption of all other HGLs from the total non-combustion consumption of HGLs as published by the EIA. Non-energy use consumption is subtracted from energy consumption, therefore this methodology change impacts industrial petroleum consumption values. Additionally, the energy HGL carbon contents are now calculated following the above methodology and have therefore increased across the timeseries, impacting U.S. Territories petroleum and industrial petroleum CO_2 emissions.

Overall, these four updates to EIA (2024a) data and methodology caused U.S. Territories petroleum CO_2 emissions to decrease by an average annual amount of less than 0.1 MMT CO_2 Eq. (less than half a percent) for the timeseries, and industrial petroleum CO_2 emissions to increase by an average annual amount of 5.0 MMT CO_2 Eq. (1.8 percent) for the timeseries.

EPA revised its calculation of change in total energy use in the industrial sector to include renewable energy and electricity. The value previously included only fossil fuel energy consumption. Additionally, EPA revised power sector carbon intensity data to correct for an error and ensure total renewable energy consumed from EIA's *Monthly Energy Review* (EIA 2024a) was being used. There were also very minor updates associated with changes in residential and commercial petroleum use due to MER updates changes in industrial coal use due to updated data on CO_2 exports.

Overall, these changes resulted in an average annual increase of 5.8 MMT CO_2 Eq. (0.1 percent) in CO_2 emissions from fossil fuel combustion for the period 1990 through 2021, relative to the previous *Inventory*.

Planned Improvements

To reduce the uncertainty of CO_2 from fossil fuel combustion estimates for U.S. Territories, further expert elicitation may be conducted to better quantify the total uncertainty associated with emissions from U.S. Territories. Additionally, although not technically a fossil fuel, since geothermal energy-related CO_2 emissions are included for reporting purposes, further expert elicitation may be conducted to better quantify the total uncertainty associated with CO_2 emissions from geothermal energy use.

EPA will continue to examine the availability of facility-level combustion emissions through EPA's GHGRP to help better characterize the industrial sector's energy consumption in the United States and further classify total industrial sector fossil fuel combustion emissions by business establishments according to industrial economic activity type. Most methodologies used in EPA's GHGRP are consistent with IPCC methodologies, although for EPA's GHGRP, facilities collect detailed information specific to their operations according to detailed measurement standards, which may differ with the more aggregated data collected for the *Inventory* to estimate total national U.S. emissions. In addition, and unlike the reporting requirements for this chapter under the Paris Agreement and UNFCCC reporting guidelines, some facility-level fuel combustion emissions reported under the GHGRP may also include industrial process emissions.[46] In line with the Paris Agreement and UNFCCC reporting guidelines, fuel combustion emissions are included in this chapter, while process emissions are included in the Industrial Processes and Product Use chapter of this report. In examining data from EPA's GHGRP that would be useful to improve the emission estimates for the CO_2 from fossil fuel combustion category, particular attention will also be made to ensure time-series consistency, as the facility-level reporting data from EPA's GHGRP are not available for all inventory years as reported in this *Inventory*.

Additional analyses will be conducted to align reported facility-level fuel types and IPCC fuel types per the national energy statistics. For example, additional work will look at CO_2 emissions from biomass to ensure they are

[46] See https://unfccc.int/resource/docs/2013/cop19/eng/10a03.pdf#page=2.

separated in the facility-level reported data and maintaining consistency with national energy statistics provided by EIA. In implementing improvements and integration of data from EPA's GHGRP, the latest guidance from the IPCC on the use of facility-level data in national inventories will continue to be relied upon.[47]

EPA is also evaluating the methods used to adjust for conversion of fuels and exports of CO_2. EPA is exploring the approach used to account for CO_2 transport, injection, and geologic storage; as part of this there may be changes made to the accounting for CO_2 exports.

Finally, another ongoing planned improvement is to evaluate data availability to update the carbon and heat content of more fuel types accounted for in this *Inventory*. This update will impact consumption and emissions across all sectors and will improve consistency with EIA data as carbon and heat contents of fuels will be accounted for as annually variable and therefore improve accuracy across the time series. Some of the fuels considered in this effort include petroleum coke, residual fuel, and woody biomass.

CH_4 and N_2O from Stationary Combustion

Methodology and Time-Series Consistency

Methane and N_2O emissions from stationary combustion were estimated by multiplying fossil fuel and wood consumption data by emission factors (by sector and fuel type for industrial, residential, commercial, and U.S. Territories; and by fuel and technology type for the electric power sector). The electric power sector utilizes a Tier 2 methodology, whereas all other sectors utilize a Tier 1 methodology in accordance with IPCC methodological decision tree Figure 2.1 in the *2006 IPCC Guidelines for National Greenhouse Gas Inventories* (IPCC 2006) and available data. The activity data and emission factors used are described in the following subsections.

More detailed information on the methodology for calculating emissions from stationary combustion, including emission factors and activity data, is provided in Annex 3.1.

Industrial, Residential, Commercial, and U.S. Territories

National coal, natural gas, fuel oil, and wood consumption data were grouped by sector: industrial, commercial, residential, and U.S. Territories. For the CH_4 and N_2O emission estimates, consumption data for each fuel were obtained from EIA's *Monthly Energy Review* (EIA 2024a). Because the United States does not include territories in its national energy statistics, fuel consumption data for territories were provided separately by EIA's International Energy Statistics (EIA 2024b).[48] Fuel consumption for the industrial sector was adjusted to subtract out mobile source construction and agricultural use, which is reported under mobile sources. Construction and agricultural mobile source fuel use was obtained from EPA (2022) and FHWA (1996 through 2023). Estimates for wood biomass consumption for fuel combustion do not include municipal solid waste, tires, etc., that are reported as biomass by EIA. Non-CO_2 emissions from combustion of the biogenic portion of municipal solid waste and tires is included under waste incineration (Section 3.2). Estimates for natural gas combustion do not include biogas, and therefore non-CO_2 emissions from biogas are not included (see the Planned Improvements section, below). Tier 1 default emission factors for the industrial, commercial, and residential end-use sectors were provided by the *2006 IPCC Guidelines for National Greenhouse Gas Inventories* (IPCC 2006). U.S. Territories' emission factors were estimated using the U.S. emission factors for the primary sector in which each fuel was combusted.

Electric Power Sector

The electric power sector uses a Tier 2 emission estimation methodology as fuel consumption for the electric

[47] See http://www.ipcc-nggip.iges.or.jp/public/tb/TFI_Technical_Bulletin_1.pdf.

[48] U.S. Territories data also include combustion from mobile activities because data to allocate territories' energy use were unavailable. For this reason, CH_4 and N_2O emissions from combustion by U.S. Territories are only included in the stationary combustion totals.

power sector by control-technology type is based on EPA's Acid Rain Program Dataset (EPA 2024). Total fuel consumption in the electric power sector from EIA (2024a) was apportioned to each combustion technology type and fuel combination using a ratio of fuel consumption by technology type derived from EPA (2024) data. The combustion technology and fuel use data by facility obtained from EPA (2024) were only available from 1996 to 2022 so the consumption estimates from 1990 to 1995 were estimated by applying the 1996 consumption ratio by combustion technology type from EPA (2024) to the total EIA (2024a) consumption for each year from 1990 to 1995.

Emissions were estimated by multiplying fossil fuel and wood consumption by technology-, fuel-, and country-specific Tier 2 emission factors. The Tier 2 emission factors used are based in part on emission factors published by EPA, and EPA's Compilation of Air Pollutant Emission Factors, AP-42 (EPA 1997) for coal wall-fired boilers, residual fuel oil, diesel oil and wood boilers, natural gas-fired turbines, and combined cycle natural gas units.[49]

Methodological recalculations were applied to the entire time series to ensure time-series consistency from 1990 through 2022 as discussed below. As discussed in Annex 5, data are unavailable to include estimates of CH_4 and N_2O emissions from biomass use in Territories, but those emissions are assumed to be insignificant.

Uncertainty

Methane emission estimates from stationary sources exhibit high uncertainty, primarily due to difficulties in calculating emissions from wood combustion (i.e., fireplaces and wood stoves). The estimates of CH_4 and N_2O emissions presented are based on broad indicators of emissions (i.e., fuel use multiplied by an aggregate emission factor for different sectors), rather than specific emission processes (i.e., by combustion technology and type of emission control).

An uncertainty analysis was performed by primary fuel type for each end-use sector, using the IPCC-recommended Approach 2 uncertainty estimation methodology, Monte Carlo stochastic simulation technique, with @RISK software.

The uncertainty estimation model for this source category was developed by integrating the CH_4 and N_2O stationary source inventory estimation models with the model for CO_2 from fossil fuel combustion to realistically characterize the interaction (or endogenous correlation) between the variables of these three models. About 55 input variables were simulated for the uncertainty analysis of this source category (about 20 from the CO_2 emissions from fossil fuel combustion inventory estimation model and about 35 from the stationary source inventory models).

In developing the uncertainty estimation model, uniform distribution was assumed for all activity-related input variables and N_2O emission factors, based on the SAIC/EIA (2001) report.[50] For these variables, the uncertainty ranges were assigned to the input variables based on the data reported in SAIC/EIA (2001).[51] However, the CH_4 emission factors differ from those used by EIA. These factors and uncertainty ranges are based on IPCC default uncertainty estimates (IPCC 2006).

[49] Several of the U.S. Tier 2 emission factors were used in IPCC (2006) as Tier 1 emission factors. See Table A-67 in Annex 3.1 for emission factors by technology type and fuel type for the electric power sector.

[50] SAIC/EIA (2001) characterizes the underlying probability density function for the input variables as a combination of uniform and normal distributions (the former distribution to represent the bias component and the latter to represent the random component). However, for purposes of the current uncertainty analysis, it was determined that uniform distribution was more appropriate to characterize the probability density function underlying each of these variables.

[51] In the SAIC/EIA (2001) report, the quantitative uncertainty estimates were developed for each of the three major fossil fuels used within each end-use sector; the variations within the sub-fuel types within each end-use sector were not modeled. However, for purposes of assigning uncertainty estimates to the sub-fuel type categories within each end-use sector in the current uncertainty analysis, SAIC/EIA (2001)-reported uncertainty estimates were extrapolated.

The results of the Approach 2 quantitative uncertainty analysis are summarized in Table 3-20. Stationary combustion CH_4 emissions in 2022 (including biomass) were estimated to be between 5.9 and 19.1 MMT CO_2 Eq. at a 95 percent confidence level. This indicates a range of 31 percent below to 122 percent above the 2022 emission estimate of 8.6 MMT CO_2 Eq.[52] Stationary combustion N_2O emissions in 2022 (including biomass) were estimated to be between 16.5 and 33.4 MMT CO_2 Eq. at a 95 percent confidence level. This indicates a range of 33 percent below to 35 percent above the 2022 emission estimate of 24.7 MMT CO_2 Eq.

Table 3-20: Approach 2 Quantitative Uncertainty Estimates for CH_4 and N_2O Emissions from Energy-Related Stationary Combustion, Including Biomass (MMT CO_2 Eq. and Percent)

Source	Gas	2022 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Stationary Combustion	CH_4	8.6	5.9	19.1	-31%	122%
Stationary Combustion	N_2O	24.7	16.5	33.4	-33%	35%

[a] Range of emission estimates predicted by Monte Carlo stochastic simulation for a 95 percent confidence interval.

The uncertainties associated with the emission estimates of CH_4 and N_2O are greater than those associated with estimates of CO_2 from fossil fuel combustion, which mainly rely on the carbon content of the fuel combusted. Uncertainties in both CH_4 and N_2O estimates are due to the fact that emissions are estimated based on emission factors representing only a limited subset of combustion conditions. For the indirect greenhouse gases, uncertainties are partly due to assumptions concerning combustion technology types, age of equipment, emission factors used, and activity data projections.

QA/QC and Verification

In order to ensure the quality of the non-CO_2 emission estimates from stationary combustion, general (IPCC Tier 1) and category-specific (Tier 2) Quality Assurance/Quality Control (QA/QC) procedures were implemented consistent with the U.S. Inventory QA/QC plan outlined in Annex 8. The Tier 2 procedures that were implemented involved checks specifically focusing on the activity data and emission factor sources and methodology used for estimating CH_4, N_2O, and the greenhouse gas precursors from stationary combustion in the United States. Emission totals for the different sectors and fuels were compared and trends were investigated.

Recalculations Discussion

EIA (2024a) updated industrial HGL statistics, which caused CH_4 and N_2O emissions from industrial fuel oil to decrease slightly for the years 2010 through 2021.

In addition, EIA (2023b) shifted all 2022 product supplied of natural gasoline and unfinished oils to crude oil transfers. This change was made to reflect the fact that these fuels are used as feedstocks in crude oil production instead of directly consumed as end-use fuels. EPA made the change across the time series. This change impacted energy consumption across the timeseries as well as non-energy use consumption, which impacts energy consumption values.

To better align with EIA methodology, the non-energy use consumption of HGLs is now calculated for the entire timeseries by assuming that 100 percent of ethane, ethylene, and propylene consumption is for non-combustion use and 85 percent of normal butane, butylene, isobutane, and isobutylene is for non-combustion use. Non-energy use consumption of propane is calculated by subtracting the non-energy consumption of all other HGLs from the

[52] The low emission estimates reported in this section have been rounded down to the nearest integer values and the high emission estimates have been rounded up to the nearest integer values.

total non-combustion consumption of HGLs as published by the EIA. Non-energy use consumption is subtracted from energy consumption, therefore this methodology change impacts industrial fuel oil consumption values.

Other small updates included changes in residential and commercial/institutional fuel oil are use and changes in industrial coal due to updated CO_2 export data.

Overall, these updates to EIA data and methodology (2024a) caused CH_4 and N_2O emissions from industrial fuel oil to increase by an average annual amount of 0.01 MMT CO_2 Eq. and 0.01 MMT CO_2 Eq. (3 percent and 3 percent), respectively, for the time series. EIA (2024a) updated 2020 and 2021 wood energy consumed by the residential sector due to new underlying data collected by the Residential Energy Consumption Survey (RECS), which collects data about once every 5 years and uses Annual Energy Outlook growth rates to estimate data for other years. This caused CH_4 and N_2O emissions from residential wood consumption to decrease by 0.76 MMT CO_2 Eq. and 0.10 MMT CO_2 Eq. (22 percent and 13 percent) in 2020, respectively, and 0.94 MMT CO_2 Eq. and 0.12 MMT CO_2 Eq. (26 percent and 15 percent) in 2021, respectively.

Planned Improvements

Several items are being evaluated to improve the CH_4 and N_2O emission estimates from stationary combustion and to reduce uncertainty for U.S. Territories. Efforts will be taken to work with EIA and other agencies to improve the quality of the U.S. Territories data. Because these data are not broken out by stationary and mobile uses, further research will be aimed at trying to allocate consumption appropriately. In addition, the uncertainty of biomass emissions will be further investigated because it was expected that the exclusion of biomass from the estimates would reduce the uncertainty; and in actuality the exclusion of biomass increases the uncertainty. These improvements are not all-inclusive but are part of an ongoing analysis and efforts to continually improve these stationary combustion estimates from U.S. Territories.

Other forms of biomass-based gas consumption include biogas. As an additional planned improvement, EPA will examine EIA and GHGRP data on biogas collected and burned for energy use and determine if CH_4 and N_2O emissions from biogas can be included in future Inventories. EIA (2024a) natural gas data already deducts biogas used in the natural gas supply, so no adjustments are needed to the natural gas fuel consumption data to account for biogas.

CH_4 and N_2O from Mobile Combustion

Methodology and Time-Series Consistency

Estimates of CH_4 and N_2O emissions from mobile combustion were calculated by multiplying emission factors by measures of activity for each fuel and vehicle type (e.g., light-duty gasoline trucks). Activity data included vehicle miles traveled (VMT) for on-road vehicles and fuel consumption for non-road mobile sources. The activity data and emission factors used in the calculations are described in the subsections that follow. A complete discussion of the methodology used to estimate CH_4 and N_2O emissions from mobile combustion and the emission factors used in the calculations is provided in Annex 3.2.

On-Road Vehicles

Estimates of CH_4 and N_2O emissions from gasoline and diesel on-road vehicles are based on VMT and emission factors (in grams of CH_4 and N_2O per mile) by vehicle type, fuel type, model year, and emission control technology. Emission estimates for alternative fuel vehicles (AFVs) are based on VMT and emission factors (in grams of CH_4 and N_2O per mile) by vehicle and fuel type.[53]

[53] Alternative fuel and advanced technology vehicles are those that can operate using a motor fuel other than gasoline or diesel. This includes electric or other bi-fuel or dual-fuel vehicles that may be partially powered by gasoline or diesel.

CH_4 and N_2O emissions factors by vehicle type and emission tier for newer (starting with model year 2004) on-road gasoline vehicles were calculated by Browning (2019) from annual vehicle certification data compiled by EPA. CH_4 and N_2O emissions factors for older (model year 2003 and earlier) on-road gasoline vehicles were developed by ICF (2004). These earlier emission factors were derived from EPA, California Air Resources Board (CARB) and Environment and Climate Change Canada (ECCC) laboratory test results of different vehicle and control technology types. The EPA, CARB and ECCC tests were designed following the Federal Test Procedure (FTP). The procedure covers three separate driving segments, since vehicles emit varying amounts of greenhouse gases depending on the driving segment. These driving segments are: (1) a transient driving cycle that includes cold start and running emissions, (2) a cycle that represents running emissions only, and (3) a transient driving cycle that includes hot start and running emissions. For each test run, a bag was affixed to the tailpipe of the vehicle and the exhaust was collected; the content of this bag was then analyzed to determine quantities of gases present. The emissions characteristics of driving segment 2 tests were used to define running emissions. Running emissions were subtracted from the total FTP emissions to determine start emissions. These were then recombined to approximate average driving characteristics, based upon the ratio of start to running emissions for each vehicle class from MOBILE6.2, an EPA emission factor model that predicts grams per mile emissions of CO_2, CO, HC, NO_x, and PM from vehicles under various conditions.[54]

Diesel on-road vehicle emission factors were developed by ICF (2006). CH_4 and N_2O emissions factors for newer (starting with model year 2007) on-road diesel vehicles (those using engine aftertreatment systems) were calculated from annual vehicle certification data compiled by EPA.

CH_4 and N_2O emission factors for AFVs were developed based on the 2022 Greenhouse gases, Regulated Emissions, and Energy use in Transportation (GREET) model (ANL 2022). For light-duty trucks, EPA used travel fractions for LDT1 and LDT2 (MOVES Source Type 31 for LDT1 and MOVES Source Type 32 for LDT2; see Annex 3.2 for information about the MOVES model) to determine emission factors. For medium-duty vehicles, EPA used emission factors for light heavy-duty vocational trucks. For heavy-duty vehicles, EPA used emission factors for long-haul combination trucks. For buses, EPA used emission factors for transit buses. These values represent vehicle operations only (tank-to-wheels); upstream well-to-tank emissions are calculated elsewhere in the Inventory. Biodiesel CH_4 emission factors were corrected from GREET values to be the same as CH_4 emission factors for diesel vehicles. GREET overestimated biodiesel CH_4 emission factors based upon an incorrect CH_4-to-THC ratio for diesel vehicles with aftertreatment technology.

Annual VMT data for 1990 through 2022 were obtained from the Federal Highway Administration's (FHWA) Highway Performance Monitoring System database as reported in Highway Statistics (FHWA 1996 through 2023). VMT estimates were then allocated to vehicle type using ratios of VMT per vehicle type to total VMT, derived from EPA's MOVES3 model (see Annex 3.2 for information about the MOVES model). This corrects time series inconsistencies in FHWA definitions of vehicle types (Browning 2022a). VMT for alternative fuel vehicles (AFVs) were estimated based on Browning (2022b). The age distributions of the U.S. vehicle fleet were obtained from EPA (2004, 2022), and the average annual age-specific vehicle mileage accumulation of U.S. vehicles were obtained from EPA (2022).

Control technology and standards data for on-road vehicles were obtained from EPA's Office of Transportation and Air Quality (EPA 1998, 2022b, and 2023) and Browning (2005). These technologies and standards are defined in Annex 3.2, and were compiled from EPA (1994a, 1994b, 1998, 1999) and IPCC (2006) sources.

Non-Road Mobile Sources

The nonroad mobile category for CH_4 and N_2O includes ships and boats, aircraft, locomotives, and other mobile non-road sources (e.g., construction or agricultural equipment). For locomotives, aircraft, ships, and non-recreational boats, fuel-based emission factors are applied to data on fuel consumption, following the IPCC Tier 1 approach. The Tier 2 approach for these sources would require separate fuel-based emissions factors by

[54] Additional information regarding the MOBILE model can be found at https://www.epa.gov/moves/description-and-history-mobile-highway-vehicle-emission-factor-model.

technology, for which data are not currently available. For other non-road sources, EPA uses the Nonroad component of the MOVES model to estimate fuel use. Emission factors by horsepower bin are estimated from EPA engine certification data. Because separate emission factors are applied to specific engine technologies; these non-road sources utilize a Tier 2 approach.

To estimate CH_4 and N_2O emissions from non-road mobile sources, fuel consumption data were employed as a measure of activity and multiplied by fuel-specific emission factors (in grams of N_2O and CH_4 per kilogram of fuel consumed).[55] Activity data were obtained from AAR (2008 through 2023), APTA (2007 through 2023), Rail Inc (2014 through 2022), APTA (2006), BEA (1991 through 2015), Benson (2002 through 2004), Bureau of Transportation Statistics (BTS; 2023), DLA Energy (2022), DOC (1991 through 2022), DOE (1993 through 2022), DOT (1991 through 2023), EIA (2002, 2007, 2023a, 2023b), EIA (1991 through 2022), EPA (2022), Esser (2003 through 2004), FAA (2024), FHWA (1996 through 2023),[56] Gaffney (2007), FTA (2023), and Whorton (2006 through 2014). Fuel consumption data for boats and vessels in U.S. Territories data and vessel domestic vessel bunkering is proxied from 2021 proxy data. Emission factors for non-road modes were taken from IPCC (2006) and Browning (2020 and 2018).

Uncertainty

A quantitative uncertainty analysis was conducted for the mobile source sector using the IPCC-recommended Approach 2 uncertainty estimation methodology, Monte Carlo stochastic simulation technique, using @RISK software. The uncertainty analysis was performed on 2022 estimates of CH_4 and N_2O emissions, incorporating probability distribution functions associated with the major input variables. For the purposes of this analysis, the uncertainty was modeled for the following four major sets of input variables: (1) VMT data, by on-road vehicle and fuel type, (2) emission factor data, by on-road vehicle, fuel, and control technology type, (3) fuel consumption, data, by non-road vehicle and equipment type, and (4) emission factor data, by non-road vehicle and equipment type.

Uncertainty analyses were not conducted for NO_x, CO, or NMVOC emissions. Emission factors for these gases have been extensively researched because emissions of these gases from motor vehicles are regulated in the United States, and the uncertainty in these emission estimates is believed to be relatively low. For more information, see Section 3.11. However, a much higher level of uncertainty is associated with CH_4 and N_2O emission factors due to limited emission test data, and because, unlike CO_2 emissions, the emission pathways of CH_4 and N_2O are highly complex.

Based on the uncertainty analysis, mobile combustion CH_4 emissions from all mobile sources in 2022 were estimated to be between 2.5 and 3.4 MMT CO_2 Eq. at a 95 percent confidence level. This indicates a range of 4 percent below to 30 percent above the corresponding 2022 emission estimate of 2.6 MMT CO_2 Eq. Mobile combustion N_2O emissions from mobile sources in 2022 were estimated to be between 15.3 and 20.1MMT CO_2 Eq. at a 95 percent confidence level. This indicates a range of 8 percent below to 20 percent above the corresponding 2022 emission estimate of 16.7 MMT CO_2 Eq.

[55] The consumption of international bunker fuels is not included in these activity data, but emissions related to the consumption of international bunker fuels are estimated separately under the International Bunker Fuels source category.

[56] This Inventory uses FHWA's Agriculture, Construction, and Commercial/Industrial MF-24 fuel volumes along with the MOVES model gasoline volumes to estimate non-road mobile source CH_4 and N_2O emissions for these categories. For agriculture, the MF-24 gasoline volume is used directly because it includes both non-road trucks and equipment. For construction and commercial/industrial category gasoline estimates, the 2014 and older MF-24 volumes represented non-road trucks only; therefore, the MOVES gasoline volumes for construction and commercial/industrial categories are added to the respective categories in the Inventory. Beginning in 2015, this addition is no longer necessary since the FHWA updated its methods for estimating on-road and non-road gasoline consumption. Among the method updates, FHWA now incorporates MOVES equipment gasoline volumes in the construction and commercial/industrial categories.

Table 3-21: Approach 2 Quantitative Uncertainty Estimates for CH_4 and N_2O Emissions from Mobile Sources (MMT CO_2 Eq. and Percent)

Source	Gas	2022 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Mobile Sources	CH_4	2.6	2.5	3.4	-4%	+30%
Mobile Sources	N_2O	16.7	15.3	20.1	-8%	+20%

[a] Range of emission estimates predicted by Monte Carlo stochastic simulation for a 95 percent confidence interval.

This uncertainty analysis is a continuation of a multi-year process for developing quantitative uncertainty estimates for this source category using the IPCC Approach 2 uncertainty estimation methodology. As a result, as new information becomes available, uncertainty characterization of input variables may be improved and revised. For additional information regarding uncertainty in emission estimates for CH_4 and N_2O please refer to the Uncertainty Annex. As discussed in Annex 5, data are unavailable to include estimates of CH_4 and N_2O emissions from any liquid fuel used in pipeline transport or some biomass used in transportation sources, but those emissions are assumed to be insignificant.

QA/QC and Verification

In order to ensure the quality of the emission estimates from mobile combustion, general (IPCC Tier 1) and category-specific (Tier 2) Quality Assurance/Quality Control (QA/QC) procedures were implemented consistent with the U.S. Inventory QA/QC plan outlined in Annex 8. The specific plan used for mobile combustion was updated prior to collection and analysis of this current year of data. The Tier 2 procedures focused on the emission factor and activity data sources, as well as the methodology used for estimating emissions. These procedures included a qualitative assessment of the emission estimates to determine whether they appear consistent with the most recent activity data and emission factors available. A comparison of historical emissions between the current Inventory and the previous Inventory was also conducted to ensure that the changes in estimates were consistent with the changes in activity data and emission factors.

Recalculations Discussion

In previous *Inventories* (1990 through 2020 *Inventory* and before), on-highway greenhouse gas emissions were calculated using FHWA fuel consumption and vehicle miles traveled (VMT) data delineated by FHWA vehicle classes. These fuel consumption estimates were then combined with estimates of fuel shares by vehicle type from Oak Ridge National Laboratory's Transportation Energy Data Book (TEDB), to develop an estimate of fuel consumption for each vehicle type in the Inventory (i.e., passenger cars, light-duty trucks, buses, medium- and heavy-duty trucks, motorcycles). However, in 2011, FHWA changed its methods for estimating VMT and related data. These methodological changes included how vehicles are classified, moving from a system based on body-type to one that is based on wheelbase. These changes were first incorporated in the 1990 through 2008 *Inventory* and applied to the time series beginning in 2007. The FHWA methodology update resulted in large changes in VMT and fuel consumption by vehicle class, leading to a shift in emissions among vehicle classes. For example, FHWA replaced the vehicle category "Passenger Cars" with "Light-duty Vehicles-Short Wheelbase" and the "Other 2 axle-4 Tire Vehicles" category was replaced by "Light-duty Vehicles, Long Wheelbase." FHWA changed the definition of light-duty vehicles to less than 10,000 lbs. GVWR instead of 8,500 lbs. GVWR category updates pushed some single-unit heavy-duty trucks to the light-duty class. This change in vehicle classification also moved some smaller trucks and sport utility vehicles from the light truck category to the passenger cars category in this *Inventory*. These updates resulted in a disconnect in FHWA VMT and fuel consumption data in the 2006 to 2007 timeframe, generating a large drop in the light-duty truck VMT and fuel consumption trend lines between 2006 and 2007, and a corresponding increase in the passenger cars trend lines.

To address this inconsistency in the time series, EPA updated the methodology (starting with the 1990 through 2021 *Inventory*) to divide FHWA VMT data into vehicle classes and fuel type using distributions from EPA's *MOtor Vehicle Emission Simulator*, MOVES. The MOVES model is a nationally recognized model based on vehicle registration, travel activity, and emission rates that are updated with each model release. MOVES uses forecast growth factors which provide EPA's best estimate of likely future activity based on historical data (see Annex 3.2 for more information about the MOVES model). Thus, dividing FHWA total VMT data into vehicle class and fuel type using MOVES ratios provides a more consistent estimate of vehicle activity over the *Inventory* time series. MOVES ratios are also used to reallocate FHWA gasoline and diesel fuel use data (Browning 2022a). For this update, the MOVES3 model was run for calendar years 1990 and 1999 through 2022 for all vehicle types. Calendar years 1991 through 1998 were linearly interpolated from 1990 and 1999 calendar year MOVES3 outputs. Model outputs of VMT and fuel consumption were binned by calendar year, MOVES vehicle type, and fuel type; MOVES vehicle types were then mapped to the vehicle types used in the *Inventory*. Only outputs of gasoline and diesel fuel consumption from MOVES3 were used; alternative fuel VMT and fuel consumption outputs are ignored because they are calculated for the *Inventory* under a separate methodology. Total gasoline and diesel fuel consumption values from FHWA were then allocated to *Inventory* vehicle types using gasoline and diesel fuel consumption ratios by vehicle type from MOVES3. Similarly, VMT by vehicle type and fuel type was calculated by multiplying the total VMT from FHWA by VMT ratios by vehicle and fuel type generated by MOVES3. Overall, because total fuel consumption and VMT values are conserved, the changes in total emissions are small, within 0.1 percent. Observed differences in total emissions are due to changes in CH_4 and N_2O emissions, as the methodology for calculating these non-CO_2 emissions utilizes more detailed activity data and is therefore sensitive to the re-allocation of activity data. While total emissions estimates are not significantly impacted by this methodology update, there are significant changes in the allocation of emissions by vehicle type. The share of emissions allocated to passenger cars now generally decline through the time series while the share of emissions allocated to light-duty trucks increase over time.

In addition, the latest version of Argonne National Laboratory's *Greenhouse Gas, Regulated Emissions, and Energy Use in Transportation Model (*GREET2022*)* provided updated emission factors for all alternative fuel vehicle classes (ANL 2022). Updated emission factors from GREET2022 were implemented in this *Inventory*, across the entire time series.

Additionally, new data from BTS on Amtrak fuel consumption for the time period 2019 through 2022 were included in this *Inventory* (BTS 2023).

Planned Improvements

While the data used for this report represent the most accurate information available, several areas for improvement have been identified.

- Update emission factors for ships and non-recreational boats using residual fuel and distillate fuel. Develop emission factors for locomotives using ultra-low sulfur diesel and emission factors for aircraft using jet fuel. The Inventory currently uses IPCC default values for these emission factors.
- Continue to explore potential improvements to estimates of domestic waterborne fuel consumption for future Inventories. The *Inventory* estimates for residual and distillate fuel used by ships and boats is based in part on data on bunker fuel use from the U.S. Department of Commerce. Domestic fuel consumption is estimated by subtracting fuel sold for international use from the total sold in the United States. Since 2015, all ships travelling within 200 nautical miles of the U.S. coastlines must use distillate fuels, thereby overestimating the residual fuel used by U.S. vessels and underestimating distillate fuel use in these ships. Additionally, the EIA has stopped publishing the Fuel Oil and Kerosene Sales report, which reported data on distillate marine fuel use in the U.S. and the territories. This affects the volume of fuel and emissions that are allocated to the domestic ships and boats source, although top-down data is still available from the Monthly Energy Review that will be used to estimate total domestic emission from diesel fuel use. New data and methods are being explored to improve the diesel ships and boats emissions estimates going forward.
- Update the analyses to use a forthcoming version of MOVES when it becomes available.

3.2 Carbon Emitted from Non-Energy Uses of Fossil Fuels (CRT Source Category 1A)

In addition to being combusted for energy, fossil fuels are also consumed for non-energy uses (NEU) in the United States. The fuels used for these purposes are diverse, including natural gas, hydrocarbon gas liquids (HGL),[57] asphalt (a viscous liquid mixture of heavy crude oil distillates), petroleum coke (manufactured from heavy oil), and coal (metallurgical) coke (manufactured from coking coal). The non-energy applications of these fuels are equally diverse, including feedstocks for the manufacture of plastics, rubber, synthetic fibers and other materials; reducing agents for the production of various metals and inorganic products; and products such as lubricants, waxes, and asphalt (IPCC 2006). Emissions from non-energy use of lubricants, paraffin waxes, bitumen/asphalt, and solvents are reported in the Energy sector, as opposed to the Industrial Processes and Product Use (IPPU) sector, to reflect national circumstances in its choice of methodology and to increase transparency of this source category's unique country-specific data sources and methodology (see Box 3-5). In addition, estimates of non-energy use emissions included here do not include emissions already reflected in the IPPU sector, e.g., fuels used as reducing agents. To avoid double counting, the "raw" non-energy fuel consumption data reported by EIA are reduced to account for these emissions already included under IPPU.

Carbon dioxide emissions arise from non-energy uses via several pathways. Emissions may occur during the manufacture of a product, as is the case in producing plastics or rubber from fuel-derived feedstocks. Additionally, emissions may occur during the product's lifetime, such as during solvent use. Overall, throughout the time series and across all uses, about 64 percent of the total carbon consumed for non-energy purposes was stored in products (e.g., plastics), and not released to the atmosphere; the remaining 36 percent was emitted.

There are several areas in which non-energy uses of fossil fuels are closely related to other parts of this *Inventory*. For example, some of the non-energy use products release CO_2 at the end of their commercial life when they are combusted after disposal; these emissions are reported separately within the Energy chapter in the Incineration of Waste source category. There are also net exports of petrochemical intermediate products that are not completely accounted for in the EIA data, and the *Inventory* calculations adjust for the effect of net exports on the mass of carbon in non-energy applications.

As shown in Table 3-22, fossil fuel emissions in 2022 from the non-energy uses of fossil fuels were 102.8 MMT CO_2 Eq., which constituted approximately 2.0 percent of overall fossil fuel emissions. In 2022, the consumption of fuels for non-energy uses (after the adjustments described above) was 5,428.2 TBtu (see Table 3-23). A portion of the carbon in the 5,428.2 TBtu of fuels was stored (236.7 MMT CO_2 Eq.), while the remaining portion was emitted (102.8 MMT CO_2 Eq.). Non-energy use emissions decreased by 7.9 percent from 2021 to 2022, primarily due to decreases in industrial coal, natural gas, and HGL fuel consumption. See Annex 2.3 for more details.

[57] HGL (formerly referred to as liquefied petroleum gas, or LPG) are hydrocarbons that occur as gases at atmospheric pressure and as liquids under higher pressures. HGLs include paraffins, such as ethane, propane, butanes, isobutane, and natural gasoline (formerly referred to as pentanes plus), and HGLs include olefins, such as ethylene, propylene, butylene and isobutylene.

Table 3-22: CO_2 Emissions from Non-Energy Use Fossil Fuel Consumption (MMT CO_2 Eq. and Percent C)

Year	1990	2005	2018	2019	2020	2021	2022
Potential Emissions	292.5	357.7	341.5	334.7	328.6	345.0	339.5
C Stored	193.4	232.7	223.2	228.2	230.8	233.4	236.7
Emissions as a % of Potential	34%	35%	35%	32%	30%	32%	30%
C Emitted	**99.1**	**125.0**	**118.4**	**106.5**	**97.8**	**111.6**	**102.8**

Note: NEU emissions presented in this table differ from the NEU emissions presented in CRT Table 1.A(a)s4 as the CRT NEU emissions do not include NEU of lubricants and other petroleum in U.S. Territories. NEU emissions from U.S. Territories are reported under U.S. Territories in the CRT Table 1.A(a)s4.

Methodology and Time-Series Consistency

As per discussion of methodology for estimating CO_2 emissions from fossil fuel combustion, NEU emissions are estimated in line with a Tier 2 method described by the *IPCC in the 2006 IPCC Guidelines for National Greenhouse Gas Inventories* (IPCC 2006) Chapter 2, Figure 2.1 decision tree and available data on energy use and country specific fuel carbon contents. The first step in estimating carbon stored in products was to determine the aggregate quantity of fossil fuels consumed for non-energy uses. The carbon content of these feedstock fuels is equivalent to potential emissions, or the product of consumption and the fuel-specific carbon content values. Both the non-energy fuel consumption and carbon content data were supplied by the EIA (2023) (see Annex 2.1). Consumption values for industrial coking coal, petroleum coke, other oils, and natural gas in Table 3-23 and Table 3-24 have been adjusted to subtract non-energy uses that are included in the source categories of the Industrial Processes and Product Use chapter.[58] Consumption of natural gas, HGL, naphthas, other oils, and special naphtha were adjusted to subtract out net exports of these products that are not reflected in the raw data from EIA. Consumption values were also adjusted to subtract net exports of HGL components (e.g., propylene, ethane).

For the remaining non-energy uses, the quantity of carbon stored was estimated by multiplying the potential emissions by a storage factor.

- For several fuel types—petrochemical feedstocks (including natural gas for non-fertilizer uses, HGL, naphthas, other oils, still gas, special naphtha, and industrial other coal), asphalt and road oil, lubricants, and waxes—U.S. data on carbon stocks and flows were used to develop carbon storage factors, calculated as the ratio of (a) the carbon stored by the fuel's non-energy products to (b) the total carbon content of the fuel consumed. A lifecycle approach was used in the development of these factors in order to account for losses in the production process and during use. Because losses associated with municipal solid waste management are handled separately in the Energy sector under the Incineration of Waste source category, the storage factors do not account for losses at the disposal end of the life cycle.
- For industrial coking coal and distillate fuel oil, storage factors were taken from Marland and Rotty (1984).
- For the remaining fuel types (petroleum coke, miscellaneous products and other petroleum), IPCC (2006) does not provide guidance on storage factors, and assumptions were made based on the potential fate of carbon in the respective non-energy use products. Carbon dioxide emissions from carbide production are implicitly accounted for in the storage factor calculation for the non-energy use of petroleum coke.

[58] These source categories include iron and steel production, lead production, zinc production, ammonia manufacture, carbon black manufacture (included in petrochemical production), titanium dioxide production, ferroalloy production, silicon carbide production, and aluminum production.

Table 3-23: Adjusted Consumption of Fossil Fuels for Non-Energy Uses (TBtu)

Year	1990	2005	2018	2019	2020	2021	2022
Industry	**4,110.2**	**4,961.2**	**5,261.0**	**5,143.8**	**5,096.7**	**5,343.1**	**5,301.8**
Industrial Coking Coal	NO	80.4	124.7	112.8	79.9	77.9	46.7
Industrial Other Coal	7.6	11.0	9.5	9.5	9.5	9.5	9.5
Natural Gas to Chemical Plants	280.6	260.7	675.1	663.4	660.5	663.7	654.2
Asphalt & Road Oil	1,170.2	1,323.2	792.8	843.9	832.3	898.1	916.1
HGL[a]	1,135.0	1,554.3	2,427.6	2,372.8	2,469.5	2,639.0	2,758.8
Lubricants	186.3	160.2	122.0	118.3	111.1	113.5	119.5
Natural Gasoline[b]	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Naphtha (<401 °F)	325.4	679.2	420.6	367.7	327.8	329.3	244.2
Other Oil (>401 °F)	660.4	499.2	218.8	211.1	194.7	195.3	111.1
Still Gas	36.7	67.7	166.9	158.7	145.4	152.8	157.1
Petroleum Coke	29.1	104.2	0.0	0.0	0.0	0.0	0.0
Special Naphtha	100.6	60.9	86.9	89.1	80.4	75.7	82.4
Distillate Fuel Oil	7.0	16.0	5.8	5.8	5.8	5.8	5.8
Waxes	33.3	31.4	12.4	10.4	9.2	11.8	13.0
Miscellaneous Products	137.8	112.8	198.0	180.2	170.7	170.8	183.4
Transportation	**176.0**	**151.3**	**137.0**	**131.3**	**115.6**	**119.0**	**125.4**
Lubricants	176.0	151.3	137.0	131.3	115.6	119.0	125.4
U.S. Territories	**50.8**	**114.9**	**3.6**	**3.6**	**1.0**	**1.0**	**1.0**
Lubricants	0.7	4.6	1.0	1.0	1.0	1.0	1.0
Other Petroleum (Misc. Prod.)	50.1	110.3	2.5	2.6	0.0	0.0	0.0
Total	**4,337.1**	**5,227.5**	**5,401.6**	**5,278.8**	**5,213.4**	**5,463.2**	**5,428.2**

NO (Not Occurring)

[a] Excludes natural gasoline.

[b] Formerly referred to as "pentanes plus." This source has been adjusted and is reported separately from HGL to align with historic data and revised EIA terminology.

Table 3-24: 2022 Adjusted Non-Energy Use Fossil Fuel Consumption, Storage, and Emissions

Sector/Fuel Type	Adjusted Non-Energy Use[a] (TBtu)	Carbon Content Coefficient (MMT C/QBtu)	Potential Carbon (MMT C)	Storage Factor (MMT C)	Carbon Stored (MMT C)	Carbon Emissions (MMT C)	Carbon Emissions (MMT CO_2 Eq.)
Industry	**5,301.8**	**NA**	**90.0**	**NA**	**64.3**	**25.7**	**94.3**
Industrial Coking Coal	46.7	25.61	1.2	0.10	0.1	1.1	3.9
Industrial Other Coal	9.5	26.10	0.2	0.67	0.2	0.1	0.3
Natural Gas to Chemical Plants	654.2	14.47	9.4	0.67	6.3	3.1	11.4
Asphalt & Road Oil	916.1	20.55	18.8	1.00	18.7	0.1	0.3
HGL[b]	2,758.8	16.82	46.4	0.67	31.1	15.3	56.2
Lubricants	119.5	20.20	2.4	0.09	0.2	2.2	8.0
Natural Gasoline[c]	0.0	18.24	0.0	0.67	0.0	0.0	0.0
Naphtha (<401° F)	244.2	18.55	4.5	0.67	3.0	1.5	5.5
Other Oil (>401° F)	111.1	20.17	2.2	0.67	1.5	0.7	2.7
Still Gas	157.1	17.51	2.8	0.67	1.8	0.9	3.3
Petroleum Coke	0.0	27.85	0.0	0.30	0.0	0.0	0.0
Special Naphtha	82.4	19.74	1.6	0.67	1.1	0.5	2.0
Distillate Fuel Oil	5.8	20.22	0.1	0.50	0.1	0.1	0.2
Waxes	13.0	19.80	0.3	0.58	0.1	0.1	0.4
Miscellaneous Products	183.4	0.00	0.0	0.00	0.0	0.0	0.0
Transportation	**125.4**	**NA**	**2.5**	**NA**	**0.2**	**2.3**	**8.4**
Lubricants	125.4	20.20	2.5	0.09	0.2	2.3	8.4
U.S. Territories	**1.0**	**NA**	**+**	**NA**	**+**	**+**	**0.1**
Lubricants	1.0	20.20	+	0.09	+	+	0.1

Other Petroleum (Misc. Prod.)	+	20.00	+	0.10	+	+	+
Total	**5,428.2**		**92.6**		**64.6**	**28.0**	**102.8**

+ Does not exceed 0.05 TBtu, MMT C, or MMT CO_2 Eq.
NA (Not Applicable)
NO (Not Occurring)
[a] To avoid double counting, net exports have been deducted.
[b] Excludes natural gasoline.
[c] Formerly referred to as "pentanes plus." this source has been adjusted and is reported separately from HGL to align with historic data and revised EIA terminology.
Note: Totals may not sum due to independent rounding.

Lastly, emissions were estimated by subtracting the carbon stored from the potential emissions (see Table 3-22). More detail on the methodology for calculating storage and emissions from each of these sources is provided in Annex 2.3.

Where storage factors were calculated specifically for the United States, data were obtained on (1) products such as asphalt, plastics, synthetic rubber, synthetic fibers, cleansers (soaps and detergents), pesticides, food additives, antifreeze and deicers (glycols), and silicones; and (2) industrial releases including energy recovery (waste gas from chemicals), Toxics Release Inventory (TRI) releases, hazardous waste incineration, and volatile organic compound, solvent, and non-combustion CO emissions. Data were taken from a variety of industry sources, government reports, and expert communications. Sources include EPA reports and databases such as compilations of air emission factors (EPA 2001), EPA's Emissions Inventory System (EIS) to National Inventory Report (NIR) Mapping file (EPA 2023), *Toxics Release Inventory, 1998* (EPA 2000b), *Biennial Reporting System* (EPA 2000a, 2009), *Resource Conservation and Recovery Act Information System* (EPA 2013b, 2015, 2016b, 2018b, 2021), pesticide sales and use estimates (EPA 1998, 1999, 2002, 2004, 2011, 2017), and the Chemical Data Access Tool (EPA 2014b); the EIA Manufacturer's Energy Consumption Survey (MECS) (EIA 1994, 1997, 2001, 2005, 2010, 2013, 2017, 2021); the National Petrochemical & Refiners Association (NPRA 2002); the U.S. Census Bureau (1999, 2004, 2009, 2014, 2021); Bank of Canada (2012, 2013, 2014, 2016, 2017, 2018, 2019, 2020, 2021, 2022, 2023); Financial Planning Association (2006); INEGI (2006); the United States International Trade Commission (2023); Gosselin, Smith, and Hodge (1984); EPA's *Municipal Solid Waste (MSW) Facts and Figures* (EPA 2013, 2014a, 2016a, 2018a, 2019); the U.S. Tire Manufacturers Association (USTMA 2012, 2013, 2014, 2016, 2018, 2020, 2022); the International Institute of Synthetic Rubber Products (IISRP 2000, 2003); the Fiber Economics Bureau (FEB 2001, 2003, 2005, 2007, 2009, 2010, 2011, 2012, 2013); the Independent Chemical Information Service (ICIS 2008, 2016); the EPA Chemical Data Access Tool (CDAT) (EPA 2014b); the American Chemistry Council (ACC 2003 through 2011, 2013, 2014, 2015, 2016, 2017, 2018, 2019, 2020, 2021, 2022, 2023a); the *Guide to the Business of Chemistry* (ACC 2023b); and the Chemistry Industry Association of Canada (CIAC 2023). Specific data sources are listed in full detail in Annex 2.3.

Methodological recalculations were applied to the entire time series to ensure time-series consistency from 1990 through 2022 as discussed below.

Box 3-5: Reporting of Lubricants, Waxes, and Asphalt and Road Oil Product Use in Energy Sector

IPCC (2006) provides methodological guidance to estimate emissions from the first use of fossil fuels as a product for primary purposes other than combustion for energy purposes (including lubricants, paraffin waxes, bitumen / asphalt, and solvents) under the IPPU sector.[59] In this *Inventory*, carbon storage and carbon

[59] See for example Volume 3: Industrial Processes and Product Use, and Chapter 5: Non-Energy Products from Fuels and Solvent Use of the *2006 IPCC Guidelines for National Greenhouse Gas Inventories* (IPCC 2006).

emissions from product use of lubricants, waxes, and asphalt and road oil are reported under the Energy sector in the Carbon Emitted from Non-Energy Uses of Fossil Fuels source category (CRT Source Category 1A5).[60]

The emissions are reported in the Energy sector, as opposed to the IPPU sector, to reflect national circumstances in its choice of methodology and to increase transparency of this source category's unique country-specific data sources and methodology. Although emissions from these non-energy uses are reported in the Energy chapter the methodologies used to determine emissions are compatible with the *2006 IPCC Guidelines*. The country-specific methodology used for the Carbon Emitted from Non-Energy Uses of Fossil Fuels source category is based on a carbon balance (i.e., carbon inputs-outputs) calculation of the aggregate amount of fossil fuels used for non-energy uses, including inputs of lubricants, waxes, asphalt and road oil (see Table 3-24).

For those inputs, U.S. country-specific data on carbon stocks and flows are used to develop carbon storage factors, which are calculated as the ratio of the carbon stored by the fossil fuel non-energy products to the total carbon content of the fuel consumed, taking into account losses in the production process and during product use.[61] The country-specific methodology to reflect national circumstances starts with the aggregate amount of fossil fuels used for non-energy uses and applies a carbon balance calculation, breaking out the carbon emissions from non-energy use of lubricants, waxes, and asphalt and road oil. The emissions are reported under the Energy chapter to improve transparency, report a more complete carbon balance and to avoid double counting. Due to U.S. national circumstances, reporting these carbon emissions separately under IPPU would involve making artificial adjustments to allocate both the carbon inputs and carbon outputs of the non-energy use carbon balance. For example, only the emissions from the first use of lubricants and waxes are to be reported under the IPPU sector, emissions from use of lubricants in 2-stroke engines and emissions from secondary use of lubricants and waxes in waste incineration with energy recovery are to be reported under the Energy sector. Reporting these non-energy use emissions from only first use of lubricants and waxes under IPPU would involve making artificial adjustments to the non-energy use carbon balance and could potentially result in double counting of emissions. These artificial adjustments would also be required for asphalt and road oil and solvents (which are captured as part of petrochemical feedstock emissions) and could also potentially result in double counting of emissions. To avoid presenting an incomplete carbon balance and a less transparent approach for the Carbon Emitted from Non-Energy Uses of Fossil Fuels source category calculation, the entire calculation of carbon storage and carbon emissions is therefore conducted in the Non-Energy Uses of Fossil Fuels category calculation methodology, and both the carbon storage and carbon emissions for lubricants, waxes, and asphalt and road oil are reported under the Energy sector.

However, emissions from non-energy uses of fossil fuels as feedstocks or reducing agents (e.g., petrochemical production, aluminum production, titanium dioxide, and zinc production) are reported in the IPPU chapter, unless otherwise noted due to specific national circumstances.

Uncertainty

An uncertainty analysis was conducted to quantify the uncertainty surrounding the estimates of emissions and storage factors from non-energy uses. This analysis, performed using @RISK software and the IPCC-recommended Approach 2 methodology (Monte Carlo stochastic simulation technique), provides for the specification of probability density functions for key variables within a computational structure that mirrors the calculation of the

[60] Non-methane volatile organic compound (NMVOC) emissions from solvent use are reported separately in the IPPU sector, following Chapter 5 of the *2006 IPCC Guidelines*.

[61] Data and calculations for lubricants and waxes and asphalt and road oil are in Annex 2.3 – Methodology for Estimating Carbon Emitted from Non-Energy Uses of Fossil Fuels.

inventory estimate. The results presented below provide the 95 percent confidence interval, the range of values within which emissions are likely to fall, for this source category.

As noted above, the non-energy use analysis is based on U.S.-specific storage factors for (1) feedstock materials (natural gas, HGL, natural gasoline, naphthas, other oils, still gas, special naphthas, and other industrial coal), (2) asphalt, (3) lubricants, and (4) waxes. For the remaining fuel types (the "other" category in Table 3-23 and Table 3-24) the storage factors were taken directly from IPCC (2006), where available, and otherwise assumptions were made based on the potential fate of carbon in the respective NEU products. To characterize uncertainty, five separate analyses were conducted, corresponding to each of the five categories. In all cases, statistical analyses or expert judgments of uncertainty were not available directly from the information sources for all the activity variables; thus, uncertainty estimates were determined using assumptions based on source category knowledge.

The results of the Approach 2 quantitative uncertainty analysis are summarized in Table 3-25 (emissions) and Table 3-26 (storage factors). Carbon emitted from non-energy uses of fossil fuels in 2022 was estimated to be between 71.0 and 166.6 MMT CO_2 Eq. at a 95 percent confidence level. This indicates a range of 31 percent below to 62 percent above the 2022 emission estimate of 102.8 MMT CO_2 Eq. The uncertainty in the emission estimates is a function of uncertainty in both the quantity of fuel used for non-energy purposes and the storage factor.

Table 3-25: Approach 2 Quantitative Uncertainty Estimates for CO_2 Emissions from Non-Energy Uses of Fossil Fuels (MMT CO_2 Eq. and Percent)

Source	Gas	2022 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Feedstocks	CO_2	81.4	51.7	146.6	-37%	+80%
Asphalt	CO_2	0.3	0.1	0.7	-58%	+119%
Lubricants	CO_2	16.6	13.7	19.2	-17%	+16%
Waxes	CO_2	0.4	0.3	0.7	-23%	+77%
Other	CO_2	4.2	0.8	4.9	-81%	+17%
Total	**CO_2**	**102.8**	**71.0**	**166.6**	**-31%**	**+62%**

[a] Range of emission estimates predicted by Monte Carlo stochastic simulation for a 95 percent confidence interval.

Note: Totals may not sum due to independent rounding.

Table 3-26: Approach 2 Quantitative Uncertainty Estimates for Storage Factors of Non-Energy Uses of Fossil Fuels (Percent)

Source	Gas	2022 Storage Factor (%)	Uncertainty Range Relative to Emission Estimate[a] (%)		(%, Relative)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Feedstocks	CO_2	67.0%	52.3%	73.5%	-22%	+10%
Asphalt	CO_2	99.6%	99.1%	99.8%	0.5%	0.3%
Lubricants	CO_2	9.2%	3.9%	17.5%	-57%	+91%
Waxes	CO_2	57.8%	47.4%	67.5%	-18%	+17%
Other	CO_2	13.6%	8.1%	83.0%	-41%	+511%

[a] Range of emission estimates predicted by Monte Carlo stochastic simulation for a 95 percent confidence interval, as a percentage of the inventory value (also expressed in percent terms).

As shown in Table 3-26, waxes and asphalt contribute least to overall storage factor uncertainty on a percentage basis. Although the feedstocks category—the largest use category in terms of total carbon flows—also appears to have relatively tight confidence limits, this is to some extent an artifact of the way the uncertainty analysis was structured. As discussed in Annex 2.3, the storage factor for feedstocks is based on an analysis of six fates that result in long-term storage (e.g., plastics production), and eleven that result in emissions (e.g., volatile organic compound emissions). Rather than modeling the total uncertainty around all of these fate processes, the current analysis addresses only the storage fates, and assumes that all carbon that is not stored is emitted. As the

production statistics that drive the storage values are relatively well-characterized, this approach yields a result that is probably biased toward understating uncertainty.

As is the case with the other uncertainty analyses discussed throughout this document, the uncertainty results above address only those factors that can be readily quantified. More details on the uncertainty analysis are provided in Annex 2.3.

QA/QC and Verification

In order to ensure the quality of the emission estimates from non-energy uses of fossil fuels, general (IPCC Tier 1) and category-specific (Tier 2) Quality Assurance/Quality Control (QA/QC) procedures were implemented consistent with the U.S. Inventory QA/QC plan outlined in Annex 8. This effort included a general analysis, as well as portions of a category specific analysis for non-energy uses involving petrochemical feedstocks and for imports and exports. The Tier 2 procedures that were implemented involved checks specifically focusing on the activity data and methodology for estimating the fate of carbon (in terms of storage and emissions) across the various end-uses of fossil C. Emission and storage totals for the different subcategories were compared, and trends across the time series were analyzed to determine whether any corrective actions were needed. Corrective actions were taken to rectify minor errors and to improve the transparency of the calculations, facilitating future QA/QC.

For petrochemical import and export data, special attention was paid to NAICS numbers and titles to verify that none had changed or been removed. Import and export totals were compared with 2021 totals as well as their trends across the time series.

It is important to ensure no double counting of emissions between fuel combustion, non-energy use of fuels and industrial process emissions. For petrochemical feedstock production, our review of the categories suggests this is not a significant issue since the non-energy use industrial release data includes different categories of sources and sectors than those included in the Industrial Processes and Product Use (IPPU) emissions category for petrochemicals. Further data integration is not available at this time because feedstock data from the EIA used to estimate non-energy uses of fuels are aggregated by fuel type, rather than disaggregated by both fuel type and particular industries. Also, GHGRP-reported data on quantities of fuel consumed as feedstocks by petrochemical producers are unable to be used due to the data failing GHGRP CBI aggregation criteria. This country-specific approach taken is better able to reflect the national situation because it is accounting for secondary product imports and exports that are not included directly in the national energy statistics. Furthermore, it is compatible with the *2006 IPCC Guidelines* as discussed in Box 3-5 above, but also as the NEU emissions are here represent different emissions from those covered in the IPPU petrochemical production category.

Recalculations Discussion

Several updates to activity data factors lead to recalculations of previous year results. The major updates are as follows:

- U.S. International Trade Commission (2023) made changes to the classification of certain cleanser types, which doubled the historic emissions data for cleanser imports while exports remained constant.
- ACC (2023b) updated polyester, polyolefin and nylon fiber, ethylene glycol, maleic anhydride, adipic acid, and acetic acid production in 2021 which resulted in a slight decrease in emissions relative to the previous *Inventory*.
- U.S. International Trade Commission (2023) updated historical import and export data from 1996 to 2021, resulting in greater net exports relative to the previous *Inventory*.
- EIA (2024) shifted all 2022 product supplied of natural gasoline and unfinished oils to crude oil transfers, reflecting that, in actuality, nearly the full volume of these fuels is used as a feedstock in crude oil production, instead of directly consumed as an end-use fuel. Under EIA's guidance, EPA shifted all product supplied of natural gasoline to crude oil transfers for the time series. Natural gasoline was entirely

recategorized, which resulted in zero emissions for the time series from 1990 to 2022. Natural gasoline previously made up 1.7 percent of total emissions on average across the time series for non-energy uses of fossil fuels.

- To better align with EIA methodology, the non-energy use consumption of HGLs is now calculated for the entire timeseries by assuming that 100 percent of ethane, ethylene, and propylene consumption is for non-combustion use and 85 percent of normal butane, butylene, isobutane, and isobutylene is for non-combustion use. Non-energy use consumption of propane is calculated by subtracting the non-energy consumption of all other HGLs from the total non-combustion consumption of HGLs as published by the EIA. A further adjustment is made to natural gas, HGL, naphtha, other oil, and special naphtha consumption to account for exports of organic chemicals, cleansers, and pesticides. Because this adjustment is apportioned based on the relative ratios of each fuel, the emissions from these fuels have also changed slightly across the time series. Additionally, to better align with EIA methodology, the non-combustion and energy HGL carbon contents are now calculated for the entire timeseries following the above methodology. Overall, this update caused emissions from the non-energy use of natural gas to decrease an average of 27 MMT CO_2 Eq. annually, or 23 percent.

Overall, these changes resulted in an average annual decrease of 10.1 MMT CO_2 Eq. (8.2 percent) in carbon emissions from non-energy uses of fossil fuels for the period 1990 through 2021, relative to the previous *Inventory*.

Planned Improvements

There are several future improvements planned:

- More accurate accounting of carbon in petrochemical feedstocks. EPA has worked with EIA to determine the cause of input/output discrepancies in the carbon mass balance contained within the NEU model. In the future, two strategies to reduce or eliminate this discrepancy will continue to be pursued as part of quality control procedures. First, accounting of carbon in imports and exports will be improved. The import/export adjustment methodology will be examined to ensure that net exports of intermediaries such as ethylene and propylene are fully accounted for. Second, the use of top-down carbon input calculation in estimating emissions will be reconsidered. Alternative approaches that rely more substantially on the bottom-up carbon output calculation will be considered instead.
- Improving the uncertainty analysis. Most of the input parameter distributions are based on professional judgment rather than rigorous statistical characterizations of uncertainty.
- Better characterizing flows of fossil carbon. Additional fates may be researched, including the fossil carbon load in organic chemical wastewaters, plasticizers, adhesives, films, paints, and coatings. There is also a need to further clarify the treatment of fuel additives and backflows (especially methyl tert-butyl ether, MTBE).
- Reviewing the trends in fossil fuel consumption for non-energy uses. Annual consumption for several fuel types is highly variable across the time series, including industrial coking coal and other petroleum. A better understanding of these trends will be pursued to identify any mischaracterized or misreported fuel consumption for non-energy uses.
- Updating the average carbon content of solvents was researched, since the entire time series depends on one year's worth of solvent composition data. The data on carbon emissions from solvents that were readily available do not provide composition data for all categories of solvent emissions and also have conflicting definitions for volatile organic compounds, the source of emissive carbon in solvents. Additional sources of solvents data will be investigated in order to update the carbon content assumptions.
- Updating the average carbon content of cleansers (soaps and detergents) was researched; although production and consumption data for cleansers are published every 5 years by the Census Bureau, the composition (C content) of cleansers has not been recently updated. Recently available composition data

sources may facilitate updating the average carbon content for this category.

- Revising the methodology for consumption, production, and carbon content of plastics was researched; because of recent changes to the type of data publicly available for plastics, the NEU model for plastics applies data obtained from personal communications. Potential revisions to the plastics methodology to account for the recent changes in published data will be investigated.
- Although U.S.-specific storage factors have been developed for feedstocks, asphalt, lubricants, and waxes, default values from IPCC are still used for two of the non-energy fuel types (industrial coking coal, distillate oil), and broad assumptions are being used for miscellaneous products and other petroleum. Over the long term, there are plans to improve these storage factors by analyzing carbon fate similar to those described in Annex 2.3 or deferring to more updated default storage factors from IPCC where available.
- Reviewing the storage of carbon black across various sectors in the *Inventory*; in particular, the carbon black abraded and stored in tires.
- Assess the current method and/or identify new data sources (e.g., EIA) for estimating emissions from ammonia/fertilizer use of natural gas.
- Investigate EIA NEU and MECS data to update, as needed, adjustments made for ammonia production and "natural gas to chemical plants, other uses" and "natural gas to other" non-energy uses, including iron and steel production, in energy uses and IPPU.

3.3 Incineration of Waste (CRT Source Category 1A)

Combustion is used to manage about 7 to 19 percent of the solid wastes generated in the United States, depending on the source of the estimate and the scope of materials included in the definition of solid waste (EPA 2000; EPA 2020; Goldstein and Madtes 2001; Kaufman et al. 2004; Simmons et al. 2006; van Haaren et al. 2010). In the context of this section, waste includes all municipal solid waste (MSW) as well as scrap tires. In the United States, combustion of MSW tends to occur at waste-to-energy facilities or industrial facilities where useful energy is recovered, and thus emissions from waste combustion are accounted for in the Energy chapter. Similarly, scrap tires are combusted for energy recovery in industrial and utility boilers, pulp and paper mills, and cement kilns. Combustion of waste results in conversion of the organic inputs to CO_2. According to the *2006 IPCC Guidelines*, when the CO_2 emitted is of fossil origin, it is counted as a net anthropogenic emission of CO_2 to the atmosphere. Thus, the emissions from waste combustion are calculated by estimating the quantity of waste combusted and the fraction of the waste that is carbon derived from fossil sources.

Most of the organic materials in MSW are of biogenic origin (e.g., paper, yard trimmings), and have their net carbon flows accounted for under the Land Use, Land-Use Change, and Forestry chapter. However, some components of MSW and scrap tires—plastics, synthetic rubber, synthetic fibers, and carbon black—are of fossil origin. Plastics in the U.S. waste stream are primarily in the form of containers, packaging, and durable goods. Rubber is found in durable goods, such as carpets, and in non-durable goods, such as clothing and footwear. Fibers in MSW are predominantly from clothing and home furnishings. As noted above, scrap tires (which contain synthetic rubber and carbon black) are also considered a "non-hazardous" waste and are included in the waste combustion estimate, though waste disposal practices for tires differ from MSW. Estimates on emissions from hazardous waste combustion can be found in Annex 2.3 and are accounted for as part of the carbon mass balance for non-energy uses of fossil fuels.

Approximately 26.3 million metric tons of MSW were combusted in 2022 (EPA 2022). Carbon dioxide emissions from combustion of waste decreased 4.2 percent since 1990, to an estimated 12.4 MMT CO_2 (12,357 kt) in 2022. Emissions across the time series are shown in Table 3-27 and Table 3-28.

Waste combustion is also a source of CH_4 and N_2O emissions (De Soete 1993; IPCC 2006). Methane emissions from the combustion of waste were estimated to be less than 0.05 MMT CO_2 Eq. (less than 0.05 kt CH_4) in 2022 and have remained steady since 1990. Nitrous oxide emissions from the combustion of waste were estimated to be 0.3 MMT CO_2 Eq. (1.3 kt N_2O) in 2022 and have decreased by 18 percent since 1990. This decrease is driven by the decrease in total MSW combusted.

Table 3-27: CO_2, CH_4, and N_2O Emissions from the Combustion of Waste (MMT CO_2 Eq.)

Gas	1990	2005	2018	2019	2020	2021	2022
CO_2	12.9	13.3	13.3	12.9	12.9	12.5	12.4
CH_4	+	+	+	+	+	+	+
N_2O	0.4	0.3	0.4	0.4	0.3	0.4	0.3
Total	**13.3**	**13.6**	**13.7**	**13.3**	**13.3**	**12.8**	**12.7**

+ Does not exceed 0.05 MMT CO_2 Eq.
Note: Totals may not sum due to independent rounding.

Table 3-28: CO_2, CH_4, and N_2O Emissions from the Combustion of Waste (kt)

Gas	1990	2005	2018	2019	2020	2021	2022
CO_2	12,900	13,254	13,339	12,948	12,921	12,476	12,357
CH_4	+	+	+	+	+	+	+
N_2O	2	1	1	1	1	1	1

+ Does not exceed 0.05 kt.

Methodology and Time-Series Consistency

Municipal Solid Waste Combustion

To determine both CO_2 and non-CO_2 emissions from the combustion of waste, the tonnage of waste combusted and an estimated emissions factor are needed. Emission estimates from the combustion of tires are discussed separately. Data for total waste combusted was derived from *BioCycle* (van Haaren et al. 2010), EPA Facts and Figures Report, Energy Recovery Council (ERC), EPA's Greenhouse Gas Reporting Program (GHGRP), and the U.S. Energy Information Administration (EIA). Multiple sources were used to ensure a complete, quality dataset, as each source encompasses a different timeframe.

EPA determined the MSW tonnages based on data availability and accuracy throughout the time series.

- 1990-2006: MSW combustion tonnages are from Biocycle combustion data. Tire combustion data from the U.S. Tire Manufacturers Association (USTMA) are removed to arrive at MSW combusted without tires.
- 2006-2010: MSW combustion tonnages are an average of Biocycle (with USTMA tire data tonnage removed), U.S. EPA Facts and Figures, EIA, and Energy Recovery Council data (with USTMA tire data tonnage removed).
- 2011-2022: MSW combustion tonnages are from EPA's GHGRP data.

Table 3-29 provides the estimated tons of MSW combusted including and excluding tires.

Table 3-29: Municipal Solid Waste Combusted (Short Tons)

	1990	2005	2018	2019	2020	2021	2022
Waste Combusted *(excluding tires)*	33,344,839	26,486,414	29,162,364	28,174,311	27,586,271	27,867,446	26,338,130
Waste Combusted *(including tires)*	33,766,239	28,631,054	30,853,949	29,821,141	29,106,686	29,261,446	27,732,130

Sources: BioCycle, EPA Facts and Figures, ERC, GHGRP, EIA, USTMA.

CO_2 Emissions from MSW Excluding Scrap Tires

Fossil CO_2 emission factors were calculated from EPA's GHGRP data for non-biogenic sources. Using GHGRP-reported emissions for CH_4 and N_2O and assumed emission factors, the tonnage of waste combusted, excluding tires, was derived. Methane and N_2O emissions and assumed emission factors were used to estimate the amount of MSW combusted in terms of energy content. The energy content of MSW combusted was then converted into tonnage based on assumed MSW heating value. Two estimates were generated (one for CH_4 and one for N_2O) and the two were averaged together. Dividing fossil CO_2 emissions from GHGRP FLIGHT data for MSW combustors by this estimated tonnage yielded an annual CO_2 emission factor. As this data was only available following 2011, all years prior use an average of the emission factors from 2011 through 2015. See Annex 3.7 for more detail on how MSW carbon factors were calculated.

Finally, CO_2 emissions were calculated by multiplying the annual tonnage estimates, excluding tires, by the calculated emissions factor. Calculated fossil CO_2 emission factors are shown in Table 3-30.

Table 3-30: Calculated Fossil CO_2 Content per Ton Waste Combusted (kg CO_2/Short Ton Combusted)

Year	1990	2005	2018	2019	2020	2021	2022
CO_2 Emission Factors	366	366	361	363	377	365	382

CO_2 Emissions from Scrap Tires

Scrap tires contain several types of synthetic rubber, carbon black, and synthetic fibers. Each type of synthetic rubber has a discrete carbon content, and carbon black is 100 percent C. For synthetic rubber and carbon black in scrap tires, information on average weight, disposal percentage, and total tires incinerated for energy was obtained biannually from U.S. Scrap Tire Management Summary for 2005 through 2022 data (USTMA 2022). Information about scrap tire composition was taken from the Rubber Manufacturers' Association internet site (USTMA 2012a). Emissions of CO_2 were calculated based on the amount of scrap tires used for fuel and the synthetic rubber and carbon black content of scrap tires. The mass of combusted material is multiplied by its carbon content to calculate the total amount of carbon stored. 2022 values are proxied from 2021 data. More detail on the methodology for calculating emissions from each of these waste combustion sources is provided in Annex 3.7. Table 3-31 provides CO_2 emissions from combustion of waste tires.

Table 3-31: CO_2 Emissions from Combustion of Tires (MMT CO_2 Eq.)

Year	1990	2005	2018	2019	2020	2021	2022
Synthetic Rubber	0.3	1.6	1.3	1.2	1.1	1.0	1.0
C Black	0.4	2.0	1.5	1.5	1.4	1.3	1.3
Total	**0.7**	**3.6**	**2.8**	**2.7**	**2.5**	**2.3**	**2.3**

Non-CO_2 Emissions

Combustion of waste also results in emissions of CH_4 and N_2O. These emissions were calculated by multiplying the total estimated mass of waste combusted, including tires, by the respective emission factors. The emission factors for CH_4 and N_2O emissions per quantity of MSW combusted are default emission factors for the default continuously-fed stoker unit MSW combustion technology type and were taken from IPCC (2006).

Uncertainty

An Approach 2 Monte Carlo analysis was performed to determine the level of uncertainty surrounding the estimates of CO_2 emissions and N_2O emissions from the incineration of waste (given the very low emissions for CH_4, no uncertainty estimate was derived). IPCC Approach 2 analysis allows the specification of probability density functions for key variables within a computational structure that mirrors the calculation of the *Inventory* estimate. Statistical analyses or expert judgments of uncertainty were not available directly from the information sources for most variables; thus, uncertainty estimates for these variables were determined using assumptions based on source category knowledge and the known uncertainty estimates for the waste generation variables.

The uncertainties in the waste incineration emission estimates arise from both the assumptions applied to the data and from the quality of the data. Key factors include reported CO_2 emissions; N_2O and CH_4 emissions factors, and tire synthetic rubber and black carbon contents. The highest levels of uncertainty surround the reported emissions from GHGRP; the lowest levels of uncertainty surround variables that were determined by quantitative measurements (e.g., combustion efficiency, carbon content of carbon black).

The results of the Approach 2 quantitative uncertainty analysis are summarized in Table 3-32. Waste incineration CO_2 emissions in 2022 were estimated to be between 10.3 and 14.4 MMT CO_2 Eq. at a 95 percent confidence level. This indicates a range of 17 percent below to 16 percent above the 2022 emission estimate of 12.4 MMT CO_2 Eq. Also at a 95 percent confidence level, waste incineration N_2O emissions in 2022 were estimated to be between 0.2 and 0.9 MMT CO_2 Eq. This indicates a range of 54 percent below to 164 percent above the 2022 emission estimate of 0.3 MMT CO_2 Eq.

Table 3-32: Approach 2 Quantitative Uncertainty Estimates for CO_2 and N_2O from the Incineration of Waste (MMT CO_2 Eq. and Percent)

Source	Gas	2022 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Incineration of Waste	CO_2	12.4	10.3	14.4	-17%	16%
Incineration of Waste	N_2O	0.3	0.2	0.9	-54%	164%

[a] Range of emission estimates predicted by Monte Carlo Simulation for a 95 percent confidence interval.

QA/QC and Verification

In order to ensure the quality of the emission estimates from waste combustion, general (IPCC Tier 1) and category-specific (Tier 2) Quality Assurance/Quality Control (QA/QC) procedures were implemented consistent with the U.S. Inventory QA/QC plan outlined in Annex 8. The Tier 2 procedures that were implemented involved checks specifically focusing on the activity data and specifically focused on the emission factor and activity data sources and methodology used for estimating emissions from combustion of waste. Trends across the time series were analyzed to determine whether any corrective actions were needed. Corrective actions were taken to rectify minor errors in the use of activity data.

Recalculations Discussion

No recalculations were performed for the current *Inventory*.

Planned Improvements

Research was conducted to review the composition of carbon black abraded and stored in tires. No definitive sources were found that support updating the current factor of 28 percent carbon black for commercial and light duty tires. This factor was not updated, but additional research can be completed in future *Inventory* cycles.

3.4 Coal Mining (CRT Source Category 1B1a)

Three types of coal mining-related activities release CH_4 and CO_2 to the atmosphere: underground mining, surface mining, and post-mining (i.e., coal-handling) activities. While surface coal mines account for the majority of U.S. coal production, underground coal mines contribute the largest share of fugitive CH_4 emissions (see Table 3-34 and Table 3-35) due to the higher CH_4 content of coal in the deeper underground coal seams. In 2022, 185 underground coal mines and 354 surface mines were operating in the United States (EIA 2023). In recent years, the total number of active coal mines in the United States has declined. In 2022, the United States was the fourth largest coal producer in the world, after China, India, and Indonesia (IEA 2022).

Table 3-33: Coal Production (kt)

Year	1990	2005	2018	2019	2020	2021	2022
Underground							
Number of Mines	1,683	586	236	226	196	174	185
Production	384,244	334,399	249,804	242,557	177,380	200,122	201,525
Surface							
Number of Mines	1,656	789	430	432	350	332	354
Production	546,808	691,447	435,521	397,750	307,944	323,142	336,990
Total							
Number of Mines	**3,339**	**1,398**	**666**	**658**	**546**	**506**	**539**
Production	**931,052**	**1,025,846**	**685,325**	**640,307**	**485,324**	**523,264**	**538,515**

Fugitive CH_4 Emissions

Underground coal mines liberate CH_4 from ventilation systems and from degasification systems. Ventilation systems pump air through the mine workings to dilute noxious gases and ensure worker safety; these systems can exhaust significant amounts of CH_4 to the atmosphere in low concentrations. Degasification systems are wells drilled from the surface or boreholes drilled inside the mine that remove large, often highly concentrated volumes of CH_4 before, during, or after mining. Some mines recover and use CH_4 generated from ventilation and degasification systems, thereby reducing emissions to the atmosphere.

Surface coal mines liberate CH_4 as the overburden is removed and the coal is exposed to the atmosphere. Methane emissions are normally a function of coal rank (a classification related to the percentage of carbon in the coal) and depth. Surface coal mines typically produce lower-rank coals and remove less than 250 feet of overburden, so their level of emissions is much lower than from underground mines.

In addition, CH_4 is released during post-mining activities, as the coal is processed, transported, and stored for use.

Total CH_4 emissions in 2022 were estimated to be 1,558 kt (43.6 MMT CO_2 Eq.), a decline of approximately 60 percent since 1990 (see Table 3-34 and Table 3-35). In 2022, underground mines accounted for approximately 72 percent of total emissions, surface mines accounted for 14 percent, and post-mining activities accounted for 14 percent. In 2022, total CH_4 emissions from coal mining decreased by approximately 2 percent relative to the previous year. Total coal production in 2022 increased by 3 percent compared to 2021. This resulted in an increase of 4 percent in CH_4 emissions from surface mining and post-mining activities in 2022. However, surface mining and post-mining activities have a lower impact on total CH_4 compared to underground mining (72 percent of total emissions in 2022). The number of operating underground mines increased in 2022 and the amount of CH_4 recovered and used in 2022 increased by 25 percent compared to 2021. This resulted in a slight decrease in overall CH_4 emissions in 2022 (2 percent), compared to 2021.

Table 3-34: CH_4 Emissions from Coal Mining (MMT CO_2 Eq.)

Activity	1990	2005	2018	2019	2020	2021	2022
Underground (UG) Mining	**83.1**	**46.7**	**43.6**	**38.5**	**35.2**	**32.9**	**31.5**
Liberated	90.6	66.9	66.7	56.6	53.7	52.3	55.7
Recovered & Used	(7.5)	(20.1)	(23.1)	(18.1)	(18.5)	(19.4)	(24.2)
Surface Mining	**12.0**	**13.3**	**7.8**	**7.2**	**5.4**	**5.7**	**6.0**
Post-Mining (UG)	**10.3**	**8.6**	**5.9**	**5.8**	**4.3**	**4.8**	**4.8**
Post-Mining (Surface)	**2.6**	**2.9**	**1.7**	**1.5**	**1.2**	**1.2**	**1.3**
Total	**108.1**	**71.5**	**59.1**	**53.0**	**46.2**	**44.7**	**43.6**

Notes: Parentheses indicate negative values. Totals may not sum due to independent rounding.

Table 3-35: CH_4 Emissions from Coal Mining (kt)

Activity	1990	2005	2018	2019	2020	2021	2022
Underground (UG) Mining	**2,968**	**1,669**	**1,557**	**1,375**	**1,257**	**1,176**	**1,124**
Liberated	3,237	2,388	2,382	2,022	1,917	1,868	1,989
Recovered & Used	(269)	(720)	(825)	(646)	(660)	(692)	(865)
Surface Mining	**430**	**475**	**280**	**255**	**194**	**205**	**215**
Post-Mining (UG)	**368**	**306**	**212**	**206**	**155**	**170**	**173**
Post-Mining (Surface)	**93**	**103**	**61**	**55**	**42**	**44**	**47**
Total	**3,860**	**2,552**	**2,110**	**1,892**	**1,648**	**1,595**	**1,558**

Note: Parentheses indicate negative values. Totals may not sum due to independent rounding.

Methodology and Time-Series Consistency

EPA uses an IPCC Tier 3 method for estimating CH_4 emissions from underground coal mining and an IPCC Tier 2 method for estimating CH_4 emissions from surface mining and post-mining activities (for coal production from both underground mines and surface mines) in accordance with methodological decisions trees in IPCC guidelines (Volume 2, Chapter 4, Figure 4.1.1 and 4.1.2) and available data (IPCC 2006). The methodology for estimating CH_4 emissions from coal mining consists of two steps:

- Estimate CH_4 emissions from underground mines. These emissions have two sources: ventilation systems and degasification systems. They are estimated using mine-specific data, then summed to determine total CH_4 liberated. The CH_4 recovered and used is then subtracted from this total, resulting in an estimate of net emissions to the atmosphere.
- Estimate CH_4 emissions from surface mines and post-mining activities. Unlike the methodology for underground mines, which uses mine-specific data, the methodology for estimating emissions from surface mines and post-mining activities consists of multiplying basin-specific coal production by basin-specific gas content and an emission factor.

Step 1: Estimate CH_4 Liberated and CH_4 Emitted from Underground Mines

Underground mines generate CH_4 from ventilation systems and degasification systems. Some mines recover and

use the liberated CH_4, thereby reducing emissions to the atmosphere. Total CH_4 emitted from underground mines equals the CH_4 liberated from ventilation systems, plus the CH_4 liberated from degasification systems, minus the CH_4 recovered and used.

Step 1.1: Estimate CH_4 Liberated from Ventilation Systems

To estimate CH_4 liberated from ventilation systems, EPA uses data collected through its Greenhouse Gas Reporting Program (GHGRP)[62] (Subpart FF, "Underground Coal Mines"), data provided by the U.S. Mine Safety and Health Administration (MSHA) (MSHA 2023), and occasionally data collected from other sources on a site-specific level (e.g., state gas production databases). Since 2011, the nation's "gassiest" underground coal mines—those that liberate more than 36,500,000 actual cubic feet of CH_4 per year (about 17,525 MT CO_2 Eq.)—have been required to report to EPA's GHGRP (EPA 2023).[63] Mines that report to EPA's GHGRP must report quarterly measurements of CH_4 emissions from ventilation systems; they have the option of recording and reporting their own measurements, or using the measurements taken by MSHA as part of that agency's quarterly safety inspections of all mines in the United States with detectable CH_4 concentrations.[64]

Since 2013, ventilation CH_4 emission estimates have been calculated based on both quarterly GHGRP data submitted by underground mines and on quarterly measurement data obtained directly from MSHA. Because not all mines report under EPA's GHGRP, the emissions of the mines that do not report must be calculated using MSHA data. The MSHA data also serves as a quality assurance tool for validating GHGRP data. For GHGRP data, reported quarterly ventilation methane emissions (metric tons) are summed for each mine to develop mine-specific annual ventilation emissions. For MSHA data, the average daily CH_4 emission rate for each mine is determined using the CH_4 total for all data measurement events conducted during the calendar year and total duration of all data measurement events (in days). The calculated average daily CH_4 emission rate is then multiplied by 365 days to estimate annual ventilation CH_4 emissions for the MSHA dataset.

Step 1.2: Estimate CH_4 Liberated from Degasification Systems

Particularly gassy underground mines also use degasification systems (e.g., wells or boreholes) to remove CH_4 before, during, or after mining. This CH_4 can then be collected for use or vented to the atmosphere. Nineteen mines used degasification systems in 2022 and all of these mines reported the CH_4 removed through these systems to EPA's GHGRP under Subpart FF (EPA 2023). Based on the weekly measurements reported to EPA's GHGRP, degasification data summaries for each mine are added to estimate the CH_4 liberated from degasification systems. Twelve of the 19 mines with degasification systems had operational CH_4 recovery and use projects, including two mines with two recovery and use projects each (see step 1.3 below).[65]

Degasification data reported to EPA's GHGRP by underground coal mines is the primary source of data used to develop estimates of CH_4 liberated from degasification systems. Data reported to EPA's GHGRP were used exclusively to estimate CH_4 liberated from degasification systems at 13 of the 19 mines that used degasification systems in 2022. Data from state gas well production databases were used to supplement GHGRP degasification data for the remaining six mines (DMME 2023; GSA 2023; WVGES 2023; McElroy OVS 2013).

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[62] In implementing improvements and integrating data from EPA's GHGRP, EPA followed the latest guidance from the IPCC on the use of facility-level data in national inventories (IPCC 2011).

[63] Underground coal mines report to EPA under Subpart FF of the GHGRP (40 CFR Part 98). In 2022, 61 underground coal mines reported to the program.

[64] MSHA records coal mine CH_4 readings with concentrations of greater than 50 ppm (parts per million) CH_4. Readings below this threshold are considered non-detectable.

[65] Several of the mines venting CH_4 from degasification systems use a small portion of the gas to fuel gob well blowers in remote locations where electricity is not available. However, this CH_4 use is not considered to be a formal recovery and use project.

For pre-mining wells, cumulative degasification volumes that occur prior to the well being mined through are attributed to the mine in the inventory year in which the well is mined through.[66] EPA's GHGRP does not require gas production from virgin coal seams (coalbed methane) to be reported by coal mines under Subpart FF.[67] Most pre-mining wells drilled from the surface are considered coalbed methane wells prior to mine-through and associated CH_4 emissions are reported under another subpart of the GHGRP (Subpart W, "Petroleum and Natural Gas Systems"). As a result, GHGRP data must be supplemented to estimate cumulative degasification volumes that occurred prior to well mine-through. There were four mines with degasification systems that include pre-mining wells that were mined through in 2022. For all of these mines, GHGRP data were supplemented with historical data from state gas well production databases (ERG 2023; GSA 2023), as well as with mine-specific information regarding the locations and dates on which the pre-mining wells were mined through (JWR 2010; El Paso 2009; ERG 2023).

Step 1.3: Estimate CH_4 Recovered from Ventilation and Degasification Systems, and Utilized or Destroyed (Emissions Avoided)

Twelve mines had a total of fourteen CH_4 recovery and use projects in place in 2022, including two mines that each have two recovery and use projects. Thirteen of these projects involved degasification systems with one mine having a ventilation air methane abatement project (VAM). Eleven of these mines sold the recovered CH_4 to a pipeline, including one that also used CH_4 to fuel a thermal coal dryer. One mine destroyed the recovered CH_4 (VAM) using regenerative thermal oxidation (RTO) without energy recovery and using enclosed flares.

The CH_4 recovered and used (or destroyed) at the twelve mines described above are estimated using the following methods:

- EPA's GHGRP data was exclusively used to estimate the CH_4 recovered and used from six of the 12 mines that deployed degasification systems in 2022. Based on quarterly measurements, the GHGRP degasification destruction data summaries for each mine are added together to estimate the CH_4 recovered and used from degasification systems.
- State sales data were used to supplement GHGRP data to estimate CH_4 recovered and used from five mines that deployed degasification systems in 2022 (DMME 2023, ERG 2023, GSA 2023, and WVGES 2023). Four of these mines intersected pre-mining wells in 2022. Supplemental information is used for these mines because estimating CH_4 recovery and use from pre-mining wells requires additional data not reported under Subpart FF of EPA's GHGRP (see discussion in step 1.2 above) to account for the emissions avoided prior to the well being mined through. The supplemental data is obtained from state gas production databases as well as mine-specific information on the location and timing of mined-through pre-mining wells.
- For the single mine that employed VAM for CH_4 recovery and use, the estimates of CH_4 recovered and used were obtained from the mine's offset verification statement (OVS) submitted to the California Air Resources Board (CARB) (McElroy OVS 2023). This mine also reported CH_4 reductions from flaring. GHGRP data were used to estimate CH_4 recovered and flared in 2022.

Step 2: Estimate CH_4 Emitted from Surface Mines and Post-Mining Activities

Mine-specific data are not available for estimating CH_4 emissions from surface coal mines or for post-mining activities. For surface mines, basin-specific coal production obtained from the Energy Information Administration's *Annual Coal Report* (EIA 2023) is multiplied by basin-specific CH_4 contents (EPA 1996, 2005) and a 150 percent emission factor (to account for CH_4 from over- and under-burden) to estimate CH_4 emissions (King 1994; Saghafi

[66] A well is "mined through" when coal mining development or the working face intersects the borehole or well.

[67] This applies for pre-drainage in years prior to the well being mined through. Beginning with the year the well is mined through, the annual volume of CH_4 liberated from a pre-drainage well is reported under Subpart FF of EPA's GHGRP.

2013). For post-mining activities, basin-specific coal production is multiplied by basin-specific CH_4 contents and a mid-range 32.5 percent emission factor for CH_4 desorption during coal transportation and storage (Creedy 1993). Basin-specific in situ gas content data were compiled from AAPG (1984) and USBM (1986).

Fugitive CO_2 Emissions

Methane and CO_2 are naturally occurring in coal seams and are collectively referred to as coal seam gas. These gases remain trapped in the coal seam until coal is mined (i.e., coal seam is exposed and fractured during mining operations). Fugitive CO_2 emissions occur during underground coal mining, surface coal mining, and post-mining activities. Methods and data to estimate fugitive CO_2 emissions from underground and surface coal mining are presented in the sections below. Fugitive CO_2 emissions from post-mining activities were not estimated due to the lack of an IPCC method and unavailability of data.

Total fugitive CO_2 emissions in 2022 were estimated to be 2,474 kt (2.5 MMT CO_2 Eq.), a decline of approximately 46 percent since 1990. In 2022, underground mines accounted for approximately 89 percent of total fugitive CO_2 emissions. In 2022, total fugitive CO_2 emissions from coal mining increased by approximately 1 percent relative to the previous year. This increase was due to an increase in annual coal production.

Table 3-36: CO_2 Emissions from Coal Mining (MMT CO_2 Eq.)

Activity	1990	2005	2018	2019	2020	2021	2022
Underground (UG) Mining	**4.2**	**3.6**	**2.8**	**2.7**	**1.9**	**2.2**	**2.2**
Liberated	4.2	3.6	2.7	2.6	1.9	2.2	2.2
Recovered & Used	(+)	(+)	(+)	(+)	(+)	(+)	(+)
Flaring	NO	NO	0.1	0.1	+	+	+
Surface Mining	**0.4**	**0.6**	**0.4**	**0.3**	**0.2**	**0.3**	**0.3**
Total	**4.6**	**4.2**	**3.1**	**3.0**	**2.2**	**2.5**	**2.5**

+ Does not exceed 0.05 MMT CO_2 Eq.
NO (Not Occurring)
Notes: Parentheses indicate negative values. Totals may not sum due to independent rounding.

Table 3-37: CO_2 Emissions from Coal Mining (kt)

Activity	1990	2005	2018	2019	2020	2021	2022
Underground (UG) Mining	**4,164**	**3,610**	**2,787**	**2,670**	**1,948**	**2,193**	**2,201**
Liberated	4,171	3,630	2,712	2,633	1,926	2,173	2,188
Recovered & Used	(8)	(21)	(23)	(18)	(19)	(19)	(24)
Flaring	NO	NO	97	55	41	40	38
Surface Mining	**443**	**560**	**353**	**322**	**249**	**262**	**273**
Total	**4,606**	**4,169**	**3,139**	**2,992**	**2,197**	**2,455**	**2,474**

NO (Not Occurring)
Notes: Parentheses indicate negative values. Totals may not sum due to independent rounding.

Methodology and Time-Series Consistency

EPA uses an IPCC Tier 1 method for estimating fugitive CO_2 emissions from underground coal mining and surface mining in accordance with methodological decisions trees in IPCC guidelines (Volume 2, Chapter 4, Figure 4.1.1a) and available data (IPCC 2019). IPCC methods and data to estimate fugitive CO_2 emissions from post-mining activities (for both underground and surface coal mining) are currently not available.

Step 1: Underground Mining

EPA used the following overarching IPCC equation to estimate fugitive CO_2 emissions from underground coal mines (IPCC 2019):

Equation 3-1: Estimating Fugitive CO_2 Emissions from Underground Mines

$$Total\ CO_2\ from\ Underground\ Mines = CO_2\ from\ underground\ mining - Amount\ of\ CO_2\ in\ gas\ recovered + CO_2\ from\ methane\ flaring$$

Step 1.1: Estimate Fugitive CO_2 Emissions from Underground Mining

EPA estimated fugitive CO_2 emissions from underground mining using the IPCC Tier 1 emission factor (5.9 m^3/metric ton) and annual coal production from underground mines (EIA 2023). The underground mining default emission factor accounts for all the fugitive CO_2 likely to be emitted from underground coal mining. Therefore, the amount of CO_2 from coal seam gas recovered and utilized for energy is subtracted from underground mining estimates in Step 2, below. Under IPCC methods, the CO_2 emissions from gas recovered and utilized for energy use (e.g., injected into a natural gas pipeline) are reported under other sectors of the *Inventory* (e.g., stationary combustion of fossil fuel or oil and natural gas systems) and not under the coal mining sector.

Step 1.2: Estimate Amount of CO_2 In Coal Seam Gas Recovered for Energy Purposes

EPA estimated fugitive CO_2 emissions from coal seam gas recovered and utilized for energy purposes by using the IPCC Tier 1 default emission factor (19.57 metric tons CO_2/million cubic meters of coal bed methane (CBM) produced) and quantity of coal seam gas recovered and utilized. Data on annual quantity of coal seam gas recovered and utilized are available from GHGRP and state sales data (GHGRP 2023; DMME 2023; ERG 2023; GSA 2023; WVGES 2023). The quantity of coal seam gas recovered and destroyed without energy recovery (e.g., VAM projects with RTO) is deducted from the total coal seam gas recovered quantity (McElroy OVS 2023).

Step 1.3: Estimate Fugitive CO_2 Emissions from Flaring

The IPCC method includes combustion CO_2 emissions from gas recovered for non-energy uses (i.e., flaring, or catalytic oxidation) under fugitive CO_2 emission estimates for underground coal mining. In effect, these emissions, though occurring through stationary combustion, are categorized as fugitive emissions in the *Inventory*. EPA estimated CO_2 emissions from methane flaring using the following equation:

Equation 3-2: Estimating CO_2 Emissions from Drained Methane Flared or Catalytically Oxidized

$$CO_2\ from\ flaring = 0.98 \times Volume\ of\ methane\ flared \times Conversion\ Factor \times Stoichiometric\ Mass\ Factor$$

Currently there are three mines that report destruction of recovered methane through flaring without energy use. Annual data for 2022 were obtained from one mine's offset verification statement (OVS) submitted to the California Air Resources Board (CARB) and the GHGRP for the remaining two mines (McElroy OVS 2023; GHGRP 2023).

Step 2: Surface Mining

EPA estimated fugitive CO_2 emissions from surface mining using the IPCC Tier 1 emission factor (0.44 m^3/metric ton) and annual coal production from surface mines (EIA 2023).

Uncertainty

A quantitative uncertainty analysis was conducted for the coal mining source category using the IPCC-recommended Approach 2 uncertainty estimation methodology. Because emission estimates of CH_4 from underground ventilation systems were based on actual measurement data from EPA's GHGRP or from MSHA, uncertainty is relatively low. A degree of imprecision was introduced because the ventilation air measurements

used were not continuous but rather quarterly instantaneous readings that were used to determine the average annual emission rates. Additionally, the measurement equipment used can be expected to have resulted in an average of 10 percent overestimation of annual CH_4 emissions (Mutmansky & Wang 2000). Equipment measurement uncertainty is applied to GHGRP data.

Estimates of CH_4 liberated and recovered by degasification systems are relatively certain for utilized CH_4 because of the availability of EPA's GHGRP data and state gas sales information. Many of the liberation and recovery estimates use data on wells within 100 feet of a mined area. However, uncertainty exists concerning the radius of influence of each well. The number of wells counted, and thus the liberated CH_4 and avoided emissions, may vary if the drainage area is found to be larger or smaller than estimated.

EPA's GHGRP requires weekly CH_4 monitoring of mines that report degasification systems, and continuous CH_4 monitoring is required for CH_4 utilized on- or off-site. Since 2012, GHGRP data have been used to estimate CH_4 emissions from vented degasification wells, reducing the uncertainty associated with prior MSHA estimates used for this sub-source. Beginning in 2013, GHGRP data were also used for determining CH_4 recovery and use at mines without publicly available gas usage or sales records, which has reduced the uncertainty from previous estimation methods that were based on information from coal industry contacts.

Surface mining and post-mining emissions are associated with considerably more uncertainty than underground mines, because of the difficulty in developing accurate emission factors from field measurements. However, since underground coal mining, as a general matter, results in significantly larger CH_4 emissions due to production of higher-rank coal and greater depth, and estimated emissions from underground mining constitute the majority of estimated total coal mining CH_4 emissions, the uncertainty associated with underground emissions is the primary factor that determines overall uncertainty.

The major sources of uncertainty for estimates of fugitive CO_2 emissions are the Tier 1 IPCC default emission factors used for underground mining (-50 percent to +100 percent) and surface mining (-67 percent to +200 percent) (IPCC 2019). Additional sources of uncertainty for fugitive CO_2 emission estimates include EIA's annual coal production data and data used for gas recovery projects, such as GHGRP data, state gas sales data, and VAM estimates for the single mine that operates an active VAM project. Uncertainty ranges for these additional data sources are already available, as these are the same data sources used for CH_4 emission estimates.

The results of the Approach 2 quantitative uncertainty analysis are summarized in Table 3-38. Coal mining CH_4 emissions in 2022 were estimated to be between 34.8 and 47.8 MMT CO_2 Eq. at a 95 percent confidence level. This indicates a range of 20.3 percent below to 9.5 percent above the 2022 emission estimate of 43.6 MMT CO_2 Eq. Coal mining fugitive CO_2 emissions in 2022 were estimated to be between 0.8 and 4.3 MMT CO_2 Eq. at a 95 percent confidence level. This indicates a range of 68.5 percent below to 75.4 percent above the 2022 emission estimate of 2.5 MMT CO_2 Eq.

Table 3-38: Approach 2 Quantitative Uncertainty Estimates for CH_4 and CO_2 Emissions from Coal Mining (MMT CO_2 Eq. and Percent)

Source	Gas	2022 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Coal Mining	CH_4	43.6	34.8	47.8	-20%	+9%
Coal Mining	CO_2	2.5	0.8	4.3	-69%	+75%

[a] Range of emission estimates predicted by Monte Carlo stochastic simulation for a 95 percent confidence interval.

QA/QC and Verification

In order to ensure the quality of the emission estimates for coal mining, general (IPCC Tier 1) and category-specific (Tier 2) Quality Assurance/Quality Control (QA/QC) procedures were implemented consistent with the U.S. Inventory QA/QC plan outlined in Annex 8. The Tier 2 procedures that were implemented involved checks specifically focusing on the activity data and reported emissions data used for estimating fugitive emissions from

coal mining. Trends across the time series were analyzed to determine whether any corrective actions were needed.

Emission estimates for coal mining rely in large part on data reported by coal mines to EPA's GHGRP. EPA verifies annual facility-level reports through a multi-step process to identify potential errors and ensure that data submitted to EPA are accurate, complete, and consistent. All reports submitted to EPA are evaluated by electronic validation and verification checks. If potential errors are identified, EPA will notify the reporter, who can resolve the issue either by providing an acceptable response describing why the flagged issue is not an error or by correcting the flagged issue and resubmitting their annual report. Additional QA/QC and verification procedures occur for each GHGRP subpart. No QA/QC issues or errors were identified in the 2022 Subpart FF data.

Recalculations Discussion

Time series recalculations were performed due to revised historical data from state natural gas sales databases for five mines, which are used to estimate avoided CH_4 emissions. Additionally, calculation errors were identified and corrected for CH_4 emissions avoided from two mines. As a result of recalculations, CH_4 emissions decreased by an average of 0.03 percent across the time series, compared to the previous *Inventory*. The biggest increase in CH_4 emissions was in 1991 where emissions increased by 0.14 percent, compared to the previous *Inventory*. The biggest decrease in CH_4 emissions was in 2006 (0.6 percent). As a result of recalculations, there was a very minor decrease in CH_4 emissions in 2021 (less than 0.005 percent), compared to the previous *Inventory*.

Planned Improvements

EPA is assessing planned improvements for future reports, but at this time has no specific planned improvements for estimating CH_4 and CO_2 emissions from underground and surface mining and CH_4 emissions from post-mining.

3.5 Abandoned Underground Coal Mines (CRT Source Category 1B1a)

Underground coal mines contribute the largest share of coal mine methane (CMM) emissions, with active underground mines the leading source of underground emissions. However, mines also continue to release CH_4 after closure. As mines mature and coal seams are mined through, mines are closed and abandoned. Many are sealed and some flood through intrusion of groundwater or surface water into the void. Shafts or portals are generally filled with gravel and capped with a concrete seal, while vent pipes and boreholes are plugged in a manner similar to oil and gas wells. Some abandoned mines are vented to the atmosphere to prevent the buildup of CH_4 that may find its way to surface structures through overburden fractures. As work stops within the mines, CH_4 liberation decreases but it does not stop completely. Following an initial decline, abandoned mines can liberate CH_4 at a near-steady rate over an extended period of time, or if flooded, produce gas for only a few years. The gas can migrate to the surface through the conduits described above, particularly if they have not been sealed adequately. In addition, diffuse emissions can occur when CH_4 migrates to the surface through cracks and fissures in the strata overlying the coal mine. The following factors influence abandoned mine emissions:

- Time since abandonment;
- Gas content and adsorption characteristics of coal;
- CH_4 flow capacity of the mine;
- Mine flooding;
- Presence of vent holes; and
- Mine seals.

Annual gross abandoned mine CH_4 emissions ranged from 8.1 to 12.1 MMT CO_2 Eq. from 1990 to 2022, varying, in general, by less than 1 percent to approximately 19 percent from year to year. Fluctuations were due mainly to the number of mines closed during a given year as well as the magnitude of the emissions from those mines when active. Gross abandoned mine emissions peaked in 1996 (12.1 MMT CO_2 Eq.) due to the large number of gassy mine[68] closures from 1994 to 1996 (72 gassy mines closed during the three-year period). In spite of this rapid rise, abandoned mine emissions have been generally on the decline since 1996. Since 2002, there have been fewer than twelve gassy mine closures each year. In 2022 there was one gassy mine closure. Gross abandoned mine emissions decreased slightly from 9.2 MMT CO_2 Eq. (330 kt CH_4) in 2021 to 9.1 (324 kt CH_4) MMT CO_2 Eq. in 2022 (see Table 3-39 and Table 3-40). Gross emissions are reduced by CH_4 recovered and used at 51 mines, resulting in net emissions in 2022 of 6.3 MMT CO_2 Eq. (225 kt CH_4).

Table 3-39: CH_4 Emissions from Abandoned Coal Mines (MMT CO_2 Eq.)

Activity	1990	2005	2018	2019	2020	2021	2022
Abandoned Underground Mines	8.1	9.3	9.9	9.6	9.4	9.2	9.1
Recovered & Used	NO	(2.0)	(3.0)	(2.9)	(2.9)	(3.0)	(2.8)
Total	**8.1**	**7.4**	**6.9**	**6.6**	**6.5**	**6.3**	**6.3**

NO (Not Occurring)
Notes: Parentheses indicate negative values. Totals may not sum due to independent rounding.

Table 3-40: CH_4 Emissions from Abandoned Coal Mines (kt)

Activity	1990	2005	2018	2019	2020	2021	2022
Abandoned Underground Mines	288	334	355	341	335	330	324
Recovered & Used	NO	(70)	(107)	(104)	(103)	(106)	(100)
Total	**288**	**264**	**247**	**237**	**232**	**224**	**225**

NO (Not Occurring)
Note: Parentheses indicate negative values. Totals may not sum due to independent rounding.

Methodology and Time-Series Consistency

Estimating CH_4 emissions from an abandoned coal mine requires predicting the emissions of a mine from the time of abandonment through the inventory year of interest. The flow of CH_4 from the coal to the mine void is primarily dependent on the mine's emissions when active and the extent to which the mine is flooded or sealed. The CH_4 emission rate before abandonment reflects the gas content of the coal, the rate of coal mining, and the flow capacity of the mine in much the same way as the initial rate of a water-free conventional gas well reflects the gas content of the producing formation and the flow capacity of the well. A well or a mine that produces gas from a coal seam and the surrounding strata will produce less gas through time as the reservoir of gas is depleted. Depletion of a reservoir will follow a predictable pattern depending on the interplay of a variety of natural physical conditions imposed on the reservoir. The depletion of a reservoir is commonly modeled by mathematical equations and mapped as a type curve. Type curves, which are referred to as decline curves, have been developed for abandoned coal mines. Existing data on abandoned mine emissions through time, although sparse, appear to fit the hyperbolic type of decline curve used in forecasting production from natural gas wells.

There are sufficient mine level data available to establish decline curves for individual gassy mines abandoned since 1972. For mines abandoned prior to 1972, county level data are available. Mine status information (i.e., whether a mine is sealed, venting, or flooded) is not available for all the abandoned gassy mines. Therefore, a hybrid Tier 2/Tier 3 method was developed to model abandoned gassy mine emissions using Monte Carlo simulations. Tier 3 calculations are used for mines with known status information where decline curves can be used to directly estimate abandoned mine emissions. For mines with unknown status, a Tier 2 approach that estimates basin level emissions is used. This Tier 2 approach relies on data from other mines with known status

[68] A mine is considered a "gassy" mine if it emits more than 100 thousand cubic feet of CH_4 per day (100 Mcfd).

and located within the same basin as the unknown status mines. This approach is consistent with the IPCC 2006 Guidelines as underground mines can be considered point sources and measurement methods are available.

To estimate CH_4 emissions over time for a given abandoned mine, it is necessary to apply a decline function, initiated upon abandonment, to that mine. In the analysis, mines were grouped by coal basin with the assumption that they will generally have the same initial pressures, permeability, and isotherm. As CH_4 leaves the system, the reservoir pressure (Pr) declines as described by the isotherm's characteristics. The emission rate declines because the mine pressure (Pw) is essentially constant at atmospheric pressure for a vented mine, and the productivity index (PI), which is expressed as the flow rate per unit of pressure change, is essentially constant at the pressures of interest (atmospheric to 30 psia). The CH_4 flow rate is determined by the laws of gas flow through porous media, such as Darcy's Law. A rate-time equation can be generated that can be used to predict future emissions. This decline through time is hyperbolic in nature and can be empirically expressed as:

Equation 3-3: Decline Function to Estimate Venting Abandoned Mine Methane Emissions

$$q = q_i \left(1 + bD_i t\right)^{\left(-\frac{1}{b}\right)}$$

where,

q = Gas flow rate at time t in million cubic feet per day (mmcfd)

q_i = Initial gas flow rate at time zero (t_o), mmcfd

b = The hyperbolic exponent, dimensionless

D_i = Initial decline rate, 1/year

t = Elapsed time from t_o (years)

This equation is applied to mines of various initial emission rates that have similar initial pressures, permeability, and adsorption isotherms (EPA 2004).

The decline curves created to model the gas emission rate of coal mines must account for factors that decrease the rate of emissions after mining activities cease, such as sealing and flooding. Based on field measurement data, it was assumed that most U.S. mines prone to flooding will become completely flooded within eight years and therefore will no longer have any measurable CH_4 emissions. Based on this assumption, an average decline rate for flooded mines was established by fitting a decline curve to emissions from field measurements. An exponential equation was developed from emissions data measured at eight abandoned mines known to be filling with water located in two of the five basins. Using a least squares, curve-fitting algorithm, emissions data were matched to the exponential equation shown below. For this analysis of flooded abandoned mines, there was not enough data to establish basin-specific equations, as was done with the vented, non-flooding mines (EPA 2004). This decline through time can be empirically expressed as:

Equation 3-4: Decline Function to Estimate Flooded Abandoned Mine Methane Emissions

$$q = q_i e^{(-Dt)}$$

where,

q = Gas flow rate at time t in mmcfd

q_i = Initial gas flow rate at time zero (t_o), mmcfd

D = Decline rate, 1/year

t = Elapsed time from t_o (years)

Seals have an inhibiting effect on the rate of flow of CH_4 into the atmosphere compared to the flow rate that would exist if the mine had an open vent. The total volume emitted will be the same, but emissions will occur over a longer period of time. The methodology, therefore, treats the emissions prediction from a sealed mine similarly to the emissions prediction from a vented mine, but uses a lower initial rate depending on the degree of sealing. A

computational fluid dynamics simulator was used with the conceptual abandoned mine model to predict the decline curve for inhibited flow. The percent sealed is defined as 100 × (1 – [initial emissions from sealed mine / emission rate at abandonment prior to sealing]). Significant differences are seen between 50 percent, 80 percent, and 95 percent closure. These decline curves were therefore used as the high, middle, and low values for emissions from sealed mines (EPA 2004).

For active coal mines, those mines producing over 100 thousand cubic feet per day (Mcfd) of CH_4 account for about 98 percent of all CH_4 emissions. This same relationship is assumed for abandoned mines. It was determined that the 531 abandoned mines closed since 1972 produced CH_4 emissions greater than 100 Mcfd when active. Further, the status of 307 of the 531 mines (or 58 percent) is known to be either: 1) vented to the atmosphere; 2) sealed to some degree (either earthen or concrete seals); or 3) flooded (enough to inhibit CH_4 flow to the atmosphere). The remaining 42 percent of the mines whose status is unknown were placed in one of these three categories by applying a probability distribution analysis based on the known status of other mines located in the same coal basin (EPA 2004). Table 3-41 presents the count of mines by post-abandonment state, based on EPA's probability distribution analysis.

Table 3-41: Number of Gassy Abandoned Mines Present in U.S. Basins in 2022, Grouped by Class According to Post-Abandonment State

Basin	Sealed	Vented	Flooded	Total Known	Unknown	Total Mines
Central Appl.	43	25	50	118	144	262
Illinois	35	3	14	52	31	83
Northern Appl.	49	23	15	87	39	126
Warrior Basin	0	0	16	16	0	16
Western Basins	28	4	2	34	10	44
Total	**155**	**55**	**97**	**307**	**224**	**531**

Note: Totals may not sum due to independent rounding.

Inputs to the decline equation require the average CH_4 emission rate prior to abandonment and the date of abandonment. Generally, these data are available for mines abandoned after 1971; however, such data are largely unknown for mines closed before 1972. Information that is readily available, such as coal production by state and county, is helpful but does not provide enough data to directly employ the methodology used to calculate emissions from mines abandoned before 1972. It is assumed that pre-1972 mines are governed by the same physical, geologic, and hydrologic constraints that apply to post-1971 mines; thus, their emissions may be characterized by the same decline curves.

During the 1970s, 78 percent of CH_4 emissions from coal mining came from seventeen counties in seven states. Mine closure dates were obtained for two states, Colorado and Illinois, for the hundred-year period extending from 1900 through 1999. The data were used to establish a frequency of mine closure histogram (by decade) and applied to the other five states with gassy mine closures. As a result, basin-specific decline curve equations were applied to the 145 gassy coal mines estimated to have closed between 1920 and 1971 in the United States, representing 78 percent of the emissions. State-specific, initial emission rates were used based on average coal mine CH_4 emission rates during the 1970s (EPA 2004).

Abandoned mine emission estimates are based on all closed mines known to have active mine CH_4 ventilation emission rates greater than 100 Mcfd at the time of abandonment. For example, for 1990 the analysis included 145 mines closed before 1972 and 258 mines closed between 1972 and 1990. Initial emission rates based on MSHA reports, time of abandonment, and basin-specific decline curves influenced by a number of factors were used to calculate annual emissions for each mine in the database (MSHA 2023). Coal mine degasification data are not available for years prior to 1990, thus the initial emission rates used reflect only ventilation emissions for pre-1990 closures. Methane degasification amounts were added to the quantity of CH_4 vented to determine the total CH_4 liberation rate for all mines that closed between 1992 and 2022. Since the sample of gassy mines described above is assumed to account for 78 percent of the pre-1972 and 98 percent of the post-1971 abandoned mine emissions, the modeled results were multiplied by 1.22 and 1.02, respectively, to account for all U.S. abandoned mine emissions.

From 1993 through 2022, emission totals were downwardly adjusted to reflect CH_4 emissions avoided from abandoned mines with CH_4 recovery and use or destruction systems. Currently, there are 51 abandoned mines with recovery projects, including 11 projects at mines abandoned before 1972 (pre-1972 mines) (EPA 2004, CMOP 2022). Because CH_4 recovered by these projects is expected to decline with the age of the mine, CH_4 recovery is assumed to be the total estimated CH_4 liberated based on the mine's decline function except for three recovery projects where additional data are available (COGIS 2018, MSHA 2023).[69]

The *Inventory* totals were not adjusted for abandoned mine CH_4 emissions avoided from 1990 through 1992 due to unavailability of data. Avoided CH_4 emissions from pre-1972 abandoned mines are estimated by multiplying the total estimated emissions from these mines in each decade by the fraction of mines with recovery projects in that decade. For recovery projects at pre-1972 abandoned mines, four projects are at mines abandoned in the 1920s, three in the 1930s, two in the 1950s, and two in the 1960s (EPA 2004).

Reviewing Coalbed Methane Outreach Program data (CMOP 2023) revealed four additional recovery projects starting in 2021. In addition to reviewing CMOP data, the recovery project list was checked against the International Coal Mine Methane Database (GMI 2021). Of the 24 operational recovery projects for U.S. abandoned coal mines currently available in the GMI dataset, 18 are already included in the AMM model. The remaining six projects in the GMI dataset are for mines that are not yet abandoned according to MSHA records (MSHA 2023). Therefore, no new recovery projects were added from the GMI database for the 1990 through 2022 *Inventory*.

Uncertainty

A quantitative uncertainty analysis was conducted for the abandoned coal mine source category using the IPCC-recommended Approach 2 uncertainty estimation methodology. The uncertainty analysis provides for the specification of probability density functions for key variables within a computational structure that mirrors the calculation of the *Inventory* estimate. The results provide the range within which, with 95 percent certainty, emissions from this source category are likely to fall.

As discussed above, the parameters for which values must be estimated for each mine to predict its decline curve are: 1) the coal's adsorption isotherm; 2) CH_4 flow capacity as expressed by permeability; and 3) pressure at abandonment. Because these parameters are not available for each mine, a methodological approach to estimating emissions was used that generates a probability distribution of potential outcomes based on the most likely value and the probable range of values for each parameter. The range of values is not meant to capture the extreme values, but rather values that represent the highest and lowest quartile of the cumulative probability density function of each parameter. Once the low, mid, and high values are selected, they are applied to a probability density function.

The results of the Approach 2 quantitative uncertainty analysis are summarized in Table 3-42. Annual abandoned coal mine CH_4 emissions in 2022 were estimated to be between 5.0 and 7.5 MMT CO_2 Eq. at a 95 percent confidence level. This indicates a range of 21 percent below to 20 percent above the 2022 emission estimate of 6.3 MMT CO_2 Eq. One of the reasons for the relatively narrow range is that mine-specific data is available for use in the methodology for mines closed in 1972 and later years. Emissions from mines closed prior to 1972 have the largest degree of uncertainty because no mine-specific CH_4 liberation rates at the time of abandonment exist.

[69] Data from a state oil and gas database (COGIS) is used for one project and the mine status information from MSHA for two mines (sealed and flooded) indicate zero recovery emissions for these projects.

Table 3-42: Approach 2 Quantitative Uncertainty Estimates for CH_4 Emissions from Abandoned Underground Coal Mines (MMT CO_2 Eq. and Percent)

Source	Gas	2022 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Abandoned Underground Coal Mines	CH_4	6.3	5.0	7.5	-21%	+20%

[a] Range of emission estimates predicted by Monte Carlo Simulation for a 95 percent confidence interval.

QA/QC and Verification

In order to ensure the quality of the emission estimates for abandoned coal mines, general (IPCC Tier 1) and category-specific (Tier 2) Quality Assurance/Quality Control (QA/QC) procedures were implemented consistent with the U.S. Inventory QA/QC plan outlined in Annex 8. The Tier 2 procedures that were implemented involved checks specifically focusing on the activity data and reported emissions data used for estimating emissions from abandoned coal mines. Trends across the time series were analyzed to determine whether any corrective actions were needed.

Recalculations Discussion

Four new abandoned mine methane recovery projects were added to the AMM model during the current *Inventory* (CMOP 2023). CMOP data indicate these recovery projects were started in 2021. Time series recalculations were performed for 2021. As a result of recalculations, CH_4 emissions decreased by 2 percent in 2021, compared to the previous *Inventory*.

3.6 Petroleum Systems (CRT Source Category 1B2a)

This category (1B2a) is defined in the IPCC methodological guidance as fugitive emissions from petroleum systems, which per IPCC guidelines include emissions from leaks, venting, and flaring. Methane emissions from petroleum systems are primarily associated with onshore and offshore crude oil exploration, production, transportation, and refining operations. During these activities, CH_4 is released to the atmosphere as emissions from leaks, venting (including emissions from operational upsets), and flaring. Carbon dioxide emissions from petroleum systems are primarily associated with onshore and offshore crude oil production and refining operations. Note, CO_2 emissions in petroleum systems exclude all combustion emissions (e.g., engine combustion) except for flaring CO_2 emissions. All combustion CO_2 emissions (except for flaring) are accounted for in the fossil fuel combustion chapter (see Section 3.1). Emissions of N_2O from petroleum systems are primarily associated with flaring. Total greenhouse gas emissions (CH_4, CO_2, and N_2O) from petroleum systems in 2022 were 61.6 MMT CO_2 Eq., an increase of 4 percent from 1990, primarily due to increases in CO_2 emissions. Total emissions decreased by 6 percent from 2010 levels and have decreased by 15 percent since 2021. Total CO_2 emissions from petroleum systems in 2022 were 21.97 MMT CO_2 (21,967 kt CO_2), 2.3 times higher than in 1990. Total CO_2 emissions in 2022 were 1.6 times higher than in 2010 and 9 percent lower than in 2021. Total CH_4 emissions from petroleum systems in 2022 were 39.6 MMT CO_2 Eq. (1,415 kt CH_4), a decrease of 20 percent from 1990. Since 2010, total CH_4 emissions decreased by 24 percent; and since 2021, CH_4 emissions decreased by 19 percent. Total N_2O emissions from petroleum systems in 2022 were 0.048 MMT CO_2 Eq. (0.179 kt N_2O), 3.8 times higher than in 1990, 2.8 times higher than in 2010, and 142 percent higher than in 2021. Since 1990, U.S. oil production has increased by 56 percent. In 2022, U.S. oil production was 163 percent higher than in 2010 and 7 percent higher than in 2021.

Each year, some estimates in the *Inventory* are recalculated with improved methods and/or data. These improvements are implemented consistently across the entire *Inventory's* time series (i.e., 1990 to 2022) to ensure that the trend is representative of changes in emissions levels. Recalculations in petroleum systems in this year's *Inventory* include:

- Updates to oil and gas production volumes, produced water production volumes, and well counts using the most recent data from Enverus.
- Updates to oil and gas production volumes using the most recent data from the United States Energy Information Administration (EIA)
- Recalculations due to Greenhouse Gas Reporting Program (GHGRP) submission revisions
- Recalculations due to methodological updates to completions and workovers.

The Recalculations Discussion section below provides more details on the updated methods.

Exploration. Exploration includes well drilling, testing, and completions. Exploration accounts for less than 0.5 percent of total CH_4 emissions (including leaks, vents, and flaring) from petroleum systems in 2022. The predominant sources of CH_4 emissions from exploration are hydraulically fractured oil well completions. Other sources include well testing, well drilling, and well completions without hydraulic fracturing. Since 1990, exploration CH_4 emissions have decreased 96 percent, and while the number of hydraulically fractured wells completed increased 64 percent, there were decreases in the fraction of such completions without reduced emissions completions (RECs) or flaring. Emissions of CH_4 from exploration were highest in 2008, over 70 times higher than in 2022; and lowest in 2022. Emissions of CH_4 from exploration decreased 39 percent from 2021 to 2022, due to a decrease in emissions from hydraulically fractured oil well completions with RECs. Exploration accounts for 1 percent of total CO_2 emissions (including leaks, vents, and flaring) from petroleum systems in 2022. Emissions of CO_2 from exploration in 2022 were 25 percent lower than in 1990, and decreased by 50 percent from 2021, largely due to a decrease in emissions from hydraulically fractured oil well completions with REC and flaring (by 58 percent from 2021). Emissions of CO_2 from exploration were highest in 2014, over 13 times higher than in 2022. Exploration accounts for less than 0.5 percent of total N_2O emissions from petroleum systems in 2022. Emissions of N_2O from exploration in 2022 are 29 percent lower than in 1990, and 56 percent lower than in 2021, due to hydraulically fractured oil well completions with flaring.

Production. Production accounts for 97 percent of total CH_4 emissions (including leaks, vents, and flaring) from petroleum systems in 2022. The predominant sources of emissions from production field operations are pneumatic controllers, offshore oil platforms, equipment leaks, produced water, gas engines, chemical injection pumps, and associated gas flaring. In 2022, these seven sources together accounted for 93 percent of the CH_4 emissions from production. Since 1990, CH_4 emissions from production have decreased by 15 percent primarily due to decreases in emissions from offshore production. Overall, production segment CH_4 emissions decreased by 19 percent from 2021 levels due primarily to lower pneumatic controller emissions. Production emissions account for 86 percent of the total CO_2 emissions (including leaks, vents, and flaring) from petroleum systems in 2022. The principal sources of CO_2 emissions are associated gas flaring, miscellaneous production flaring, and oil tanks with flares. In 2022, these three sources together accounted for 96 percent of the CO_2 emissions from production. In 2022, CO_2 emissions from production were 3.1 times higher than in 1990, due to increases in flaring emissions from associated gas flaring, miscellaneous production flaring, and tanks. Overall, in 2022, production segment CO_2 emissions decreased by 8 percent from 2021 levels primarily due to decreases in associated gas flaring in the Williston Basin and oil tanks with flares. Production emissions accounted for 84 percent of the total N_2O emissions from petroleum systems in 2022. The principal sources of N_2O emissions are oil tanks with flares and associated gas flaring, accounting for 90% of N_2O emissions from the production segment in 2022. In 2022, N_2O emissions from production were 8.0 times higher than in 1990 and were 3.5 times higher than in 2021.

Crude Oil Transportation. Emissions from crude oil transportation account for a very small percentage of the total emissions (including leaks, vents, and flaring) from petroleum systems. Crude oil transportation activities account for 0.6 percent of total CH_4 emissions from petroleum systems. Emissions from tanks, marine loading, and truck loading operations accounted for 81 percent of CH_4 emissions from crude oil transportation in 2022. Since 1990,

CH_4 emissions from transportation have increased by 27 percent. In 2022, CH_4 emissions from transportation increased by 6 percent from 2021 levels. Crude oil transportation activities account for less than 0.01 percent of total CO_2 emissions from petroleum systems. Emissions from tanks, marine loading, and truck loading operations account for 81 percent of CO_2 emissions from crude oil transportation.

Crude Oil Refining. Crude oil refining processes and systems account for 2 percent of total fugitive (including leaks, vents, and flaring) CH_4 emissions from petroleum systems in 2022. This low share is because most of the CH_4 in crude oil is removed or escapes before the crude oil is delivered to the refineries. There is a negligible amount of CH_4 in all refined products. Within refineries, flaring accounts for 42 percent of the CH_4 emissions, while delayed cokers, uncontrolled blowdowns, and equipment leaks account for 19, 14 and 11 percent, respectively. Fugitive CH_4 emissions from refining of crude oil have decreased by 4 percent since 1990, and decreased by 3 percent from 2021; however, like the transportation subcategory, this increase has had little effect on the overall emissions of CH_4 from petroleum systems. Crude oil refining processes and systems account for 13 percent of total fugitive (including leaks, vents, and flaring) CO_2 emissions from petroleum systems. Of the total fugitive CO_2 emissions from refining, almost all (about 99 percent) of it comes from flaring.[70] Since 1990, refinery fugitive CO_2 emissions decreased by 10 percent and have decreased by 5 percent from 2021 levels, due to a decrease in flaring. Flaring occurring at crude oil refining processes and systems accounts for 16 percent of total fugitive N_2O emissions from petroleum systems. In 2022, refinery fugitive N_2O emissions increased by 4 percent since 1990 and decreased by 5 percent from 2021 levels.

Table 3-43: Total Greenhouse Gas Emissions (CO_2, CH_4, and N_2O) from Petroleum Systems (MMT CO_2 Eq.)

Activity	1990	2005	2018	2019	2020	2021	2022
Exploration	3.4	5.7	3.2	2.5	1.1	0.8	0.4
Production	51.6	48.1	86.7	90.6	77.3	68.0	57.4
Transportation	0.2	0.1	0.2	0.3	0.2	0.2	0.2
Crude Refining	3.9	4.4	3.7	4.4	3.6	3.7	3.6
Total	**59.0**	**58.5**	**93.8**	**97.8**	**82.3**	**72.8**	**61.6**

Note: Totals may not sum due to independent rounding.

Table 3-44: CH_4 Emissions from Petroleum Systems (MMT CO_2 Eq.)

Activity	1990	2005	2018	2019	2020	2021	2022
Exploration	**3.0**	**5.3**	**0.5**	**0.5**	**0.3**	**0.2**	**0.1**
Production	**45.5**	**42.0**	**57.5**	**50.6**	**52.0**	**47.5**	**38.6**
Pneumatic Controllers	21.3	22.7	34.7	24.7	31.3	28.1	19.4
Offshore Production	9.9	7.2	5.5	5.4	5.1	5.1	5.1
Equipment Leaks	2.3	2.8	3.7	3.9	3.2	3.2	3.1
Gas Engines	2.3	2.0	2.5	2.6	2.5	2.4	2.5
Produced Water	2.6	1.8	2.7	2.8	2.5	2.6	2.7
Chemical Injection Pumps	1.3	2.2	3.0	3.4	2.7	2.4	2.2
Assoc Gas Flaring	0.6	0.4	1.9	2.5	1.3	1.0	0.8
Other Sources	5.3	2.8	3.5	5.3	3.3	2.7	2.7
Crude Oil Transportation	**0.2**	**0.1**	**0.2**	**0.3**	**0.2**	**0.2**	**0.2**
Refining	**0.7**	**0.8**	**0.8**	**0.9**	**0.7**	**0.7**	**0.7**
Total	**49.4**	**48.2**	**59.0**	**52.2**	**53.3**	**48.6**	**39.6**

Note: Totals may not sum due to independent rounding.

[70] Petroleum Systems includes fugitive emissions (leaks, venting, and flaring). In many industries, including petroleum refineries, the largest source of onsite CO_2 emissions is often fossil fuel combustion, which is covered in Section 3.1 of this chapter.

Table 3-45: CH_4 Emissions from Petroleum Systems (kt CH_4)

Activity	1990	2005	2018	2019	2020	2021	2022
Exploration	**106**	**189**	**19**	**16**	**12**	**7**	**4**
Production	**1,626**	**1,500**	**2,052**	**1,809**	**1,858**	**1,696**	**1,377**
Pneumatic Controllers	761	811	1,240	881	1,119	1,003	694
Offshore Production	353	259	197	193	183	182	182
Equipment Leaks	82	101	132	138	115	114	112
Gas Engines	81	70	91	93	89	87	88
Produced Water	92	64	95	99	90	92	95
Chemical Injection Pumps	47	80	108	123	96	85	80
Assoc Gas Flaring	20	14	66	91	47	35	30
Other Sources	189	100	124	190	119	97	98
Crude Oil Transportation	**7**	**5**	**8**	**9**	**8**	**8**	**8**
Refining	**26**	**29**	**28**	**31**	**26**	**25**	**25**
Total	**1,765**	**1,723**	**2,108**	**1,865**	**1,904**	**1,737**	**1,415**

Note: Totals may not sum due to independent rounding.

Table 3-46: CO_2 Emissions from Petroleum Systems (MMT CO_2)

Activity	1990	2005	2018	2019	2020	2021	2022
Exploration	0.4	0.5	2.7	2.0	0.8	0.6	0.3
Production	6.0	6.1	29.2	39.9	25.2	20.5	18.8
Transportation	+	+	+	+	+	+	+
Crude Refining	3.2	3.6	2.9	3.6	2.9	3.0	2.9
Total	**9.6**	**10.2**	**34.8**	**45.5**	**28.9**	**24.1**	**22.0**

+ Does not exceed 0.05 MMT CO_2.

Note: Totals may not sum due to independent rounding.

Table 3-47: CO_2 Emissions from Petroleum Systems (kt CO_2)

Activity	1990	2005	2018	2019	2020	2021	2022
Exploration	398	465	2,684	2,044	798	601	300
Production	6,012	6,143	29,215	39,882	25,244	20,516	18,793
Transportation	0.9	0.7	1.2	1.3	1.2	1.1	1.2
Crude Refining	3,174	3,602	2,877	3,571	2,893	3,021	2,872
Total	**9,585**	**10,210**	**34,777**	**45,498**	**28,937**	**24,140**	**21,967**

Table 3-48: N_2O Emissions from Petroleum Systems (Metric Tons CO_2 Eq.)

Activity	1990	2005	2018	2019	2020	2021	2022
Exploration	180	209	1,161	820	353	290	127
Production	4,996	4,588	30,822	28,047	13,614	11,414	39,859
Transportation	NE	NE	NE	NE	NE	NE	NE
Crude Refining	7,262	8,243	7,405	9,312	7,575	7,920	7,523
Total	**12,438**	**13,040**	**39,387**	**38,180**	**21,542**	**19,624**	**47,510**

NE (Not Estimated)

Note: Totals may not sum due to independent rounding.

Table 3-49: N_2O Emissions from Petroleum Systems (Metric Tons N_2O)

Activity	1990	2005	2018	2019	2020	2021	2022
Exploration	0.7	0.8	4.4	3.1	1.3	1.1	0.5
Production	18.9	17.3	116.3	105.8	51.4	43.1	150.4
Transportation	NE	NE	NE	NE	NE	NE	NE
Crude Refining	27.4	31.1	27.9	35.1	28.6	29.9	28.4
Total	**46.9**	**49.2**	**148.6**	**144.1**	**81.3**	**74.1**	**179.3**

NE (Not Estimated)

Note: Totals may not sum due to independent rounding.

Methodology and Time-Series Consistency

See Annex 3.5 for the full time series of emissions data, activity data, emission factors, and additional information on methods and data sources.

Petroleum systems includes emission estimates for activities occurring in petroleum systems from the oil wellhead through crude oil refining, including activities for crude oil exploration, production field operations, crude oil transportation activities, and refining operations. Generally, emissions are estimated for each activity by multiplying emission factors (e.g., emission rate per equipment or per activity) by corresponding activity data (e.g., equipment count or frequency of activity). Certain sources within petroleum refineries are developed using an IPCC Tier 3 approach (i.e., all refineries in the nation report facility-level emissions data to the GHGRP, which are included directly in the national emissions estimates here). Other estimates are developed with a Tier 2 approach. Tier 1 approaches are not used.

EPA did not receive stakeholder feedback on updates in the *Inventory* through EPA's stakeholder process on oil and gas in the *Inventory*. More information on the stakeholder process can be found online.[71]

Emission Factors. Key references for emission factors include *Methane Emissions from the Natural Gas Industry by the Gas Research Institute and EPA* (GRI/EPA 1996), *Estimates of Methane Emissions from the U.S. Oil Industry* (EPA 1999), *Compilation of Air Pollutant Emission Factors, AP-42* (EPA 1997), *Global Emissions of Methane from Petroleum Sources* (API 1992), consensus of industry peer review panels, Bureau of Ocean Energy Management (BOEM) reports, *Nonpoint Oil and Gas Emission Estimation Tool* (EPA 2017), and analysis of GHGRP data (EPA 2023).

Emission factors for hydraulically fractured (HF) oil well completions and workovers (in four control categories) were developed at the basin level using EPA's GHGRP data; year-specific data were used to calculate basin-specific emission factors from 2016-forward and the year 2016 emission factors were applied to all prior years in the time series. For basins not reporting to the GHGRP, Subpart W average emission factors were used. For more information, please see the 2023 memoranda available online.[72]

The emission factors for well testing and associated gas venting and flaring were developed using year-specific GHGRP data for years 2015 forward; earlier years in the time series use 2015 emission factors. For miscellaneous production flaring, year-specific emission factors were developed for years 2015 forward from GHGRP data, an emission factor of 0 (assumption of no flaring) was assumed for 1990 through 1992, and linear interpolation was applied to develop emission factors for 1993 through 2014. For more information, please see memoranda available online.[73] For offshore oil production, emission factors were calculated using BOEM data for offshore facilities in federal waters of the Gulf of Mexico (and these data were also applied to facilities located in state waters of the Gulf of Mexico) and GHGRP data for offshore facilities off the coasts of California and Alaska. For

[71] See https://www.epa.gov/ghgemissions/natural-gas-and-petroleum-systems.

[72] See https://www.epa.gov/ghgemissions/natural-gas-and-petroleum-systems.

[73] See https://www.epa.gov/ghgemissions/natural-gas-and-petroleum-systems.

many other sources, emission factors were held constant for the period 1990 through 2022, and trends in emissions reflect changes in activity levels. Emission factors from EPA 1999 are used for all other production and transportation activities.

For associated gas venting and flaring and miscellaneous production flaring, emission factors were developed on a production basis (i.e., emissions per unit oil produced). Additionally, for these two sources, basin-specific activity and emission factors were developed for each basin that in any year from 2011 forward contributed at least 10 percent of total source emissions (on a CO_2 Eq. basis) in the GHGRP. For associated gas venting and flaring, basin-specific factors were developed for four basins: Williston, Permian, Gulf Coast, and Anadarko. For miscellaneous production flaring, basin-specific factors were developed for three basins: Williston, Permian, and Gulf Coast. For each source, data from all other basins were combined, and activity and emission factors were developed for the other basins as a single group.

For pneumatic controllers and tanks, basin-specific emission factors were calculated for all the basins reporting to the GHGRP. These emission factors were calculated for all the years with applicable GHGRP data (i.e., 2011 - 2022 or 2015 - 2022). For the remaining basins (i.e., basins not reporting to the GHGRP), Subpart W average emission factors were used. For more information, please see memoranda available online.[3]

For the exploration and production segments, in general, CO_2 emissions for each source were estimated with GHGRP data or by multiplying CO_2 content factors by the corresponding CH_4 data, as the CO_2 content of gas relates to its CH_4 content. Sources with CO_2 emission estimates calculated using GHGRP data include HF completions and workovers, associated gas venting and flaring, tanks, well testing, pneumatic controllers, chemical injection pumps, miscellaneous production flaring, and certain offshore production facilities (those located off the coasts of California and Alaska). For these sources, CO_2 was calculated using the same methods as used for CH_4. Carbon dioxide emission factors for offshore oil production in the Gulf of Mexico were derived using data from BOEM, following the same methods as used for CH_4 estimates. For other sources, the production field operations emission factors for CO_2 are generally estimated by multiplying the CH_4 emission factors by a conversion factor, which is the ratio of CO_2 content and CH_4 content in produced associated gas.

For the exploration and production segments, N_2O emissions were estimated for flaring sources using GHGRP or BOEM OGOR-B data and the same method used for CO_2. Sources with N_2O emissions in the exploration segment include well testing and HF completions with flaring. Sources with N_2O emissions in the production segment include associated gas flaring, tank flaring, miscellaneous production flaring, HF workovers with flaring, and flaring from offshore production sources.

For crude oil transportation, emission factors for CH_4 were largely developed using data from EPA (1997), API (1992), and EPA (1999). Emission factors for CO_2 were estimated by multiplying the CH_4 emission factors by a conversion factor, which is the ratio of CO_2 content and CH_4 content in whole crude post-separator.

For petroleum refining activities, year-specific emissions from 2010 forward were directly obtained from EPA's GHGRP. All U.S. refineries have been required to report CH_4, CO_2, and N_2O emissions for all major activities starting with emissions that occurred in 2010. The reported total CH_4, CO_2, and N_2O emissions for each activity was used for the emissions in each year from 2010 forward. To estimate emissions for 1990 to 2009, the 2010 to 2013 emissions data from GHGRP along with the refinery feed data for 2010 to 2013 were used to derive CH_4 and CO_2 emission factors (i.e., sum of activity emissions/sum of refinery feed) and 2010 to 2017 data were used to derive N_2O emission factors; these emission factors were then applied to the annual refinery feed in years 1990 to 2009. GHGRP delayed coker CH_4 emissions for 2010 through 2017 were increased using the ratio of certain reported emissions for 2018 to 2017, to account for a more accurate GHGRP calculation methodology that was implemented starting in reporting year 2018.

A complete list of references for emission factors and activity data by emission source is provided in Annex 3.5.

Activity Data. References for activity data include Enverus data (Enverus 2023), Energy Information Administration (EIA) reports, *Methane Emissions from the Natural Gas Industry by the Gas Research Institute and EPA* (EPA/GRI 1996), *Estimates of Methane Emissions from the U.S. Oil Industry* (EPA 1999), consensus of industry peer review panels, BOEM reports, the Oil & Gas Journal, the Interstate Oil and Gas Compact Commission, the United States Army Corps of Engineers, and analysis of GHGRP data (EPA 2023).

For HF oil well completions and workovers, pneumatic controllers, equipment leaks, chemical injection pumps, and tanks, basin-specific activity factors were calculated for all the basins reporting to the GHGRP. These factors were calculated for all the years with applicable GHGRP data (i.e., 2011 through 2022, 2016 through 2022, or 2015 through 2022). For the remaining basins (i.e., basins not reporting to the GHGRP), GHGRP average activity factors were used. For more information, please see memoranda available online.[74]

For many sources, complete activity data were not available for all years of the time series. In such cases, one of three approaches was employed to estimate values, consistent with IPCC good practice. Where appropriate, the activity data were calculated from related statistics using ratios developed based on EPA/GRI (1996) and/or GHGRP data. In some cases, activity data are developed by interpolating between recent data points (such as from GHGRP) and earlier data points, such as from EPA/GRI (1996). Lastly, in limited instances the previous year's data were used if current year data were not yet available.

A complete list of references for emission factors and activity data by emission source is provided in Annex 3.5. The United States reports data to the UNFCCC using this *Inventory* report along with Common Reporting Tables (CRTs). This note is provided for those reviewing the CRTs: The notation key "IE" is used for CO_2 and CH_4 emissions from venting and flaring in CRT 1.B.2. Disaggregating flaring and venting estimates across the Inventory would involve the application of assumptions and could result in inconsistent reporting and, potentially, decreased transparency. Data availability varies across segments within oil and gas activities systems, and emission factor data available for activities that include flaring can include emissions from multiple sources (flaring, venting and leaks).

As noted above, EPA's GHGRP data, available starting in 2010 for refineries and in 2011 for other sources, have improved estimates of emissions from petroleum systems. Many of the previously available datasets were collected in the 1990s. To develop a consistent time series for sources with new data, EPA reviewed available information on factors that may have resulted in changes over the time series (e.g., regulations, voluntary actions) and requested stakeholder feedback on trends as well. For most sources, EPA developed annual data for 1993 through 2009 or 2014 by interpolating activity data or emission factors or both between 1992 (when GRI/EPA data are available) and 2010 or 2015 data points. Information on time-series consistency for sources updated in this year's *Inventory* can be found in the Recalculations Discussion below, with additional detail provided in supporting memos (relevant memos are cited in the Recalculations Discussion). For information on other sources, please see the Methodology and Time-Series Consistency discussion above and Annex 3.5.

Methodological recalculations were applied to the entire time series to ensure time-series consistency from 1990 through 2022.

Uncertainty

EPA conducted a quantitative uncertainty analysis using the IPCC Approach 2 methodology (Monte Carlo Simulation technique) to characterize uncertainty for petroleum systems. For more information on the approach, please see the memoranda *Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-2016: Natural Gas and Petroleum Systems Uncertainty Estimates* (*2018 uncertainty memo)* and *Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-2019: Update for Natural Gas and Petroleum Systems CO_2 Uncertainty Estimates (2021 uncertainty memo)*.[75]

EPA used Microsoft Excel's @RISK add-in tool to estimate the 95 percent confidence bound around CH_4 and CO_2 emissions from petroleum systems for the current *Inventory*. For the CH_4 uncertainty analysis, EPA focused on the eight highest methane-emitting sources for the year 2022, which together emitted 75 percent of methane from petroleum systems in 2022, and extrapolated the estimated uncertainty for the remaining sources. For the CO_2 uncertainty analysis, EPA focused on the five highest-emitting sources for the year 2022 which together emitted 81 percent of CO_2 from petroleum systems in 2022, and extrapolated the estimated uncertainty for the remaining

[74] See https://www.epa.gov/ghgemissions/natural-gas-and-petroleum-systems.

[75] See https://www.epa.gov/ghgemissions/natural-gas-and-petroleum-systems.

sources. The @RISK add-in provides for the specification of probability density functions (PDFs) for key variables within a computational structure that mirrors the calculation of the inventory estimate. For emission factors that are derived from methane emissions measurement studies, the PDFs are commonly determined to be lognormally distributed (GRI/EPA 1996; EPA 1999). For activity data that are derived from national datasets, the PDFs are set to a uniform distribution (see 2018 and 2021 uncertainty memos). Many emission factors and activity factors are calculated using subpart W data, and for these, the @RISK add-in determines the best fitting PDF (e.g., lognormal, gaussian), based on bootstrapping of the underlying data (see 2018 and 2021 uncertainty memos). The IPCC guidance notes that in using this Approach 2 method, "some uncertainties that are not addressed by statistical means may exist, including those arising from omissions or double counting, or other conceptual errors, or from incomplete understanding of the processes that may lead to inaccuracies in estimates developed from models." As a result, the understanding of the uncertainty of emission estimates for this category evolves and improves as the underlying methodologies and datasets improve. The uncertainty bounds reported below only reflect those uncertainties that EPA has been able to quantify and do not incorporate considerations such as modeling uncertainty, data representativeness, measurement errors, misreporting or misclassification. To estimate uncertainty for N_2O, EPA applied the uncertainty bounds calculated for CO_2. EPA will seek to refine this estimate in future *Inventories*.

The results presented below provide the 95 percent confidence bound within which actual emissions from this source category are likely to fall for the year 2022, using the recommended IPCC methodology. The results of the Approach 2 uncertainty analysis are summarized in Table 3-50. Petroleum systems CH_4 emissions in 2022 were estimated to be between 32.7 and 48.6 MMT CO_2 Eq., while CO_2 emissions were estimated to be between 17.9 and 27.4 MMT CO_2 Eq. at a 95 percent confidence level. Petroleum systems N_2O emissions in 2022 were estimated to be between 0.039 and 0.059 MMT CO_2 Eq. at a 95 percent confidence level.

Uncertainty bounds for other years of the time series have not been calculated, but uncertainty is expected to vary over the time series. For example, years where many emission sources are calculated with interpolated data would likely have higher uncertainty than years with predominantly year-specific data. In addition, the emission sources that contribute the most to CH_4 and CO_2 emissions are different over the time series, particularly when comparing recent years to early years in the time series. For example, associated gas venting emissions were higher and flaring emissions were lower in early years of the time series, compared to recent years. Technologies also changed over the time series (e.g., reduced emissions completions were not used early in the time series).

Table 3-50: Approach 2 Quantitative Uncertainty Estimates for CH_4 and CO_2 Emissions from Petroleum Systems (MMT CO_2 Eq. and Percent)

Source	Gas	2022 Emission Estimate (MMT CO_2 Eq.)[b]	Uncertainty Range Relative to Emission Estimate[a] (MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Petroleum Systems	CH_4	39.6	32.7	48.6	-18%	+23%
Petroleum Systems	CO_2	22.0	17.9	27.4	-19%	+25%
Petroleum Systems	N_2O	0.048	0.039	0.059	-19%	+25%

[a] Range of emission estimates estimated by applying the 95 percent confidence intervals obtained from the Monte Carlo Simulation analysis conducted for the year 2022 CH_4 and CO_2 emissions.

[b] All reported values are rounded after calculation. As a result, lower and upper bounds may not be duplicable from other rounded values as shown in table.

QA/QC and Verification Discussion

In order to ensure the quality of the emission estimates for petroleum systems, general (IPCC Tier 1) Quality Assurance/Quality Control (QA/QC) procedures were implemented consistent with the U.S. Inventory QA/QC plan outlined in Annex 8.

The petroleum systems emission estimates in the *Inventory* are continually being reviewed and assessed to determine whether emission factors and activity factors accurately reflect current industry practices. A QA/QC analysis was performed for data gathering and input, documentation, and calculation. QA/QC checks are consistently conducted to minimize human error in the emission calculations. EPA performs a thorough review of information associated with new studies, GHGRP data, regulations, public webcasts, and the Natural Gas STAR Program to assess whether the assumptions in the *Inventory* are consistent with current industry practices. EPA has a multi-step data verification process for GHGRP data, including automatic checks during data-entry, statistical analyses on completed reports, and staff review of the reported data. Based on the results of the verification process, EPA follows up with facilities to resolve mistakes that may have occurred.[76]

As in previous years, EPA conducted early engagement and communication with stakeholders on updates prior to public review of the current *Inventory*. EPA held a stakeholder webinar on greenhouse gas data for oil and gas in October of 2023. EPA released memos detailing updates under consideration and requesting stakeholder feedback. EPA did not receive stakeholder feedback for the updates under consideration for the current *Inventory*.

In recent years, several studies have measured emissions at the source level and at the national or regional level and calculated emission estimates that may differ from the *Inventory*. There are a variety of potential uses of data from new studies, including replacing a previous estimate or factor, verifying or QA of an existing estimate or factor, and identifying areas for updates. In general, there are two major types of studies related to oil and gas greenhouse gas data: studies that focus on measurement or quantification of emissions from specific activities, processes, and equipment, and studies that use tools such as inverse modeling to estimate the level of overall emissions needed to account for measured atmospheric concentrations of greenhouse gases at various scales. The first type of study can lead to direct improvements to or verification of *Inventory* estimates. In the past few years, EPA has reviewed, and in many cases, incorporated data from these data sources. The second type of study can provide general indications on potential over- and under-estimates.

A key challenge in using these types of studies to assess *Inventory* results is having a relevant basis for comparison (e.g., the two data sets should have comparable time frames and geographic coverage, and the independent study should assess data from the *Inventory* and not another data set, such as the Emissions Database for Global Atmospheric Research, or "EDGAR"). In an effort to improve the ability to compare the national-level *Inventory* with measurement results that may be at other spatial and temporal scales, EPA has developed a gridded inventory of U.S. anthropogenic methane emissions with 0.1 degree x 0.1 degree spatial resolution, monthly temporal resolution, and detailed scale-dependent error characterization.[77] The most recent version of the gridded methane inventory is designed to be consistent with the U.S. EPA's *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2018* estimates for the years 2012 through 2018. The gridded inventory improves efforts to compare results of this *Inventory* with atmospheric studies.

As discussed above, refinery emissions are quantified by using the total emissions reported to GHGRP for the refinery emission categories included in petroleum systems. Subpart Y has provisions that refineries are not required to report under Subpart Y if their emissions fall below certain thresholds. Each year, a review is conducted to determine whether an adjustment is needed to the Inventory emissions to include emissions from refineries that stopped reporting to the GHGRP. Based on the review of the most recent GHGRP data, EPA did not identify any additional refineries that would require gap filling. There are a total of 7 refineries that EPA previously identified (i.e., during the 1990 through 2021 *Inventory* and prior versions) as not reporting to the GHGRP and continued to gap fill annual emissions for these refineries. EPA used the last reported emissions (by source) for these refineries as proxy to gap fill annual emissions.

[76] See https://www.epa.gov/sites/production/files/2015-07/documents/ghgrp_verification_factsheet.pdf.

[77] See https://www.epa.gov/ghgemissions/us-gridded-methane-emissions.

Recalculations Discussion

EPA received information and data related to the emission estimates through GHGRP reporting and presented information to stakeholders regarding the updates under consideration. In November 2023, EPA released draft memoranda that discussed changes under consideration and requested stakeholder feedback on those changes. EPA then released final memoranda documenting the methodology implemented in the current Inventory.[78] The memorandum cited in the Recalculations Discussion below is: Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-2022: Updates for Completion and Workover Emissions (*Completions and Workovers* memo).

EPA evaluated relevant information available and made an updates to the *Inventory* for hydraulically fractured (HF) oil well completions and workovers. General information for these source specific recalculations are presented below and details are available in the *Completions and Workovers* memo.

In addition to the updates to the sources mentioned above, for certain sources, CH_4 and/or CO_2 emissions changed by greater than 0.05 MMT CO_2 Eq., comparing the previous estimate for 2021 to the current (recalculated) estimate for 2021. The emissions changes were mostly due to GHGRP data submission revisions. These sources are discussed below and include associated gas flaring, miscellaneous production flaring, pneumatic controllers, oil tanks, chemical injection pumps, produced water, offshore production (in Gulf of Mexico federal waters), gas engines, and refinery flaring.

The combined impact of revisions to 2021 petroleum systems CH_4 emission estimates on a CO_2-equivalent basis, compared to the previous *Inventory*, is a decrease from 50.2 to 48.6 MMT CO_2 Eq. (1.5 MMT CO_2 Eq., or 3 percent). The recalculations resulted in lower CH_4 emission estimates on average across the 1990 through 2021 time series, compared to the previous *Inventory*, by 2.5 MMT CO_2 Eq., or 5 percent.

The combined impact of revisions to 2021 petroleum systems CO_2 emission estimates, compared to the previous *Inventory*, is a decrease from 24.7 to 24.1 MMT CO_2 (0.5 MMT CO_2, or 2 percent). The recalculations resulted in lower emission estimates on average across the 1990 through 2021 time series, compared to the previous *Inventory*, by 0.1 MMT CO_2 Eq., or 0.2 percent.

The combined impact of revisions to 2021 petroleum systems N_2O emission estimates on a CO_2-equivalent basis, compared to the previous *Inventory*, is a decrease of 0.002 MMT CO_2, Eq. or 10.2 percent. The recalculations resulted in an average decrease in emission estimates across the 1990 through 2021 time series, compared to the previous *Inventory*, of 0.001 MMT CO_2 Eq., or 7.4 percent.

In Table 3-51 and Table 3-52 below are categories in petroleum systems with updated methodologies or with recalculations resulting in a change of greater than 0.05 MMT CO_2 Eq., comparing the previous estimate for 2021 to the current (recalculated) estimate for 2021. For more information, please see the discussion below.

Table 3-51: Recalculations of CO_2 in Petroleum Systems (MMT CO_2)

Segment/Source	*Previous Estimate Year 2021, 2023 Inventory*	Current Estimate Year 2021, 2024 *Inventory*	Current Estimate Year 2022, 2024 *Inventory*
Exploration	***0.5***	**0.6**	**0.3**
HF Completions	*0.5*	0.6	0.3
Production	***20.0***	**20.5**	**18.8**
Tanks	*5.4*	5.6	4.5
HF Workovers	*0.2*	+	+
Pneumatic Controllers	*0.1*	0.1	0.1
Equipment Leaks	*+*	+	+
Chemical Injection Pumps	*+*	+	+

[78] Stakeholder materials including draft and final memoranda for the current (i.e., 1990 to 2022) *Inventory* are available at https://www.epa.gov/ghgemissions/natural-gas-and-petroleum-systems.

Miscellaneous Production Flaring	*4.2*	4.6	5.0
Transportation	***+***	**+**	**+**
Refining	***4.2***	**3.0**	**2.9**
Flares	*4.2*	3.0	2.8
Petroleum Systems Total	***24.7***	**24.1**	**22.0**

+ Does not exceed 0.05 MMT CO_2 Eq.

Note: Totals may not sum due to independent rounding.

Table 3-52: Recalculations of CH_4 in Petroleum Systems (MMT CO_2 Eq.)

Segment/Source	*Previous Estimate Year 2021, 2023 Inventory*	Current Estimate Year 2021, 2024 *Inventory*	Current Estimate Year 2022, 2024 *Inventory*
Exploration	***0.2***	**0.2**	**0.1**
HF Completions	*0.1*	0.2	0.1
Production	***48.9***	**47.5**	**38.6**
Pneumatic Controllers	*28.4*	28.1	19.4
Chemical Injection Pumps	*3.2*	2.4	2.2
Produced Water	*2.5*	2.6	2.7
Offshore Production from GOM Federal Waters (vented and leaks)	*4.7*	4.4	4.3
HF Workovers	*0.1*	+	+
Gas Engines	*2.5*	2.4	2.5
Associated Gas Flaring	*0.8*	1.0	0.8
Transportation	***0.2***	**0.2**	**0.2**
Refining	***0.8***	**0.7**	**0.7**
Petroleum Systems Total	***50.2***	**48.6**	**39.6**

+ Does not exceed 0.05 MMT CO_2 Eq.

Note: Totals may not sum due to independent rounding.

Exploration

HF Completions (Methodological Update)

EPA updated the calculation methodology for HF completions to use basin-level HF completion counts from Enverus and basin-specific activity factors and emission factors calculated from Subpart W data for each control category (i.e., non-reduced emission completion (REC) with venting, non-REC with flaring, REC with venting, REC with flaring). Previously, national annual average activity and emission factors calculated using Subpart W data were applied to national activity data counts to estimate HF gas well completion emissions. In this update, EPA developed national emission estimates by summing calculated basin-level total emission estimates. The *Completions and Workovers* memo presents additional information and considerations for this update.

EPA calculated basin-specific activity factors and CH_4 and CO_2 emission factors for all basins that reported Subpart W data. The factors were year-specific for reporting year (RY) 2011 (first year of GHGRP data for this source) through RY2022. For basin-level HF completion event counts, EPA used Enverus data for 1990 to 2010 and Subpart W for 2011 forward. For the fraction of completions in each control subcategory, EPA retained the previous *Inventory's* assumption that all HF gas well completions were non-REC for 1990 to 2000. The previous *Inventory* also assumed that 10 percent of HF completions were non-REC with flaring from 1990 to 2010 (based on national Subpart W data for RY2011 and RY2012); EPA updated this value using basin-specific Subpart W data for RY2011 and RY2012. For 2011 to 2022, EPA determined the percent contribution of each control category directly from Subpart W data and used linear interpolation between 2000 and 2011 to determine the percent of gas wells with RECs. EPA developed year- and basin-specific Subpart W EFs for 2011 forward. Year 2011 emission factors were applied to all prior years for each basin. For basins without Subpart W data available, EPA applied national average activity and emission factors (unweighted average of all Subpart W reported data).

Comparing the final completion emissions and those presented at the October 2023 webinar and in the November 2023 *Completions and Workovers* memo, the final estimates are higher for certain completion categories. These emissions increases are due not to the basin-level methodology changes discussed here but rather to changes in the Enverus dataset. EPA applied the same data processing steps to Enverus data in the fall of 2023 as it did for the previous Enverus data analysis (conducted in 2021) and data changes led to many more completions being classified as HF completions.

As a result of this methodological update, CH_4 emissions estimates are on average 10 percent lower across the time series than in the previous *Inventory*. The 2021 CH_4 emissions estimate is 41 percent higher than in the previous *Inventory*. The largest increase in the CH_4 emissions estimates compared to the previous *Inventory* is 42 percent in 2016, and the largest decrease is 35 percent in 1999. The decrease in CH_4 emissions is predominantly due to HF completions that were non-REC with venting. Basins such as the Permian basin (basin 430), Williston basin (basin 395), and Denver basin (basin 540) had a high number of HF oil well completion events over the time series. However, they had low EFs for non-REC with venting, decreasing the overall CH_4 emissions. The update resulted in CO_2 emissions estimates that are on average 33 percent higher across the time series than in the previous *Inventory*. The 2021 CO_2 emissions estimate is 29 percent higher than in the previous *Inventory*. The largest increase in CO_2 emissions estimates compared to the previous *Inventory* is 80 percent in 2000, and the largest decrease is 17 percent in 2018. The increase in CO_2 emissions is due to HF completions that were non-REC with flaring and REC with flaring. The Permian basin (basin 430) had the highest emissions across the time series for completions that were non-REC with flaring and REC with flaring. The Permian basin had the highest number of HF oil well completions and high EFs for both control categories.

Table 3-53: HF Completions National CH_4 Emissions (Metric Tons CH_4)

Source	1990	2005	2018	2019	2020	2021	2022
HF Completions – Non-REC with Venting	95,717	179,290	380	1,126	845	244	509
HF Completions – Non-REC with Flaring	898	1,190	2,797	2,801	1,989	1,272	1,269
HF Completions - REC with Venting	NO	NO	5,478	5,466	6,212	1,114	912
HF Completions - REC with Flaring	NO	NO	9,637	6,188	1,945	3,620	685
Total Emissions	**96,615**	**180,480**	**18,292**	**15,581**	**10,992**	**6,250**	**3,375**
Previous Estimate	*143,304*	*202,773*	*18,090*	*14,864*	*10,568*	*4,430*	*NA*

NO (Not Occurring)
NA (Not Applicable)
Note: Totals may not sum due to independent rounding.

Table 3-54: HF Completions National CO_2 Emissions (kt CO_2)

Source	1990	2005	2018	2019	2020	2021	2022
HF Completions – Non-REC with Venting	3	4	+	+	+	+	+
HF Completions – Non-REC with Flaring	155	240	485	762	355	262	131
HF Completions - REC with Venting	NO	NO	+	+	+	+	+
HF Completions - REC with Flaring	NO	NO	2,165	1,278	441	338	141
Total Emissions	**157**	**244**	**2,651**	**2,041**	**797**	**601**	**272**
Previous Estimate	*119*	*168*	*3,174*	*2,431*	*836*	*466*	*NA*

+ Does not exceed 0.5 kt.
NO (Not Occurring)
NA (Not Applicable)
Note: Totals may not sum due to independent rounding.

Production

HF Workovers (Methodological Update)

EPA updated the activity data source and calculation methodology for HF workovers to use basin-specific activity factors and emission factors, calculated from Subpart W data for each control category (i.e., non-reduced emission completion (REC) with venting, non-REC with flaring, REC with venting, REC with flaring). Previously, national HF workover counts calculated using analyses for NSPS OOOO (i.e., 1 percent of HF oil wells were worked over annually) and national annual average emission factors calculated using Subpart W data were applied to estimate HF oil well workover emissions. In this update, EPA developed national emission estimates by summing calculated basin-level total emission estimates. The *Completions and Workovers* memo presents additional information and considerations for this update.

EPA calculated basin-specific activity factors (AFs) and CH_4 and CO_2 emission factors for all basins that reported Subpart W data. For basin-level workover counts, instead of applying a 1 percent workover rate to HF oil wells, EPA developed year- and basin-specific Subpart W AFs for 2016 (the first year of GHGRP data for this source) forward that represent the number of HF workovers per oil well. Year 2016 Subpart W AFs were applied to all prior years for each basin. For the fraction of workovers in each control subcategory, EPA retained the previous *Inventory's* assumption that all HF oil well workovers were non-REC for 1990 to 2007 and 10 percent flaring from 1990 to 2007. For 2016 to 2022, EPA determined the percent contribution of each control category directly from Subpart W data at the basin level and used linear interpolation between 2008 and 2015 to determine the percent of oil wells with RECs and the percent flaring. EPA developed year- and basin-specific Subpart W EFs for 2016 forward. Year 2016 emission factors were applied to all prior years for each basin. For basins without Subpart W data available, EPA applied national average activity and emission factors (unweighted average of all Subpart W reported data).

As a result of this methodological update, CH_4 emissions estimates are on average 62 percent lower across the time series than in the previous *Inventory*. The largest decrease in CH_4 emissions estimates compared to the previous *Inventory* is 97 percent in 2021 and the smallest decrease is 39 percent in 2018. The 2021 CH_4 emissions estimate is 97 percent lower than in the previous *Inventory*. The update resulted in CO_2 emissions estimates that are on average 51 percent lower than in the previous *Inventory*. The 2021 CO_2 emissions estimate is 97 percent lower than in the previous *Inventory*. The largest decrease in CO_2 emissions estimates compared to the previous *Inventory* is 97 percent in 2021 and the smallest decrease is 26 percent in 1990. The decrease in emissions for both CH_4 and CO_2 was primarily due to the change in calculation method for workover counts. HF oil well workover counts decreased by an average of 52 percent across the 1990 to 2021 time series compared to the previous *Inventory*.

Table 3-55: HF Workovers National CH_4 Emissions (Metric Tons CH_4)

Source	1990	2005	2018	2019	2020	2021	2022
HF Workovers – Non-REC with Venting	17,639	16,244	87	1,339	5	16	35
HF Workovers – Non-REC with Flaring	104	96	11	7	11	20	NO
HF Workovers - REC with Venting	NO	NO	1,304	331	130	5	63
HF Workovers - REC with Flaring	NO	NO	222	75	14	19	33
Total Emissions	**17,744**	**16,340**	**1,623**	**1,753**	**160**	**60**	**130**
Previous Estimate	*37,696*	*41,993*	*2,670*	*3,679*	*3,873*	*2,151*	*NA*

NO (Not Occurring)
NA (Not Applicable)
Note: Totals may not sum due to independent rounding.

Table 3-56: HF Workovers National CO_2 Emissions (Metric Tons CO_2)

Source	1990	2005	2018	2019	2020	2021	2022
HF Workovers – Non-REC with Venting	431	408	5	63	+	1	6
HF Workovers – Non-REC with Flaring	22,654	21,076	2,544	2,093	1,947	2,532	NO

HF Workovers - REC with Venting	NO	NO	17	14	4	+	3
HF Workovers - REC with Flaring	NO	NO	51,135	18,285	5,987	2,768	6,095
Total Emissions	**23,085**	**21,484**	**53,701**	**20,456**	**7,939**	**5,301**	**6,105**
Previous Estimate	*31,219*	*34,778*	*89,049*	*97,515*	*97,766*	*205,160*	*NA*

+ Does not exceed 0.5 MT.
NO (Not Occurring)
NA (Not Applicable)
Note: Totals may not sum due to independent rounding.

Pneumatic Controllers (Methodological Update)

In the previous *Inventory*, EPA updated the CH_4 emissions calculation methodology for pneumatic controllers to use basin-specific activity factors and emission factors by bleed type (i.e., low, high, intermittent bleed) from GHGRP data. However, the CO_2 emissions calculation methodology was not updated and instead the previous *Inventory* still relied on a national-level methodology to estimate CO_2 emissions. For this year's *Inventory*, EPA calculated pneumatic controller CO_2 emissions using basin-specific emissions data such that the CO_2 emissions reflect the unique CO_2 composition of the gas in a basin.

The update for pneumatic controller CO_2 emission estimates resulted in an average increase of 61 percent across the time series and an increase of 57 percent in 2021, compared to the previous *Inventory*.

In addition, methane emissions for pneumatic controllers were impacted due to recalculations with updated data. Methane emissions from onshore production pneumatic controllers are an average of 2 percent lower across the time series and 1 percent lower in 2021, compared to the previous *Inventory*. The emission changes were due to GHGRP data submission revisions.

Table 3-57: Pneumatic Controllers National CO_2 Emissions (Metric Tons CO_2)

Source	1990	2005	2018	2019	2020	2021	2022
High Bleed Controllers	94,495	39,873	5,056	5,369	5,778	4,260	2,403
Low Bleed Controllers	7,109	4,132	3,740	4,819	3,704	4,561	3,992
Intermittent Bleed Controllers	NO	26,370	75,579	80,855	82,493	80,063	70,328
Total Emissions	**101,604**	**70,374**	**84,374**	**91,044**	**91,975**	**88,884**	**76,723**
Previous Estimate	*42,406*	*46,477*	*70,322*	*49,460*	*63,104*	*56,641*	*NA*

NO (Not Occurring)
NA (Not Applicable)
Note: Totals may not sum due to independent rounding.

Table 3-58: Pneumatic Controllers National CH_4 Emissions (Metric Tons CH_4)

Source	1990	2005	2018	2019	2020	2021	2022
High Bleed Controllers	709,796	481,760	71,824	72,432	86,363	44,611	23,712
Low Bleed Controllers	51,129	62,162	32,106	50,770	36,740	46,060	35,439
Intermittent Bleed Controllers	NO	267,220	1,135,995	758,001	996,250	912,391	634,400
Total Emissions	**760,925**	**811,142**	**1,239,924**	**881,203**	**1,119,352**	**1,003,063**	**693,551**
Previous Estimate	*759,970*	*832,929*	*1,260,259*	*886,382*	*1,130,899*	*1,015,080*	*NA*

NO (Not Occurring)
NA (Not Applicable)
Note: Totals may not sum due to independent rounding.

Equipment Leaks (Methodological Update)

In the previous *Inventory*, EPA updated the CH_4 emissions calculation methodology for onshore production equipment leaks to use basin-specific equipment-level activity factors (e.g., separators per well) from GHGRP data. However, the CO_2 emissions calculation methodology was not updated and instead the previous *Inventory* still relied on a national-level methodology to estimate CO_2 emissions. For this year's *Inventory*, EPA calculated

equipment leak CO_2 emissions in the same manner as CH_4 emissions. EPA calculated CO_2 estimates using the basin-specific equipment-level activity factors for RY2015 through RY2022 from GHGRP, consistent with the methodology used to calculate the CH_4 activity factors, and the CO_2 emissions factors for onshore production segment equipment leaks. Note, this methodological update applies only for activity factors. The previous *Inventory's* CO_2 emission factors for onshore production segment equipment leaks (by equipment type) were retained and used to develop CO_2 estimates.

The update for CO_2 emission estimates resulted in an average increase of 7 percent across the time series and an increase of 18 percent in 2021, compared to the previous *Inventory*. Years 2015 to 2021 were impacted more by the update, with an average increase of 28 percent compared to the previous *Inventory*.

Table 3-59: Equipment Leaks National CO_2 Emissions (Metric Tons CO_2)

Source	1990	2005	2018	2019	2020	2021	2022
Oil Wellheads (heavy crude)	2	2	2	1	1	1	1
Oil Wellheads (light crude)	3,159	2,857	3,330	3,416	3,280	3,272	3,195
Separators (heavy crude)	1	1	1	1	+	+	+
Separators (light crude)	613	868	2,280	2,114	1,601	1,443	1,411
Heater/Treaters (light crude)	508	474	786	1,028	846	951	905
Headers (heavy crude)	+	+	+	+	+	+	+
Headers (light crude)	185	458	712	843	432	430	485
Total Emissions	**4,468**	**4,660**	**7,111**	**7,403**	**6,161**	**6,098**	**5,997**
Previous Estimate	*4,453*	*4,681*	*5,396*	*5,351*	*5,159*	*5,159*	*NA*

+ Does not exceed 0.05 MT CO_2.
NA (Not Applicable)

Chemical Injection Pumps (Methodological Update)

In the previous *Inventory*, EPA updated the CH_4 emissions calculation methodology for chemical injection pumps to use basin-specific equipment-level activity factors (e.g., pumps per well) from GHGRP data. However, the CO_2 emissions calculation methodology was not updated and instead the previous *Inventory* still relied on a national-level methodology to estimate CO_2 emissions. For this year's *Inventory*, EPA calculated chemical injection pump CO_2 emissions in the same manner as CH_4 emissions. EPA calculated CO_2 estimates using the basin-specific equipment-level activity factors for RY2015 through RY2022 from GHGRP, consistent with the methodology used to calculate the CH_4 activity factors, and the CO_2 emission factor. Note, this methodological update applies only for activity factors. The previous *Inventory's* chemical injection pumps CO_2 emission factor was retained and used to develop CO_2 estimates. The update for CO_2 emission estimates resulted in an average decrease of 29 percent across the time series and a decrease of 35 percent in 2021, compared to the previous *Inventory*.

Table 3-60: Chemical Injection Pump National CO_2 Emissions (Metric Tons CO_2)

Source	1990	2005	2018	2019	2020	2021	2022
Chemical Injection Pumps	2,646	4,464	5,955	6,784	5,338	4,749	4,449
Previous Estimate	*4,506*	*6,522*	*7,689*	*7,625*	*7,351*	*7,351*	*NA*

NA (Not Applicable)

Storage Tanks (Recalculation with Updated Data)

Carbon dioxide emissions from production storage tanks are on average 0.9 percent higher across the time series compared to the previous *Inventory*. Emissions estimates for 2021 are 4 percent higher than in the previous *Inventory*, which is primarily due to large tanks with flares. The emission changes were due to GHGRP data submission revisions.

Table 3-61: Storage Tanks National CO_2 Emissions (kt CO_2)

Source	1990	2005	2018	2019	2020	2021	2022
Large Tanks w/Flares	NO	716	5,336	6,251	5,829	5,594	4,513
Large Tanks w/VRU	NO	3	3	9	2	1	1
Large Tanks w/o Control	24	8	4	9	5	4	2
Small Tanks w/Flares	NO	3	7	9	11	10	11
Small Tanks w/o Flares	12	5	5	4	4	5	5
Malfunctioning Separator Dump Valves	12	13	30	26	21	34	8
Total Emissions	**48**	**748**	**5,386**	**6,309**	**5,871**	**5,649**	**4,539**
Previous Estimate	*47*	*748*	*5,398*	*6,024*	*5,255*	*5439*	*NA*

NO (Not Occurring)
NA (Not Applicable)

Chemical injection Pumps (Recalculation with Updated Data)

Chemical injection pump CH_4 estimates decreased by an average of 19 percent across the time series and decreased by 26 percent in 2021, compared to the previous *Inventory*. The emission changes were due to GHGRP data submission revisions.

Table 3-62: Chemical Injection Pumps National CH_4 Emissions (Metric Tons CH_4)

Source	1990	2005	2018	2019	2020	2021	2022
Chemical Injection Pumps	47,425	79,968	108,147	122,967	96,186	85,494	79,712
Previous Estimate	*47,401*	*105,458*	*138,866*	*387,416*	*116,080*	*115,678*	*NA*

NA (Not Applicable)

Produced Water (Recalculation with Updated Data)

Methane estimates from produced water increased by an average of 2 percent across the time series and increased by 4 percent in 2021, compared to the previous *Inventory*. The emission changes were due to Enverus data updates.

Table 3-63: Produced Water National CH_4 Emissions (Metric Tons CH_4)

Source	1990	2005	2018	2019	2020	2021	2022
Produced Water - Regular Pressure Wells	71,854	49,840	73,727	77,370	70,374	71,749	73,665
Produced Water - Low Pressure Wells	20,482	14,207	21,016	22,055	20,061	20,452	20,998
Total Emissions	**92,336**	**64,047**	**94,743**	**99,425**	**90,435**	**92,201**	**94,663**
Previous Estimate	*91,391*	*62,458*	*92,863*	*97,735*	*88,622*	*88,622*	*NA*

NA (Not Applicable)

Associated Gas Flaring (Recalculation with Updated Data)

Associated gas flaring CH_4 emission estimates increased by an average of 2 percent across the time series and increased by 23 percent in 2021, compared to the previous *Inventory*. The emission changes were due to GHGRP data submission revisions.

Table 3-64: Associated Gas Flaring National CH_4 Emissions (Metric Tons CH_4)

Source	1990	2005	2018	2019	2020	2021	2022
220 - Gulf Coast Basin (LA, TX)	901	480	2,379	2,907	3,643	2,136	1,900
360 - Anadarko Basin	452	274	350	90	21	35	30
395 - Williston Basin	2,666	3,405	36,108	58,138	28,176	21,676	18,341

430 - Permian Basin	11,662	7,992	25,286	26,063	12,695	8,178	7,546
"Other" Basins	4,314	2,335	2,089	3,760	2,353	2,790	2,072
Total Emissions	**19,995**	**14,486**	**66,211**	**90,958**	**46,888**	**34,814**	**29,889**
220 - Gulf Coast Basin (LA, TX)	*886*	*490*	*2,440*	*2,991*	*3,692*	*1,864*	*NA*
360 - Anadarko Basin	*447*	*274*	*348*	*88*	*21*	*41*	*NA*
395 - Williston Basin	*2,665*	*3,419*	*36,120*	*48,019*	*23,556*	*18,734*	*NA*
430 - Permian Basin	*11,263*	*7,805*	*25,198*	*27,484*	*13,086*	*5,852*	*NA*
"Other" Basins	*4,369*	*2,347*	*1,992*	*3,563*	*2,295*	*1,802*	*NA*
Previous Estimate	*19,630*	*14,335*	*66,096*	*82,146*	*42,649*	*28,293*	*NA*

NA (Not Applicable)

Gas Engines (Recalculation with Updated Data)

Methane estimates from gas engines decreased by an average of 2 percent across the time series and decreased by 2 percent in 2021, compared to the previous *Inventory*. The emission changes were due to Enverus data updates.

Table 3-65: Gas Engines National CH_4 Emissions (Metric Tons CH_4)

Source	1990	2005	2018	2019	2020	2021	2022
Gas Engines	81,271	69,973	90,773	92,909	88,619	87,040	87,546
Previous Estimate	*81,916*	*71,348*	*91,719*	*93,608*	*89,497*	*89,233*	*NA*

NA (Not Applicable)

Miscellaneous Production Flaring (Recalculation with Updated Data)

Miscellaneous production flaring CO_2 emission estimates are on average 1 percent higher across the time series compared to the previous *Inventory*. Carbon dioxide emissions estimates for 2021 increased by 12 percent compared to the previous *Inventory*. The emission changes were due to GHGRP data submission revisions.

Table 3-66: Miscellaneous Production Flaring National CO_2 Emissions (kt CH_4)

Source	1990	2005	2018	2019	2020	2021	2022
220 - Gulf Coast Basin (LA, TX)	0	103	567	609	654	802	649
395 - Williston Basin	0	71	1,701	3,049	1,307	1,312	1,241
430 - Permian Basin	0	214	1,463	4,312	2,723	2,156	2,709
"Other" Basins	0	398	639	707	427	368	429
Total Emissions	**0**	**786**	**4,370**	**8,678**	**5,110**	**4,638**	**5,028**
Previous Estimate	*0*	*3,008*	*4,307*	*8,225*	*4,679*	*4,154*	*NA*

NA (Not Applicable)

Offshore Production – GOM Federal Waters (Recalculation with Updated Data)

Vented and leak CH_4 emission estimates from offshore production in GOM federal waters decreased by an average of 0.4 percent across the time series and decreased by 8 percent in 2021, compared to the previous *Inventory*. The emission changes were due to updated offshore complex counts from BOEM.

Table 3-67: Offshore Production National CH_4 Emissions (Metric Tons CH_4)

Source	1990	2005	2018	2019	2020	2021	2022
GOM Federal Waters – Vented	196,769	101,585	112,786	110,263	103,116	102,365	101,546
GOM Federal Waters - Leaks	96,575	103,712	58,938	57,577	53,860	53,395	52,961
Total Emissions	**293,344**	**205,298**	**171,724**	**167,840**	**156,976**	**155,760**	**154,507**
Previous Estimate	*293,204*	*205,207*	*171,910*	*170,190*	*162,543*	*168,798*	*NA*

NA (Not Applicable)

Transportation

Recalculations for the transportation segment have resulted in calculated CH_4 and CO_2 emissions over the time series from this segment that are lower (by less than 0.05 percent) than in the previous *Inventory*.

Refining

Recalculations due to resubmitted GHGRP data in the refining segment have resulted in a decrease in calculated CH_4 emissions by an average of 4.5 percent across the time series and a decrease of 14 percent in 2021, compared to the previous *Inventory*.

Refining CO_2 emission estimates decreased by an average of 8 percent across the time series and decreased by 28 percent in 2021, compared to the previous *Inventory*. This change in emissions is due to GHGRP resubmissions and was largely due to a change in reported flaring CO_2 emissions.

Table 3-68: Refining National CH_4 Emissions (Metric Tons CH_4)

Source	1990	2005	2018	2019	2020	2021	2022
Refining	25,742	29,218	27,804	30,814	25,861	25,366	24,685
Previous Estimate	*26,398*	*29,963*	*30,313*	*35,516*	*31,023*	*29,551*	*NA*

NA (Not Applicable)

Table 3-69: Refining National CO_2 Emissions (kt CO_2)

Source	1990	2005	2018	2019	2020	2021	2022
Flares	3,023	3,431	2,814	3,523	2,859	2,989	2,836
Total Refining	**3,174**	**3,602**	**2,877**	**3,571**	**2,893**	**3,021**	**2,872**
Previous Estimate	*3,284*	*3,728*	*3,706*	*5,009*	*4,242*	*4,216*	*NA*

NA (Not Applicable)

Planned Improvements

Planned Improvements for 2025 *Inventory*

EPA updated the Enverus data and there were notable increases in the number of wells and completions identified as being hydraulically fractured compared with previous versions of the database. EPA will assess the underlying Enverus data to determine the cause of these changes.

Upcoming Data, and Additional Data that Could Inform the *Inventory*

EPA will assess new data received by the Greenhouse Gas Reporting Program, the Methane Challenge Program, and other relevant programs on an ongoing basis, which may be used to confirm or improve existing estimates and assumptions.

EPA continues to track studies that contain data that may be used to update the *Inventory*. EPA will also continue to assess studies that include and compare both top-down and bottom-up estimates, and which could lead to improved understanding of unassigned high emitters (e.g., identification of emission sources and information on frequency of high emitters) as recommended in previous stakeholder comments.

Box 3-6: Carbon Dioxide Transport, Injection, and Geological Storage

Carbon dioxide is produced, captured, transported, and used for Enhanced Oil Recovery (EOR) as well as commercial and non-EOR industrial applications, or is stored geologically. This CO_2 is produced from both naturally-occurring CO_2 reservoirs and from industrial sources such as natural gas processing plants and ammonia plants. In the *Inventory*, emissions of CO_2 from naturally-occurring CO_2 reservoirs are estimated based

on the specific application.

In the *Inventory*, CO_2 that is used in non-EOR industrial and commercial applications (e.g., food processing, chemical production) is assumed to be emitted to the atmosphere during its industrial use. These emissions are discussed in the Carbon Dioxide Consumption section, 4.15.

For EOR CO_2, as noted in the *2006 IPCC Guidelines*, "At the Tier 1 or 2 methodology levels [EOR CO_2 is] indistinguishable from fugitive greenhouse gas emissions by the associated oil and gas activities." In the U.S. estimates for oil and gas fugitive emissions, the Tier 2 emission factors for CO_2 include CO_2 that was originally injected and is emitted along with other gas from leak, venting, and flaring pathways, as measurement data used to develop those factors would not be able to distinguish between CO_2 from EOR and CO_2 occurring in the produced natural gas. Therefore, EOR CO_2 emitted through those pathways is included in CO_2 estimates in 1B2.

IPCC includes methodological guidance to estimate emissions from the capture, transport, injection, and geological storage of CO_2. The methodology is based on the principle that the carbon capture and storage system should be handled in a complete and consistent manner across the entire Energy sector. The approach accounts for CO_2 captured at natural and industrial sites as well as emissions from capture, transport, and use. For storage specifically, a Tier 3 methodology is outlined for estimating and reporting emissions based on site-specific evaluations. However, IPCC (IPCC 2006) notes that if a national regulatory process exists, emissions information available through that process may support development of CO_2 emission estimates for geologic storage.

In the United States, facilities that produce CO_2 for various end-use applications (including capture facilities such as acid gas removal plants and ammonia plants), importers of CO_2, exporters of CO_2, facilities that conduct geologic sequestration of CO_2, and facilities that inject CO_2 underground, are required to report greenhouse gas data annually to EPA through its GHGRP. Facilities reporting geologic sequestration of CO_2 to the GHGRP develop and implement an EPA-approved site-specific monitoring, reporting and verification plan, and report the amount of CO_2 sequestered using a mass balance approach.

GHGRP data relevant for this *Inventory* estimate consists of national-level annual quantities of CO_2 captured and extracted for EOR applications for 2010 to 2022 and data reported for geologic sequestration from 2016 to 2022.

The amount of CO_2 captured and extracted from natural and industrial sites for EOR applications in 2022 is 36,680 kt (36.7 MMT CO_2 Eq.) 6. The quantity of CO_2 captured and extracted is noted here for information purposes only; CO_2 captured and extracted from industrial and commercial processes is generally assumed to be emitted and included in emissions totals from those processes.

Table 3-70: Quantity of CO_2 Captured and Extracted for EOR Operations (kt CO_2)

Stage	2018	2019	2020	2021	2022
Quantity of CO_2 Captured and Extracted for EOR Operations	48,400	52,100	35,210	35,090	36,680

Several facilities are reporting under GHGRP Subpart RR (Geologic Sequestration of Carbon Dioxide). See Table 3-71 for the number of facilities reporting under Subpart RR, the reported CO_2 sequestered in subsurface geologic formations in each year, and of the quantity of CO_2 emitted from equipment leaks in each year. The quantity of CO_2 sequestered and emitted is noted here for information purposes only; EPA is considering updates to its approach for this source and is seeking feedback as part of this public review draft on potential updates that could be incorporated in future *Inventories*.

Table 3-71: Geologic Sequestration Information Reported Under GHGRP Subpart RR

Stage	2018	2019	2020	2021	2022
Number of Reporting Facilities	5	5	6	9	13
Reported Annual CO_2 Sequestered (kt)	7,662	8,332	6,802	6,947	7,953

Reported Annual CO_2 Emissions from Equipment Leaks (kt)	11	16	13	37	27

3.7 Natural Gas Systems (CRT Source Category 1B2b)

The U.S. natural gas system encompasses hundreds of thousands of wells, hundreds of processing facilities, and over a million miles of transmission and distribution pipelines. This category (1B2b) as defined in the IPCC methodological guidance is for fugitive emissions from natural gas systems, which per IPCC guidelines include emissions from leaks, venting, and flaring. Total greenhouse gas emissions (CH_4, CO_2, and N_2O) from natural gas systems in 2022 were 209.7 MMT CO_2 Eq., a decrease of 17 percent from 1990 and a decrease of 0.3 percent from 2021, both primarily due to decreases in CH_4 emissions. From 2011, emissions decreased by 5 percent, primarily due to decreases in CH_4 emissions. National total dry gas production in the United States increased by 104 percent from 1990 to 2022, increased by 5 percent from 2021 to 2022, and increased by 59 percent from 2011 to 2022. Of the overall greenhouse gas emissions (209.7 MMT CO_2 Eq.), 83 percent are CH_4 emissions (173.1 MMT CO_2 Eq.), 17 percent are CO_2 emissions (36.5 MMT), and less than 0.1 percent are N_2O emissions (0.15 MMT CO_2 Eq.).

Overall, natural gas systems emitted 173.1 MMT CO_2 Eq. (6,183 kt CH_4) of CH_4 in 2022, a 21 percent decrease compared to 1990 emissions, and 1 percent decrease compared to 2021 emissions (see Table 3-72 and Table 3-73). For non-combustion CO_2, a total of 36.5 MMT CO_2 Eq. (36,470 kt) was emitted in 2022, a 12 percent increase compared to 1990 emissions, and a 2 percent increase compared to 2021 levels. The 2022 N_2O emissions were estimated to be 0.15 MMT CO_2 Eq. (0.57 kt N_2O), a 3205 percent increase compared to 1990 emissions, and a 1104 percent increase compared to 2021 levels.

The 1990 to 2022 emissions trend is not consistent across segments or gases. Overall, the 1990 to 2022 decrease in CH_4 emissions is due primarily to the decrease in emissions from the following segments: distribution (70 percent decrease), transmission and storage (38 percent decrease), processing (37 percent decrease), and exploration (97 percent decrease). Over the same time period, the production segment saw increased CH_4 emissions of 38 percent (with onshore production emissions increasing 16 percent, offshore production emissions decreasing 86 percent, and gathering and boosting [G&B] emissions increasing 108 percent), and post-meter emissions increasing by 65 percent. The 1990 to 2022 increase in CO_2 emissions is primarily due to an increase in CO_2 emissions in the production segment, where emissions from flaring have increased over time.

Methane and CO_2 emissions from natural gas systems include those resulting from normal operations, routine maintenance, and system upsets. Emissions from normal operations include natural gas engine and turbine uncombusted exhaust, flaring, and leak emissions from system components. Routine maintenance emissions originate from pipelines, equipment, and wells during repair and maintenance activities. Pressure surge relief systems and accidents can lead to system upset emissions. Emissions of N_2O from flaring activities are included in the *Inventory*, with most of the emissions occurring in the processing and production segments. Note, CO_2 emissions exclude all combustion emissions (e.g., engine combustion) except for flaring CO_2 emissions. All combustion CO_2 emissions (except for flaring) are accounted for in Section 3.1.

Each year, some estimates in the *Inventory* are recalculated with improved methods and/or data. These improvements are implemented consistently across the previous *Inventory's* time series (i.e., 1990 to 2022) to ensure that the trend is representative of changes in emissions. Recalculations in natural gas systems in this year's *Inventory* include:

- Methodological updates to transmission compressor station activity data, completions and workovers, and underground natural gas storage well events.
- Recalculations due to Greenhouse Gas Reporting Program (GHGRP) submission revisions.
- Recalculations due to updated well counts and production data from Enverus.

The Recalculations Discussion section below provides more details on the updated methods.

Below is a characterization of the six emission subcategories of natural gas systems: exploration, production (including gathering and boosting), processing, transmission and storage, distribution, and post-meter. Each of the segments is described and the different factors affecting CH_4, CO_2, and N_2O emissions are discussed.

Exploration. Exploration includes well drilling, testing, and completion. Emissions from exploration accounted for 0.1 percent of CH_4 emissions and 0.1% of CO_2 emissions from natural gas systems in 2022. Well completions accounted for approximately 90 percent of CH_4 emissions from the exploration segment in 2022, with the rest resulting from well testing and drilling. Well completion flaring emissions account for most of the CO_2 emissions. Methane emissions from exploration decreased by 97 percent from 1990 to 2022, with the largest decreases coming from hydraulically fractured gas well completions without reduced emissions completions (RECs). Methane emissions from exploration increased 58 percent from 2021 to 2022 due to increases in emissions from hydraulically fractured well completions (both non-REC with flaring and REC with venting). Methane emissions from exploration were highest from 2006 to 2008. Carbon dioxide emissions from exploration decreased by 94 percent from 1990 to 2022 primarily due to decreases in hydraulically fractured gas well completions. Carbon dioxide emissions from exploration increased by 14 percent from 2020 to 2021 due to increases in emissions from hydraulically fractured gas well completions (REC with flaring). Carbon dioxide emissions from exploration were highest from 2006 to 2008. Nitrous oxide emissions from exploration decreased 95 percent from 1990 to 2022 and increased 74 percent from 2021 to 2022.

Production (including gathering and boosting). In the production segment, wells are used to withdraw raw gas from underground formations. Emissions arise from the wells themselves, and from well-site equipment and activities such as pneumatic controllers, tanks and separators, and liquids unloading. Gathering and boosting emission sources are included within the production sector. The gathering and boosting sources include gathering and boosting stations (with multiple emission sources on site) and gathering pipelines. The gathering and boosting stations receive natural gas from production sites and transfer it, via gathering pipelines, to transmission pipelines or processing facilities (custody transfer points are typically used to segregate sources between each segment). Boosting processes include compression, dehydration, and transport of gas to a processing facility or pipeline. Emissions from production (including gathering and boosting) accounted for 52 percent of CH_4 emissions and 23 percent of CO_2 emissions from natural gas systems in 2022. Emissions from gathering and boosting and pneumatic controllers in onshore production accounted for most of the production segment CH_4 emissions in 2022. Within gathering and boosting, the largest sources of CH_4 are compressor exhaust slip, compressor venting and leaks, and tanks. Flaring emissions account for most of the CO_2 emissions from production, with the highest emissions coming from flare stacks at gathering stations, miscellaneous onshore production flaring, and tank flaring. Methane emissions from production increased by 38 percent from 1990 to 2022, due primarily to increases in emissions from pneumatic controllers (due to an increase in the number of controllers, particularly in the number of intermittent bleed controllers) and increases in emissions from compressor exhaust slip in gathering and boosting. Methane emissions from production decreased 3 percent from 2021 to 2022 due to decreases in emissions from pneumatic controllers and liquids unloading. Carbon dioxide emissions from production increased by approximately a factor of 2.6 from 1990 to 2022 due to increases in emissions at flare stacks in gathering and boosting and miscellaneous onshore production flaring and decreased 8 percent from 2021 to 2022 due primarily to decreases in emissions at flare stacks in miscellaneous onshore production flaring and tank venting. Nitrous oxide emissions from production were 36.9 times higher in 2022 than in 1990 and 17.5 times higher in 2022 than in 2021. The increase in N_2O emissions from 1990 to 2022 and from 2021 to 2022 is primarily due to increases in emissions from condensate tank flaring.

Processing. In the processing segment, natural gas liquids and various other constituents from the raw gas are removed, resulting in "pipeline quality" gas, which is injected into the transmission system. Methane emissions from compressors, including compressor seals, are the primary emission source from this stage. Most of the CO_2 emissions come from acid gas removal (AGR) units, which are designed to remove CO_2 from natural gas. Processing plants accounted for 9 percent of CH_4 emissions and 73 percent of CO_2 emissions from natural gas systems. Methane emissions from processing decreased by 37 percent from 1990 to 2022 as emissions from compressors (leaks and venting) and equipment leaks decreased; and increased 7 percent from 2021 to 2022 due to increased emissions from gas engines. Carbon dioxide emissions from processing decreased by 6 percent from 1990 to 2022,

due to a decrease in AGR, and increased 4 percent from 2021 to 2022 due to increased emissions from flaring emissions at processing plants. Nitrous oxide emissions increased 116 percent from 2021 to 2022.

Transmission and Storage. Natural gas transmission involves high pressure, large diameter pipelines that transport gas long distances from field production and processing areas to distribution systems or large volume customers such as power plants or chemical plants. Compressor station facilities are used to move the gas throughout the U.S. transmission system. Leak CH_4 emissions from these compressor stations and venting from pneumatic controllers account for most of the emissions from this stage. Uncombusted compressor engine exhaust and pipeline venting are also sources of CH_4 emissions from transmission. Natural gas is also injected and stored in underground formations, or liquefied and stored in above ground tanks, during periods of low demand (e.g., summer), and withdrawn, processed, and distributed during periods of high demand (e.g., winter). Leak and venting emissions from compressors are the primary contributors to CH_4 emissions from storage. Emissions from liquefied natural gas (LNG) stations and terminals are also calculated under the transmission and storage segment. Methane emissions from the transmission and storage segment accounted for approximately 23 percent of methane emissions from natural gas systems, while CO_2 emissions from transmission and storage accounted for 3 percent of the CO_2 emissions from natural gas systems. CH_4 emissions from this source decreased by 38 percent from 1990 to 2022 due to reduced pneumatic device and compressor station emissions (including emissions from compressors and leaks) and decreased 1 percent from 2021 to 2022 due to decreased emissions from pipeline venting transmission compressors. CO_2 emissions from transmission and storage were 6.6 times higher in 2022 than in 1990, due to increased emissions from LNG export terminals, and increased by 36 percent from 2021 to 2022, also due to LNG export terminals and flaring (both transmission and storage). The quantity of LNG exported from the United States increased by a factor of 74 from 1990 to 2022, and by 9 percent from 2021 to 2022. LNG emissions are about 1 percent of CH_4 and 86 percent of CO_2 emissions from transmission and storage in year 2022. Nitrous oxide emissions from transmission and storage increased by 405 percent from 1990 to 2022 and increased by 177 percent from 2021 to 2022.

Distribution. Distribution pipelines take the high-pressure gas from the transmission system at "city gate" stations, reduce the pressure and distribute the gas through primarily underground mains and service lines to individual end users. There were 1,352,384 miles of distribution mains in 2022, an increase of 408,227 miles since 1990 (PHMSA 2022). Distribution system emissions, which accounted for 9 percent of CH_4 emissions from natural gas systems and less than 0.1 percent of CO_2 emissions from natural gas systems, result mainly from leak emissions from pipelines and stations. An increased use of plastic piping, which has lower emissions than other pipe materials, has reduced both CH_4 and CO_2 emissions from this stage, as have station upgrades at metering and regulating (M&R) stations. Distribution system CH_4 emissions in 2022 were 70 percent lower than 1990 levels and 1 percent lower than 2021 emissions. Distribution system CO_2 emissions in 2022 were 70 percent lower than 1990 levels and 1 percent lower than 2021 emissions. Annual CO_2 emissions from this segment are less than 0.1 MMT CO_2 Eq. across the time series.

Post-Meter. Post-meter includes leak emissions from residential and commercial appliances, industrial facilities and power plants, and natural gas fueled vehicles. Leak emissions from residential appliances and industrial facilities and power plants account for the majority of post-meter CH_4 emissions. Methane emissions from the post-meter segment accounted for approximately 8 percent of emissions from natural gas systems in 2022. Post-meter CH_4 emissions increased by 65 percent from 1990 to 2022 and increased by 3 percent from 2021 to 2022, due to increases in the number of residential houses using natural gas and increased natural gas consumption at industrial facilities and power plants. CO_2 emissions from post-meter account for less than 0.01 percent of total CO_2 emissions from natural gas systems.

Total greenhouse gas emissions from the six subcategories within natural gas systems are shown in MMT CO_2 Eq. in Table 3-72. Total CH_4 emissions for these same segments of natural gas systems are shown in MMT CO_2 Eq. (Table 3-73) and kt (Table 3-74). Most emission estimates are calculated using a net emission approach. However, a few sources are still calculated with a potential emission approach. Reductions data are applied to those sources. In 2022, 2.6 MMT CO_2 Eq. CH_4 is subtracted from production segment emissions, 4.3 MMT CO_2 Eq. CH_4 is subtracted from the transmission and storage segment, and 0.1 MMT CO_2 Eq. CH_4 is subtracted from the distribution segment to calculate net emissions. More disaggregated information on potential emissions, net

emissions, and reductions data is available in Annex 3.6, Methodology for Estimating CH_4 and CO_2 Emissions from Natural Gas Systems.

Table 3-72: Total Greenhouse Gas Emissions (CH_4, CO_2, and N_2O) from Natural Gas Systems (MMT CO_2 Eq.)

Segment	1990	2005	2018	2019	2020	2021	2022
Exploration	7.3	22.3	2.9	2.3	0.3	0.1	0.2
Production	68.4	97.9	114.1	114.5	105.8	101.5	98.3
Processing	52.2	31.8	36.3	40.4	39.3	39.7	41.8
Transmission and Storage	64.2	46.2	41.7	41.8	43.1	40.7	40.7
Distribution	51.0	28.5	15.6	15.5	15.5	15.3	15.3
Post-Meter	8.1	9.6	12.5	12.8	13.0	13.0	13.4
Total	**251.2**	**236.5**	**223.0**	**227.3**	**217.0**	**210.4**	**209.7**

Note: Totals may not sum due to independent rounding.

Table 3-73: CH_4 Emissions from Natural Gas Systems (MMT CO_2 Eq.)

Segment	1990	2005	2018	2019	2020	2021	2022
Exploration	6.7	19.6	2.6	2.1	0.2	0.1	0.2
Production	65.2	93.4	104.9	103.6	96.7	92.2	89.7
Onshore Production	*39.9*	*64.4*	*60.5*	*58.0*	*53.1*	*48.3*	*46.2*
Gathering and Boosting	*20.5*	*27.0*	*43.6*	*44.8*	*42.7*	*43.3*	*42.8*
Offshore Production	*4.8*	*2.0*	*0.9*	*0.8*	*0.9*	*0.6*	*0.6*
Processing	23.9	13.0	13.5	14.2	13.8	14.2	15.1
Transmission and Storage	64.0	46.0	41.2	40.5	41.1	39.8	39.6
Distribution	50.9	28.5	15.6	15.5	15.5	15.3	15.2
Post-Meter	8.1	9.6	12.5	12.8	13.0	13.0	13.4
Total	**218.8**	**210.1**	**190.3**	**188.7**	**180.3**	**174.6**	**173.1**

Note: Totals may not sum due to independent rounding.

Table 3-74: CH_4 Emissions from Natural Gas Systems (kt)

Segment	1990	2005	2018	2019	2020	2021	2022
Exploration	238	700	93	75	7	4	6
Production	2,328	3,335	3,748	3,701	3,453	3,293	3,202
Onshore Production	*1,424*	*2,299*	*2,162*	*2,073*	*1,895*	*1,726*	*1,650*
Gathering and Boosting	*733*	*963*	*1,556*	*1,601*	*1,527*	*1,545*	*1,528*
Offshore Production	*170*	*73*	*31*	*28*	*32*	*22*	*23*
Processing	853	463	483	507	495	507	541
Transmission and Storage	2,285	1,645	1,470	1,448	1,468	1,421	1,413
Distribution	1,819	1,018	556	554	553	547	544
Post-Meter	290	344	445	457	463	464	477
Total	**7,813**	**7,505**	**6,795**	**6,741**	**6,439**	**6,235**	**6,183**

Note: Totals may not sum due to independent rounding.

Table 3-75: CO_2 Emissions from Natural Gas Systems (MMT)

Segment	1990	2005	2018	2019	2020	2021	2022
Exploration	0.6	2.7	0.3	0.2	0.1	+	+
Production	3.2	4.6	9.1	10.8	9.1	9.3	8.6
Processing	28.3	18.8	22.8	26.2	25.5	25.5	26.7
Transmission and Storage	0.2	0.2	0.5	1.2	2.0	0.9	1.2
Distribution	0.1	+	+	+	+	+	+
Post-Meter	+	+	+	+	+	+	+
Total	**32.4**	**26.3**	**32.8**	**38.5**	**36.7**	**35.8**	**36.5**

+ Does not exceed 0.05 MMT CO_2 Eq.

Note: Totals may not sum due to independent rounding.

Table 3-76: CO_2 Emissions from Natural Gas Systems (kt)

Segment	1990	2005	2018	2019	2020	2021	2022
Exploration	619	2,710	325	249	97	32	37
Production	3,236	4,554	9,118	10,844	9,102	9,331	8,558
Processing	28,338	18,836	22,769	26,189	25,471	25,525	26,672
Transmission and Storage	179	181	537	1,224	2,030	874	1,185
Distribution	54	30	17	16	16	16	16
Post-Meter	1	1	2	2	2	2	2
Total	**32,427**	**26,312**	**32,768**	**38,525**	**36,719**	**35,780**	**36,470**

Note: Totals may not sum due to independent rounding.

Table 3-77: N_2O Emissions from Natural Gas Systems (Metric Tons CO_2 Eq.)

Segment	1990	2005	2018	2019	2020	2021	2022
Exploration	518	1,708	148	114	46	15	27
Production	3,853	5,467	5,768	6,157	3,687	8,115	142,002
Processing	NO	2,977	3,002	5,082	4,353	4,083	8,808
Transmission and Storage	228	276	205	553	943	415	1,149
Distribution	NO	NO	NO	NO	NO	NO	NO
Post-Meter	NO	NO	NO	NO	NO	NO	NO
Total	**4,599**	**10,428**	**9,123**	**11,906**	**9,029**	**12,628**	**151,986**

NO (Not Occurring)

Note: Totals may not sum due to independent rounding.

Table 3-78: N_2O Emissions from Natural Gas Systems (Metric Tons N_2O)

Segment	1990	2005	2018	2019	2020	2021	2022
Exploration	2.0	6.4	0.6	0.4	0.2	0.1	0.1
Production	14.5	20.6	21.8	23.2	13.9	30.6	535.9
Processing	NO	11.2	11.3	19.2	16.4	15.4	33.2
Transmission and Storage	0.9	1.0	0.8	2.1	3.6	1.6	4.3
Distribution	NO	NO	NO	NO	NO	NO	NO
Post-Meter	NO	NO	NO	NO	NO	NO	NO
Total	**17.4**	**39.3**	**34.4**	**44.9**	**34.1**	**47.7**	**573.5**

NO (Not Occurring)

Note: Totals may not sum due to independent rounding.

Methodology and Time-Series Consistency

See Annex 3.6 for the full time series of emissions data, activity data, and emission factors, and additional information on methods and data sources—for example, the specific years of reporting data from EPA's GHGRP that are used to develop certain factors.

This section provides a general overview of the methodology for natural gas system emission estimates in the *Inventory*, which involves the calculation of CH_4, CO_2, and N_2O emissions for over 100 emissions sources (i.e., equipment types or processes), and then the summation of emissions for each natural gas segment.

The approach for calculating emissions for natural gas systems generally involves the application of emission factors to activity data. For most sources, the approach uses technology-specific emission factors or emission factors that vary over time and take into account changes to technologies and practices, which are used to calculate net emissions directly. For others, the approach uses what are considered "potential methane factors" and emission reduction data to calculate net emissions. The estimates are developed with an IPCC Tier 2 approach. Tier 1 approaches are not used.

Emission Factors. Key references for emission factors for CH_4 and CO_2 emissions from the U.S. natural gas industry include a 1996 study published by the Gas Research Institute (GRI) and EPA (GRI/EPA 1996), EPA's GHGRP (EPA 2023b), and others.

The 1996 GRI/EPA study developed over 80 CH_4 emission factors to characterize emissions from the various components within the operating segments of the U.S. natural gas system. The GRI/EPA study was based on a combination of process engineering studies, collection of activity data, and measurements at representative natural gas facilities conducted in the early 1990s. Year-specific natural gas CH_4 compositions are calculated using U.S. Department of Energy's Energy Information Administration (EIA) annual gross production data for National Energy Modeling System (NEMS) oil and gas supply module regions in conjunction with data from the Gas Technology Institute (GTI, formerly GRI) Unconventional Natural Gas and Gas Composition Databases (GTI 2001). These year-specific CH_4 compositions are applied to emission factors, which therefore may vary from year to year due to slight changes in the CH_4 composition of natural gas for each NEMS region.

GHGRP Subpart W data were used to develop CH_4, CO_2, and N_2O emission factors for many sources in the *Inventory*. In the exploration and production segments, GHGRP data were used to develop emission factors used for all years of the time series for well testing, gas well completions and workovers with and without hydraulic fracturing, pneumatic controllers and chemical injection pumps, condensate tanks, liquids unloading, miscellaneous flaring, gathering and boosting pipelines, and certain sources at gathering and boosting stations. In the processing segment, for recent years of the time series, GHGRP data were used to develop emission factors for leaks, compressors, flares, dehydrators, and blowdowns/venting. In the transmission and storage segment, GHGRP data were used to develop factors for all years of the time series for LNG stations and terminals and transmission pipeline blowdowns, and for pneumatic controllers for recent years of the time series.

Other data sources used for CH_4 emission factors include Zimmerle et al. (2015) for transmission and storage station leaks and compressors, GTI (2009 and 2019) for commercial and industrial meters, Lamb et al. (2015) for recent years for distribution pipelines and meter/regulator stations, Zimmerle et al. (2019) for gathering and boosting stations, Bureau of Ocean Energy Management (BOEM) reports, and Fischer et al. (2019) and IPCC (2019) for post-meter emissions.

For CO_2 emissions from sources in the exploration, production, and processing segments that use emission factors not directly calculated from GHGRP data, data from the 1996 GRI/EPA study and a 2001 GTI publication were used to adapt the CH_4 emission factors into related CO_2 emission factors. For sources in the transmission and storage segment that use emission factors not directly calculated from GHGRP data, and for sources in the distribution segment, data from the 1996 GRI/EPA study and a 1993 GTI publication were used to adapt the CH_4 emission factors into non-combustion related CO_2 emission factors. CO_2 emissions from post-meter sources (commercial, industrial and vehicles) were estimated using default emission factors from IPCC (2019). Carbon dioxide emissions from post-meter residential sources are included in fossil fuel combustion data.

Flaring N_2O emissions were estimated for flaring sources using GHGRP data.

See Annex 3.6 for more detailed information on the methodology and data used to calculate CH_4, CO_2, and N_2O emissions from natural gas systems.

Activity Data. Activity data were taken from various published data sets, as detailed in Annex 3.6. Key activity data sources include data sets developed and maintained by EPA's GHGRP (EPA 2023b); Enverus (Enverus 2023); BOEM; Federal Energy Regulatory Commission (FERC); EIA; the Natural Gas STAR and Methane Challenge Programs annual data; Oil and Gas Journal; and PHMSA.

For a few sources, recent direct activity data are not available. For these sources, either 2021 data were used as a proxy for 2022 data, or a set of industry activity data drivers was developed and used to calculate activity data over the time series. Drivers include statistics on gas production, number of wells, system throughput, miles of various kinds of pipe, and other statistics that characterize the changes in the U.S. natural gas system infrastructure and operations. More information on activity data and drivers is available in Annex 3.6.

A complete list of references for emission factors and activity data by emission source is provided in Annex 3.6.

Calculating Net Emissions. For most sources, net emissions are calculated directly by applying emission factors to activity data. Emission factors used in net emission approaches reflect technology-specific information and take into account regulatory and voluntary reductions. However, for production, transmission and storage, and distribution, some sources are calculated using potential emission factors, and CH_4 that is not emitted is deducted from the total CH_4 potential estimates. To account for use of such technologies and practices that result in lower emissions but are not reflected in "potential" emission factors, data are collected on both regulatory and voluntary reductions. Regulatory actions addressed using this method include EPA National Emission Standards for Hazardous Air Pollutants (NESHAP) regulations for dehydrator vents. Voluntary reductions included in the *Inventory* are those reported to Natural Gas STAR and Methane Challenge for certain sources.

Methodological recalculations were applied to the entire time series to ensure time-series consistency from 1990 through 2022. GHGRP data available (starting in 2011) and other recent data sources have improved estimates of emissions from natural gas systems. To develop a consistent time series, for sources with new data, EPA reviewed available information on factors that may have resulted in changes over the time series (e.g., regulations, voluntary actions) and requested stakeholder feedback on trends as well. For most sources, EPA developed annual data for 1993 through 2010 by interpolating activity data or emission factors or both between 1992 and 2011 data points. Information on time-series consistency for sources updated in this year's *Inventory* can be found in the Recalculations Discussion below, with additional detail provided in supporting memos (relevant memos are cited in the Recalculations Discussion). For detailed documentation of methodologies, please see Annex 3.5.

The United States reports data to the UNFCCC using this *Inventory* report along with Common Reporting Tables (CRTs). This note is provided for those reviewing the CRTs: The notation key "IE" is used for CO_2 and CH_4 emissions from venting and flaring in CRT 1.B.2. Disaggregating flaring and venting estimates across the *Inventory* would involve the application of assumptions and could result in inconsistent reporting and, potentially, decreased transparency. Data availability varies across segments within oil and gas activities systems, and emission factor data available for activities that include flaring can include emissions from multiple sources (flaring, venting and leaks).

Uncertainty

EPA has conducted a quantitative uncertainty analysis using the IPCC Approach 2 methodology (Monte Carlo Simulation technique) to characterize the uncertainty for natural gas systems. For more information on the approach, please see the memoranda *Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-2016: Natural Gas and Petroleum Systems Uncertainty Estimates* (*2018 uncertainty memo*) and *Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-2019: Update for Natural Gas and Petroleum Systems CO_2 Uncertainty Estimates* (*2021*

uncertainty memo).[79]

EPA used Microsoft Excel's @RISK add-in tool to estimate the 95 percent confidence bound around CH_4 and CO_2 emissions from natural gas systems for the current *Inventory*. For the CH_4 uncertainty analysis, EPA focused on the 17 highest-emitting sources for the year 2022, which together emitted 75 percent of methane from natural gas systems in 2022, and extrapolated the estimated uncertainty for the remaining sources. For the CO_2 uncertainty analysis, EPA focused on the three highest-emitting sources for the year 2022, which together emitted 81 percent of CO_2 from natural gas systems in 2022, and extrapolated the estimated uncertainty for the remaining sources. To estimate uncertainty for N_2O, EPA applied the uncertainty bounds calculated for CO_2. EPA will seek to refine this estimate in future Inventories. The @RISK add-in provides for the specification of probability density functions (PDFs) for key variables within a computational structure that mirrors the calculation of the inventory estimate. For emission factors that are derived from methane emissions measurement studies, the PDFs are commonly determined to be lognormally distributed (GRI/EPA 1996; GTI 2001; GTI 2009; Lamb et al. 2015; Zimmerle et al. 2015; Fischer et al. 2018; GTI 2019). For activity data that are derived from national datasets, the PDFs are set to a uniform distribution (see 2018 and 2021 uncertainty memos). Many emission factors and activity factors are calculated using Subpart W data, and for these, the @RISK add-in determines the best fitting PDF (e.g., lognormal, gaussian), based on bootstrapping of the underlying data (see 2018 and 2021 uncertainty memos). The IPCC guidance notes that in using this Approach 2 method, "some uncertainties that are not addressed by statistical means may exist, including those arising from omissions or double counting, or other conceptual errors, or from incomplete understanding of the processes that may lead to inaccuracies in estimates developed from models." The uncertainty bounds reported below only reflect those uncertainties that EPA has been able to quantify and do not incorporate considerations such as modeling uncertainty, data representativeness, measurement errors, misreporting or misclassification. The understanding of the uncertainty of emission estimates for this category evolves and improves as the underlying methodologies and datasets improve.

The results presented below provide the 95 percent confidence bound within which actual emissions from this source category are likely to fall for the year 2022, using the IPCC methodology. The results of the Approach 2 uncertainty analysis are summarized in Table 3-79. Natural gas systems CH_4 emissions in 2022 were estimated to be between 141.2 and 203.0 MMT CO_2 Eq. at a 95 percent confidence level. Natural gas systems CO_2 emissions in 2022 were estimated to be between 31.9 and 42.1 MMT CO_2 Eq. at a 95 percent confidence level. Natural gas systems N_2O emissions in 2022 were estimated to be between 0.13 and 0.18 MMT CO_2 Eq. at a 95 percent confidence level.

Uncertainty bounds for other years of the time series have not been calculated, but uncertainty is expected to vary over the time series. For example, years where many emission sources are calculated with interpolated data would likely have higher uncertainty than years with predominantly year-specific data. In addition, the emission sources that contribute the most to CH_4 and CO_2 emissions are different over the time series, particularly when comparing recent years to early years in the time series. For example, venting emissions were higher and flaring emissions were lower in early years of the time series, compared to recent years. Technologies also changed over the time series (e.g., liquids unloading with plunger lifts and reduced emissions completions were not used early in the time series and cast iron distribution mains were more prevalent than plastic mains in early years). Transmission and gas processing compressor leak and vent emissions were also higher in the early years of the time series.

Table 3-79: Approach 2 Quantitative Uncertainty Estimates for CH_4 and Non-combustion CO_2 Emissions from Natural Gas Systems (MMT CO_2 Eq. and Percent)

Source	Gas	2022 Emission Estimate (MMT CO_2 Eq.)[b]	Uncertainty Range Relative to Emission Estimate[a]			
			(MMT CO_2 Eq.)		(%)	
			Lower Bound[b]	Upper Bound[b]	Lower Bound[b]	Upper Bound[b]
Natural Gas Systems	CH_4	173.1	141.2	203.0	-18%	+17%

[79] See https://www.epa.gov/ghgemissions/natural-gas-and-petroleum-systems.

Natural Gas Systems	CO_2	36.5	31.9	42.1	-12%	+15%
Natural Gas Systems	N_2O	0.15	0.13	0.18	-12%	+15%

[a] Range of emission estimates estimated by applying the 95 percent confidence intervals obtained from the Monte Carlo simulation analysis conducted for the year 2022 CH_4 and CO_2 emissions.

[b] All reported values are rounded after calculation. As a result, lower and upper bounds may not be duplicable from other rounded values as shown in Table 3-73 and Table 3-74.

QA/QC and Verification Discussion

In order to ensure the quality of the emission estimates for natural gas systems, general (IPCC Tier 1) Quality Assurance/Quality Control (QA/QC) procedures were implemented consistent with the U.S. Inventory QA/QC plan outlined in Annex 8.

The natural gas systems emission estimates in the *Inventory* are continually being reviewed and assessed to determine whether emission factors and activity factors accurately reflect current industry practices. A QA/QC analysis was performed for data gathering and input, documentation, and calculation. QA/QC checks are consistently conducted to minimize human error in the model calculations. EPA performs a thorough review of information associated with new studies, GHGRP data, regulations, public webcasts, and the Natural Gas STAR Program to assess whether the assumptions in the *Inventory* are consistent with current industry practices. The EPA has a multi-step data verification process for GHGRP data, including automatic checks during data-entry, statistical analyses on completed reports, and staff review of the reported data. Based on the results of the verification process, the EPA follows up with facilities to resolve mistakes that may have occurred.[80]

As in previous years, EPA conducted early engagement and communication with stakeholders on updates prior to public review of the current *Inventory*. EPA held a stakeholder webinar in October of 2023. EPA released memos detailing updates under consideration and requesting stakeholder feedback.

In recent years, several studies have measured emissions at the source level and at the national or regional level and calculated emission estimates that may differ from the *Inventory*. There are a variety of potential uses of data from new studies, including replacing a previous estimate or factor, verifying or QA of an existing estimate or factor, and identifying areas for updates. In general, there are two major types of studies related to oil and gas greenhouse gas data: studies that focus on measurement or quantification of emissions from specific activities, processes and equipment, and studies that use tools such as inverse modeling to estimate the level of overall emissions needed to account for measured atmospheric concentrations of greenhouse gases at various scales. The first type of study can lead to direct improvements to or verification of *Inventory* estimates. In the past few years, EPA has reviewed and, in many cases, incorporated data from these data sources. The second type of study can provide general indications of potential over- and under-estimates. In addition, in recent years information from top-down studies has been directly incorporated to quantify emissions from well blowouts.

A key challenge in using these types of studies to assess *Inventory* results is having a relevant basis for comparison (e.g., the two data sets should have comparable time frames and geographic coverage, and the independent study should assess data from the *Inventory* and not another data set, such as the Emissions Database for Global Atmospheric Research, or "EDGAR"). In an effort to improve the ability to compare the national-level *Inventory* with measurement results that may be at other spatial and temporal scales, EPA has developed a gridded inventory of U.S. anthropogenic methane emissions with 0.1 degree x 0.1 degree spatial resolution, monthly temporal resolution, and detailed scale-dependent error characterization.[81] The most recent version of the gridded methane inventory is designed to be consistent with the U.S. EPA's *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2018* estimates for the years 2012 to 2018. The gridded inventory improves efforts to compare results of this *Inventory* with atmospheric studies.

[80] See https://www.epa.gov/sites/production/files/2015-07/documents/ghgrp_verification_factsheet.pdf.

[81] See https://www.epa.gov/ghgemissions/us-gridded-methane-emissions.

Recalculations Discussion

EPA received information and data related to the emission estimates through GHGRP reporting and presented information to stakeholders regarding the updates under consideration. In November 2023, EPA released draft memoranda that discussed changes under consideration and requested stakeholder feedback on those changes. EPA then released final memoranda documenting the methodology implemented in the current Inventory.[82] Memoranda cited in the Recalculations Discussion below are: Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-2022: Updates for Transmission Compressor Station Activity (*Transmission Station Activity* memo), Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-2022: Updates for Completion and Workover Emissions (*Completions and Workovers* memo), and Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-2022: Updates for Underground Natural Gas Storage Well Emission Events (*Storage Well Events* memo).

EPA evaluated relevant information available and made several updates to the *Inventory*, including for transmission compressor stations, completions and workovers, and underground natural gas storage wells. General information for these source specific recalculations are presented below and details are available in the *Transmission Station Activity*, *Completions and Workovers*, and *Storage Well Events* memos, including additional considerations for the updates.

In addition to the updates to the sources mentioned above, for certain sources, CH_4 and/or CO_2 emissions changed by greater than 0.05 MMT CO_2 Eq., comparing the previous estimate for 2021 to the current (recalculated) estimate for 2021. The emissions changes were mostly due to GHGRP data submission revisions. These sources are discussed below and include pneumatic controllers, well pad equipment leaks, condensate tanks, liquids unloading, gas engines (in production segment), miscellaneous production flaring, gathering and boosting (G&B) station blowdowns, G&B pneumatic controllers, G&B yard piping, G&B acid gas removal units (AGRU), natural gas processing flares, and transmission pipeline venting.

The combined impact of revisions to 2021 natural gas systems CH_4 emissions, compared to the previous *Inventory*, is a decrease from 181.4 to 174.6 MMT CO_2 Eq. (6.8 MMT CO_2 Eq., or 4 percent). The recalculations resulted in an average increase in the annual CH_4 emission estimates across the 1990 through 2021 time series, compared to the previous *Inventory*, of 1.9 MMT CO_2 Eq., or 0.8 percent.

The combined impact of revisions to 2021 natural gas systems CO_2 emissions, compared to the previous *Inventory*, is a decrease from 36.2 MMT to 35.8 MMT, or 1.1 percent. The recalculations resulted in an average increase in emission estimates across the 1990 through 2021 time series, compared to the previous *Inventory*, of 0.4 MMT CO_2 Eq., or 1.5 percent.

The combined impact of revisions to 2021 natural gas systems N_2O emissions, compared to the previous *Inventory*, is an increase from 7.6 kt CO_2 Eq. to 12.6 kt CO_2 Eq., or 65 percent. The recalculations resulted in an average increase in emission estimates across the 1990 through 2021 time series, compared to the previous *Inventory*, of 10.4 percent.

In Table 3-80 and Table 3-81 below are categories in natural gas systems with recalculations resulting in a change of greater than 0.05 MMT CO_2 Eq., comparing the previous estimate for 2021 to the current (recalculated) estimate for 2021. No changes made to N_2O estimates resulted in a change greater than 0.05 MMT CO_2 Eq. For more information, please see the Recalculations Discussion below.

[82] Stakeholder materials including draft and final memoranda for the current (i.e., 1990 to 2022) *Inventory* are available at https://www.epa.gov/ghgemissions/natural-gas-and-petroleum-systems.

Table 3-80: Recalculations of CO_2 in Natural Gas Systems (MMT CO_2)

Segment and Emission Sources with Changes of Greater than 0.05 MMT CO_2 due to Recalculations	*Previous Estimate Year 2021, 2023 Inventory*	Current Estimate Year 2021, 2024 *Inventory*	Current Estimate Year 2022, 2024 *Inventory*
Exploration	***+***	**+**	**+**
Gas Well Completions	*+*	+	+
Production	***9.1***	**9.3**	**8.6**
Gas Well Workovers	*+*	+	+
Pneumatic Controllers	*0.1*	+	+
Well Pad Equipment Leaks	*+*	0.1	0.1
Chemical Injection Pumps	*+*	+	+
Misc. Onshore Production Flaring	*1.0*	1.1	0.7
Condensate Tanks	*0.9*	1.1	0.6
G&B Station - AGRU	*2.3*	2.2	2.0
Processing	***26.1***	**25.5**	**26.7**
Flares	*7.4*	6.9	8.5
Transmission and Storage	***0.9***	**0.9**	**1.2**
Transmission Compressor Station Leaks and Venting	*0.1*	0.1	0.1
Storage Wells	*+*	+	+
Distribution	***+***	**+**	**+**
Post-Meter	***+***	**+**	**+**
Total	**36.2**	**35.8**	**36.5**

+ Does not exceed 0.05 MMT CO_2.

Note: Totals may not sum due to independent rounding.

Table 3-81: Recalculations of CH_4 in Natural Gas Systems (MMT CO_2 Eq.)

Segment and Emission Sources with Changes of Greater than 0.05 MMT CO_2 due to Recalculations	*Previous Estimate Year 2021, 2023 Inventory*	Current Estimate Year 2021, 2024 *Inventory*	Current Estimate Year 2022, 2024 *Inventory*
Exploration	***0.2***	**0.1**	**0.2**
Gas Well Completions	*0.2*	0.1	0.2
Production	***94.1***	**92.2**	**89.7**
Gas Well Workovers	*0.2*	0.04	0.05
Well Pad Equipment Leaks	*9.6*	9.4	10.8
Pneumatic Controllers	*21.3*	20.9	18.0
Condensate Tanks	*1.2*	1.2	1.1
Liquids Unloading	*3.4*	2.8	2.4
Gas Engines	*5.5*	5.3	5.3
G&B Stations – Station Blowdowns	*1.2*	1.0	0.9
G&B Stations – Pneumatic Controllers	*0.7*	0.6	0.5
G&B Station – Yard Piping	*2.6*	2.7	2.8
Processing	***14.3***	**14.2**	**15.1**
Flares	*0.8*	0.8	0.9
Transmission and Storage	***44.5***	**39.8**	**39.6**
Transmission Compressor Station Leaks and Venting	*25.9*	21.3	21.5
Storage Wells	*0.3*	0.3	0.3
Pipeline Venting	*4.8*	4.6	3.7
Distribution	***15.3***	**15.3**	**15.2**
Post-Meter	***13.0***	**13.0**	**13.4**
Total	***181.4***	**174.6**	**173.1**

Note: Totals may not sum due to independent rounding.

Exploration

HF Completions (Methodological Update)

EPA updated the calculation methodology for HF completions to use basin-level HF completion counts from Enverus and basin-specific activity factors and emission factors calculated from Subpart W data for each control category (i.e., non-reduced emission completion (REC) with venting, non-REC with flaring, REC with venting, REC with flaring). Previously, national annual average activity and emission factors calculated using Subpart W data were applied to national completion counts to estimate HF gas well completion emissions. In this update, EPA developed national emission estimates by summing calculated basin-level total emission estimates. The *Completions and Workovers* memo presents additional information and considerations for this update.

EPA calculated basin-specific activity factors and CH_4 and CO_2 emission factors for all basins that reported Subpart W data. The factors were year-specific for reporting year (RY) 2011 through RY2022. For basin-level HF completion event counts, EPA used Enverus data for 1990 to 2010 and Subpart W for 2011 forward. For the fraction of completions in each control subcategory, EPA retained the previous *Inventory's* assumption that all HF gas well completions were non-REC for 1990 to 2000. The previous *Inventory* also assumed that 10 percent of HF completions were non-REC with flaring from 1990 to 2010 (based on national Subpart W data for RY2011 and RY2012); EPA updated this value using basin-specific Subpart W data for RY2011 and RY2012. For 2011 to 2022, EPA determined the percent contribution of each control category directly from Subpart W data and used linear interpolation between 2000 and 2011 to determine the percent of gas wells with RECs. EPA developed year- and basin-specific Subpart W EFs for 2011 forward. Year 2011 emission factors were applied to all prior years for each basin. For basins without Subpart W data available, EPA applied national average activity and emission factors (unweighted average of all Subpart W reported data).

Comparing the final completion emissions and those presented at the October 2023 webinar and in the November 2023 *Completions and Workovers* memo, the final estimates are higher for certain completion categories. These emissions increases are due not to the basin-level methodology changes discussed here but rather to changes in the Enverus dataset. EPA applied the same data processing steps to Enverus data in the fall of 2023 as it did for the previous Enverus data analysis (conducted in 2021) and data changes led to many more completions being classified as HF completions.

As a result of this methodological update, CH_4 emissions estimates for HF completions are on average 55 percent higher across the time series than in the previous *Inventory*. The 2021 CH_4 emissions estimate is 54 percent lower than in the previous *Inventory*. The largest increase between the updates and the previous *Inventory* for CH_4 emissions is 134 percent in 1998 with an average increase of 92 percent over the 1990 through 2010 time period. CH_4 emissions decreased or were similar for 2011 forward and the largest decrease between the updates and the previous *Inventory* is 54 percent in 2021. CH_4 emissions increased on average across the time series, but particularly in earlier years due to gas well HF completions that were non-REC with venting, particularly in the Appalachian basin (Eastern Overthrust) [basin 160a]. The Appalachian basin (Eastern Overthrust) had a large number of gas well HF completion events that were non-REC with venting and the highest EF of any basin. The update resulted in CO_2 emissions estimates that are on average 54 percent higher across the time series than in the previous *Inventory*. The 2021 CO_2 emissions estimate is 3 percent lower than in the previous *Inventory*. The largest increase between the updates and the previous *Inventory* for CO_2 emissions is 141 percent in 1996, and the largest decrease between the updates and the previous *Inventory* is 44 percent in 2013. CO_2 emissions increased predominantly due to non-REC with flaring events in the Appalachian basin (basin 160A) and the East Texas basin (basin 260); these two basins had the highest EFs of any basin.

Table 3-82: HF Completions National CH_4 Emissions (Metric Tons CH_4)

Source	1990	2005	2018	2019	2020	2021	2022
HF Completions – Non-REC with Venting	187,841	590,423	1,210	678	75	166	83
HF Completions – Non-REC with Flaring	3,112	11,791	652	399	154	31	1,605
HF Completions - REC with Venting	NO	6,710	28,946	18,150	4,594	2,487	3,376

HF Completions - REC with Flaring	NO	2,238	1,345	1,148	634	127	190
Total Emissions	**190,954**	**611,162**	**32,154**	**20,375**	**5,458**	**2,811**	**5,253**
Previous Estimate	*111,265*	*345,098*	*32,147*	*20,002*	*5,220*	*6,111*	*NA*

NO (Not Occurring)
NA (Not Applicable)

Table 3-83: HF Completions National CO_2 Emissions (kt CO_2)

Source	1990	2005	2018	2019	2020	2021	2022
HF Completions – Non-REC with Venting	15	50	+	+	+	+	+
HF Completions – Non-REC with Flaring	472	2,023	57	43	10	2	5
HF Completions - REC with Venting	NO	4	3	+	+	+	+
HF Completions - REC with Flaring	NO	496	233	199	87	13	31
Total Emissions	**487**	**2,573**	**293**	**243**	**97**	**15**	**36**
Previous Estimate	*289*	*1,418*	*290*	*214*	*96*	*15*	*NA*

+ Does not exceed 0.5 kt.
NO (Not Occurring)
NA (Not Applicable)

Non-HF Completions (Methodological Update)

EPA updated the activity data sources and calculation methodology for non-HF completions to use basin-level non-HF completion counts from Enverus and basin-specific activity factors and emission factors, calculated from Subpart W data for each control category (i.e., vented, flared). Previously, national non-HF completion counts and national annual average activity and emission factors calculated using historical data analyses, and Subpart W data were applied to estimate non-HF gas well completion emissions. In this update, EPA developed national emission estimates by summing calculated basin-level total emission estimates. The *Completions and Workovers* memo presents additional information and considerations for this update.

EPA calculated basin-specific activity factors and CH_4 and CO_2 emission factors for all basins that reported Subpart W data. The factors were year-specific for reporting year (RY) 2011 through RY2022. For basin-level non-HF gas well completion event counts, EPA used Enverus data across the time series. For the fraction of completions in each control category, EPA implemented at the basin level the previous *Inventory's* approach and the percent of non-HF gas well completions that are vented in 2011 is applied to all prior years. For 2011 to 2022, EPA determined the percent contribution of each control category directly from Subpart W data for each basin. EPA developed year- and basin-specific Subpart W EFs for 2011 forward. Year 2011 emission factors were applied to all prior years for each basin. For basins without Subpart W data available, EPA applied national average activity and emission factors (unweighted average of all Subpart W reported data).

As a result of this methodological update, CH_4 emissions estimates for non-HF completions are on average 419 percent higher across the time series than in the previous *Inventory*. The 2021 CH_4 estimate is 43 percent higher than in the previous *Inventory*. The largest increase between the updates and the previous *Inventory* for CH_4 emissions is 1,533 percent in 1991, and the largest decrease between the updates and the previous *Inventory* is 63 percent in 2018. Methane emissions increased primarily due to gas well non-HF completions that were vented. The Appalachian basin (Eastern Overthrust) [basin 160a] and the Appalachian basin (basin 160) had many non-HF completion events that were vented and average EFs more than 2 times higher than the national average across the 1990-2022 time series. The update resulted in CO_2 emissions estimates that are on average 1,312 percent higher across the time series than in the previous *Inventory*. The 2021 CO_2 emissions estimate is 7,331 percent higher than in the previous *Inventory*. The largest increase between the updates and the previous *Inventory* for CO_2 emissions is 7,331 percent in 2021, and the largest decrease between the updates and the previous *Inventory* is 47 percent in 2018. The increase in CO_2 emissions is due to non-HF completions that were flared, primarily in the Gulf Coast basin (basin 220). The Gulf Coast basin had the highest fraction of non-HF completions that were flared of any basin.

Table 3-84: Non-HF Completions National CH_4 Emissions (Metric Tons CH_4)

Source	1990	2005	2018	2019	2020	2021	2022
Non-HF Completions - vented	44,362	84,955	79	319	1,548	284	159
Non-HF Completions - flared	547	545	113	+	NO	98	NO
Total Emissions	**44,909**	**85,500**	**192**	**320**	**1,548**	**381**	**159**
Previous Estimate	*5,736*	*10,363*	*513*	*796*	*2,659*	*267*	*NA*

+ Does not exceed 0.5 MT.
NO (Not Occurring)
NA (Not Applicable)

Table 3-85: Non-HF Completions National CO_2 Emissions (Metric Tons CO_2)

Source	1990	2005	2018	2019	2020	2021	2022
Non-HF Completions - vented	1,398	3,531	1	8	197	8	549
Non-HF Completions - flared	127,316	126,743	15,699	42	NO	16,449	NO
Total Emissions	**128,714**	**130,274**	**15,700**	**50**	**197**	**16,457**	**549**
Previous Estimate	*4,862*	*8,784*	*29,834*	*81*	*364*	*221*	*NA*

NO (Not Occurring)
NA (Not Applicable)

Production

HF Workovers (Methodological Update)

EPA updated the activity data source and calculation methodology for HF workovers to use basin-specific activity factors and emission factors, calculated from Subpart W data for each control category (i.e., non-reduced emission completion (REC) with venting, non-REC with flaring, REC with venting, REC with flaring). Previously, national HF workover counts calculated using analyses for NSPS OOOO (i.e., 1 percent of HF gas wells were worked over annually) and national annual average emission factors calculated using Subpart W data were applied to estimate HF gas well workover emissions. In this update, EPA developed national emission estimates by summing calculated basin-level total emission estimates. The *Completions and Workovers* memo presents additional information and considerations for this update.

EPA calculated basin-specific activity factors and CH_4 and CO_2 emission factors for all basins that reported Subpart W data. For basin-level workover counts, instead of applying a 1 percent workover rate to HF gas wells, EPA developed year- and basin-specific Subpart W AFs for 2015 forward that represent the number of HF workovers per gas well. Year 2015 Subpart W AFs were applied to all prior years for each basin. For the fraction of workovers in each control subcategory, EPA retained the previous *Inventory's* assumption that all HF gas well workovers were non-REC for 1990 to 2000. The previous Inventory also assumed that 10 percent of HF workovers were non-REC with flaring from 1990 to 2010; EPA updated this value using basin-specific data from Subpart W. For 2011 forward, EPA determined the percent contribution of each control category directly from Subpart W data at the basin-level. EPA used linear interpolation for interpolation between 2000 and 2011 to determine the percent of gas wells with RECs. EPA developed year-and basin-specific Subpart W EFs for 2011 forward. Year 2011 emission factors were applied to all prior years for each basin. For basins without Subpart W data available, EPA applied national average activity and emission factors (unweighted average of all Subpart W reported data).

As a result of this methodological update, CH_4 emissions estimates for HF workovers are on average 43 percent lower across the time series than in the previous *Inventory*. The 2021 CH_4 emissions estimate is 94 percent lower than in the previous *Inventory*. The largest increase between the updates and the previous *Inventory* for CH_4 emissions is 5 percent in 1990, and the largest decrease between the updates and the previous *Inventory* is 99 percent in 2019. The update resulted in CO_2 emissions estimates that are on average 60 percent lower than in the previous *Inventory*. The 2021 CO_2 emissions estimate is 67 percent lower than in the previous *Inventory*. The largest increase between the updates and the previous *Inventory* for CO_2 emissions is 53 percent in 2013, and the

largest decrease between the updates and the previous *Inventory* is 99 percent in 2019. The decrease in emissions for both CH_4 and CO_2 was primarily due to the change in calculation method for workover counts. HF gas well workover counts decreased by an average of 73 percent across the 1990 through 2021 time series compared to the previous *Inventory*.

Table 3-86: HF Workovers National CH_4 Emissions (Metric Tons CH_4)

Source	1990	2005	2018	2019	2020	2021	2022
HF Workovers – Non-REC with Venting	22,198	37,917	114	96	4	17	35
HF Workovers – Non-REC with Flaring	242	483	29	2	1	+	19
HF Workovers - REC with Venting	NO	231	1,667	73	229	457	113
HF Workovers - REC with Flaring	NO	+	6	4	1	2	17
Total Emissions	**22,440**	**38,632**	**1,816**	**174**	**234**	**476**	**185**
Previous Estimate	*21,427*	*57,972*	*19,594*	*13,612*	*6,771*	*8,144*	*NA*

+ Does not exceed 0.5 mt.
NO (Not Occurring)
NA (Not Applicable)

Table 3-87: HF Workovers National CO_2Emissions (kt CO_2)

Source	1990	2005	2018	2019	2020	2021	2022
HF Workovers – Non-REC with Venting	1	2	+	+	+	+	+
HF Workovers – Non-REC with Flaring	32	67	2	+	+	+	+
HF Workovers - REC with Venting	NO	+	+	+	+	+	+
HF Workovers - REC with Flaring	NO	+	1	+	+	+	3
Total Emissions	**33**	**69**	**4**	**1**	**+**	**+**	**3**
Previous Estimate	*56*	*165*	*99*	*86*	*8*	*1*	*NA*

+ Does not exceed 0.5 kt.
NO (Not Occurring)
NA (Not Applicable)

Non-HF Workovers (Methodological Update)

EPA updated the activity data source and calculation methodology for non-HF workovers to use basin-specific activity factors and emission factors, calculated from Subpart W data for each control category (i.e., vented, flared). Previously, national annual average activity and emission factors calculated using historical data analyses and Subpart W data were applied along with national gas well counts to estimate non-HF gas well workover emissions. In this update, EPA developed national emission estimates by summing calculated basin-level total emission estimates. The *Completions and Workovers* memo presents additional information and considerations for this update.

EPA calculated basin-specific activity factors and CH_4 and CO_2 emission factors for all basins that reported Subpart W data. For basin-level workover counts, EPA developed year-specific Subpart W AFs for 2015 forward. Year 2015 Subpart W data was applied to prior years for each basin. For the fraction of workovers in each control subcategory, EPA applied year- and basin-specific AFs for 2011 forward, retained the previous *Inventory's* assumption that all non-HF workovers were vented in 1990 to 1992, and used linear interpolation between the 1992 and 2011 activity factors at the basin-level. EPA developed year- and basin-specific Subpart W EFs for 2011 forward. Year 2011 emission factors were applied to all prior years for each basin. For basins without Subpart W data available, EPA applied national average activity and emission factors (unweighted average of all Subpart W reported data).

As a result of this methodological update, CH_4 emissions estimates for non-HF workovers are on average 277 percent higher than in the previous *Inventory*. The 2021 estimate is 180 percent higher than in the previous *Inventory*. The largest increase between the estimates and the previous *Inventory* for CH_4 emissions is 698 percent

in 2017, and the smallest increase is 78 percent in 2018. The increase in CH_4 emissions is due to non-HF workovers that were vented. In the Chautauqua Platform basin (basin 355), all non-HF workovers were vented, and it had the highest CH_4 EF in 2017. The update resulted in CO_2 emissions estimates for non-HF workovers that are higher across the entire time series than the previous *Inventory* (on average 3,067 percent higher). The 2021 CO_2 emissions estimate is 116 percent higher than in the previous *Inventory*. The largest increase between estimates and the previous *Inventory* for CO_2 emissions is 7,432 percent in 1994, and the smallest increase is 78 percent in 2018. The increase in CO_2 emissions is due to non-HF workovers that were flared, particularly in the Bend Arch basin (basin 425). The Bend Arch basin has a high non-HF completion per total gas well AF and a high fraction of non-HF workovers that were flared compared to other basins over the time series.

Table 3-88: Non-HF Workovers National CH_4 Emissions (Metric Tons CH_4)

Source	1990	2005	2018	2019	2020	2021	2022
Non-HF Workovers - vented	1,415	2,083	1,139	866	959	1,068	1,594
Non-HF Workovers - flared	NO	1,077	1	5	+	43	3
Total Emissions	**1,415**	**3,159**	**1,140**	**870**	**959**	**1,111**	**1,597**
Previous Estimate	*532*	*752*	*415*	*436*	*259*	*396*	*NA*

+ Does not exceed 0.5 MT.
NO (Not Occurring)
NA (Not Applicable)

Table 3-89: Non-HF Workovers National CO_2 Emissions (Metric Tons CO_2)

Source	1990	2005	2018	2019	2020	2021	2022
Non-HF Workovers - vented	87	180	61	51	2,163	199	460
Non-HF Workovers - flared	NO	174,881	269	665	34	9,591	424
Total Emissions	**87**	**175,062**	**329**	**716**	**2,197**	**9,790**	**885**
Previous Estimate	*32*	*3,701*	*185*	*294*	*476*	*4,539*	*NA*

NO (Not Occurring)
NA (Not Applicable)

Equipment Leaks (Methodological Update)

In the previous *Inventory*, EPA updated the CH_4 emissions calculation methodology for onshore production equipment leaks to use basin-specific equipment-level activity factors (e.g., separators per well) from GHGRP data. However, the CO_2 emissions calculation methodology was not updated and instead the previous *Inventory* still relied on a national-level methodology to estimate CO_2 emissions. For this year's *Inventory*, EPA calculated equipment leak CO_2 emissions in the same manner as CH_4 emissions. EPA calculated CO_2 estimates using the basin-specific equipment-level activity factors for RY2015 through RY2022 from GHGRP, consistent with the methodology used to calculate the CH_4 activity factors, and the CO_2 emissions factors for onshore production segment equipment leaks. Note, this methodological update applies only for activity factors. The previous *Inventory's* CO_2 emission factors for onshore production segment equipment leaks (by equipment type) were retained and used to develop CO_2 estimates.

The update for CO_2 emission estimates for equipment leaks resulted in an average increase of 12 percent across the time series compared to the previous *Inventory*. Years 1990 through 2002 were minimally impacted by the updates, with an increase of 2 percent for CO_2 emissions. Years 2020 and 2021 showed larger increases of 69 and 48 percent for 2020 and 2021, respectively, which is mostly due to much higher emissions from meters and piping in the Powder River Basin.

Methane emissions for equipment leaks were impacted due to recalculations with updated data. CH_4 emission estimates were an average of 5 percent lower across the time series compared to the previous *Inventory*. The 2021 CH_4 estimate is 2 percent lower in 2021 compared to the previous *Inventory*. These CH_4 emissions changes were due to GHGRP submission revisions.

Table 3-90: Production Equipment Leaks National CO_2 Emissions (Metric Tons CO_2)

Source	1990	2005	2018	2019	2020	2021	2022
Heaters	1,639	3,642	10,485	3,412	4,261	4,014	4,359
Separators	5,372	14,404	19,114	19,689	21,306	17,239	15,518
Dehydrators	1,261	1,690	794	677	589	893	683
Meters/Piping	5,400	10,527	11,199	11,775	30,564	24,424	11,022
Compressors	2,673	7,178	7,818	7,236	6,966	9,079	20,310
Total Emissions	**16,344**	**37,441**	**49,410**	**42,789**	**63,686**	**55,649**	**51,893**
Previous Estimate	*18,497*	*33,300*	*38,458*	*37,974*	*37,608*	*37,608*	*NA*

NA (Not Applicable)

Table 3-91: Production Equipment Leaks National CH_4 Emissions (Metric Tons CH_4)

Source	1990	2005	2018	2019	2020	2021	2022
Heaters	12,305	18,436	79,890	16,158	18,568	17,581	18,476
Separators	41,579	80,745	121,349	126,037	129,133	109,610	94,591
Dehydrators	12,904	11,381	5,449	3,656	3,070	4,078	3,105
Meters/Piping	43,055	63,764	79,864	84,730	153,917	130,390	75,719
Compressors	30,307	61,753	71,705	64,771	60,637	73,636	193,389
Total Emissions	**140,150**	**236,079**	**358,256**	**295,352**	**365,325**	**335,295**	**385,280**
Previous Estimate	*137,647*	*262,188*	*363,367*	*298,930*	*369,466*	*343,686*	*NA*

NA (Not Applicable)

Chemical Injection Pumps (Methodological Update)

In the previous *Inventory*, EPA updated the CH_4 emissions calculation methodology for chemical injection pumps to use basin-specific equipment-level activity factors (e.g., pumps per well) from GHGRP data. However, the CO_2 emissions calculation methodology was not updated and instead the previous *Inventory* still relied on a national-level methodology to estimate CO_2 emissions. For the current *Inventory*, EPA calculated chemical injection pump CO_2 emissions in the same manner as CH_4 emissions. EPA calculated CO_2 estimates using the basin-specific equipment-level activity factors for RY2015 through RY2022 from GHGRP, consistent with the methodology used to calculate the CH_4 activity factors, and the CO_2 emission factor. Note, this methodological update applies only for activity factors. The previous *Inventory's* chemical injection pumps CO_2 emission factor was retained and used to develop CO_2 estimates.

The update for CO_2 emission estimates resulted in an average decrease of 9 percent across the time series compared to the previous *Inventory*. There were larger decreases of 31 and 39 percent for 2020 and 2021, respectively. The recent years of the time series used basin-specific activity factors and certain basins had lower activity factors compared to the national average factors (e.g., Permian Basin, Denver Basin, San Juan, Paradox, AK Cook Inlet).

Table 3-92: Chemical Injection Pumps National CO_2 Emissions (Metric Tons CO_2)

Source	1990	2005	2018	2019	2020	2021	2022
Chemical Injection Pumps	2,153	6,749	10,254	9,392	7,339	6,469	6,428
Previous Estimate	*2,275*	*7,760*	*11,053*	*10,899*	*10,635*	*10,635*	*NA*

NA (Not Applicable)

Pneumatic Controllers (Methodological Update)

In the previous *Inventory*, EPA updated the CH_4 emissions calculation methodology for pneumatic controllers to use basin-specific activity factors and emission factors by bleed type (i.e., low, high, intermittent bleed) from GHGRP data. However, the CO_2 emissions calculation methodology was not updated and instead the previous

Inventory still relied on a national-level methodology to estimate CO_2 emissions. For the current *Inventory*, EPA calculated pneumatic controller CO_2 emissions using basin-specific emissions data such that the CO_2 emissions reflect the unique CO_2 composition of the gas in a basin.

The update for pneumatic controller CO_2 emission estimates resulted in an average decrease of 44 percent across the time series compared to the previous *Inventory*. This average decrease is generally consistent for all years.

Methane emissions for pneumatic controllers were impacted due to recalculations with updated data. Methane emissions estimates are on average 0.3 percent lower across the time-series than in the previous *Inventory*. The estimate for 2021 is 2 percent lower than in the previous *Inventory*. These changes were due to GHGRP submission revisions.

Table 3-93: Pneumatic Controllers National CO_2 Emissions (Metric Tons CO_2)

Source	1990	2005	2018	2019	2020	2021	2022
Low Bleed Controllers	NO	1,318	2,325	2,283	2,047	1,773	2,180
High Bleed Controllers	23,058	32,794	4,378	2,898	2,373	2,418	1,726
Intermittent Bleed Controllers	15,076	41,267	56,974	57,147	48,052	44,964	37,897
Total Emissions	**38,135**	**75,378**	**63,677**	**62,328**	**52,472**	**49,155**	**41,803**
Previous Estimate	*70,028*	*129,648*	*115,235*	*115,591*	*98,144*	*91,662*	*NA*

NO (Not Occurring)
NA (Not Applicable)

Table 3-94: Pneumatic Controllers National CH_4 Emissions (Metric Tons CH_4)

Source	1990	2005	2018	2019	2020	2021	2022
Low Bleed Controllers	NO	22,656	33,220	31,099	27,238	25,247	29,877
High Bleed Controllers	355,671	480,272	86,764	52,676	42,269	41,435	30,700
Intermittent Bleed Controllers	233,661	565,070	830,140	875,168	748,219	680,708	583,144
Total Emissions	**589,332**	**1,067,997**	**950,124**	**958,943**	**817,727**	**747,391**	**643,721**
Previous Estimate	*581,039*	*1,075,712*	*956,125*	*959,080*	*814,318*	*760,534*	*NA*

NO (Not Occurring)
NA (Not Applicable)

Storage Tanks (Recalculation with Updated Data)

Methane emissions for production condensate storage tanks are on average lower than the previous *Inventory* by less than 0.1 percent across the 1990 to 2021 time series. The 2021 estimate is 6 percent lower than in the previous *Inventory*. The production storage tanks CO_2 emissions estimates are on average 3 percent higher across the 1990 to 2021 time series than in the previous Inventory. The 2021 estimate is 25 percent higher than in the previous *Inventory*. These changes were due to GHGRP submission revisions.

Table 3-95: Storage Tanks National CH_4 Emissions (Metric Tons CH_4)

Source	1990	2005	2018	2019	2020	2021	2022
Large Tanks w/Flares	520	337	1,284	819	765	715	467
Large Tanks w/VRU	NO	27	141	464	743	597	94
Large Tanks w/o Control	16,743	6,828	15,179	3,149	5,323	4,205	3,319
Small Tanks w/Flares	NO	51	235	207	200	161	166
Small Tanks w/o Flares	92,334	31,003	43,050	61,331	47,423	35,460	33,455
Malfunctioning Separator Dump Valves	7	4	40	79	255	212	67
Total Emissions	109,605	38,250	59,929	66,049	54,708	41,351	37,567
Previous Estimate	*106,429*	*38,461*	*60,556*	*67,595*	*53,613*	*44,217*	*NA*

NO (Not Occurring)
NA (Not Applicable)

Table 3-96: Storage Tanks National CO_2 Emissions (kt CO_2)

Source	1990	2005	2018	2019	2020	2021	2022
Large Tanks w/Flares	587	421	1,476	974	1,108	1,049	575
Large Tanks w/VRU	NO	2	+	+	1	1	+
Large Tanks w/o Control	2	1	36	1	1	1	+
Small Tanks w/Flares	NO	13	86	82	41	27	20
Small Tanks w/o Flares	48	17	26	32	23	17	18
Malfunctioning Separator Dump Valves	+	+	+	+	1	+	+
Total Emissions	**637**	**455**	**1,625**	**1,089**	**1,175**	**1,094**	**613**
Previous Estimate	*628*	*456*	*1,507*	*956*	*862*	*873*	*NA*

+ Does not exceed 0.5 kt.
NO (Not Occurring)
NA (Not Applicable)

Liquids Unloading (Recalculation with Updated Data)

Liquids unloading CH_4 emissions estimates decreased by an average of 9 percent across the 1990 to 2021 time series compared with the previous *Inventory*. The 2021 estimate decreased by 17 percent compared with the previous *Inventory*. These changes were due to GHGRP submission revisions.

Table 3-97: Liquids Unloading National CH_4 Emissions (Metric Tons CH_4)

Source	1990	2005	2018	2019	2020	2021	2022
Liquids Unloading With Plunger Lifts	0	128,295	82,501	75,081	51,457	33,916	30,384
Liquids Unloading Without Plunger Lifts	77,767	198,728	132,866	104,484	84,251	65,655	54,227
Total Emissions	**77,767**	**327,023**	**215,367**	**179,565**	**135,707**	**99,572**	**84,611**
Previous Estimate	*76,815*	*358,925*	*265,173*	*209,964*	*158,968*	*120,145*	*NA*

NA (Not Applicable)

Gas Engines (Recalculation with Updated Data)

Gas engines CH_4 emissions estimates are on average 2 percent lower across the 1990 to 2021 time series compared with the previous *Inventory*. The 2021 estimate is 4 percent lower than in the previous *Inventory*. These changes were due to revisions to Enverus data.

Table 3-98: Production Gas Engines National CH_4 Emissions (Metric Tons CH_4)

Source	1990	2005	2018	2019	2020	2021	2022
Gas Engines	116,587	194,140	201,660	196,996	192,854	188,374	188,611
Previous Estimate	*115,689*	*198,005*	*207,052*	*202,060*	*197,027*	*197,027*	*NA*

NA (Not Applicable)

Miscellaneous Production Flaring (Recalculation with Updated Data)

Miscellaneous production flaring CO_2 emissions estimates are on average 1 percent higher across the 1993 to 2021 time series compared with the previous *Inventory*, and the 2021 estimate is 12 percent higher compared to the previous *Inventory*. These changes were due to GHGRP submission revisions.

Table 3-99: Miscellaneous Production Flaring National Emissions (kt CO_2)

Source	1990	2005	2018	2019	2020	2021	2022
Miscellaneous Flaring-Gulf Coast Basin	NO	164	135	395	251	316	206
Miscellaneous Flaring-Williston Basin	NO	+	6	3	4	7	+
Miscellaneous Flaring-Permian Basin	NO	263	690	926	808	578	231

Miscellaneous Flaring-Other Basins	NO	117	476	334	237	211	238
Total Emissions	**NO**	**544**	**1,308**	**1,659**	**1,301**	**1,112**	**676**
Previous Estimate	*NO*	*543*	*1,326*	*1,595*	*1,298*	*991*	*NA*

+ Does not exceed 0.5 kt.
NO (Not Occurring)
NA (Not Applicable)

Gathering and Boosting – Station Blowdowns (Recalculation with Updated Data)

Methane emissions estimates for gathering and boosting station blowdowns are on average 0.7 percent lower across the 1990 to 2021 time series than in the previous *Inventory*. The 2021 estimate is 17 percent lower than in the previous *Inventory*. These changes were due to GHGRP submission revisions.

Table 3-100: Station Blowdowns National Emissions (Metric Tons CH_4)

Source	1990	2005	2018	2019	2020	2021	2022
Station Blowdowns	20,218	26,155	79,313	39,059	40,519	35,161	32,036
Previous Estimate	*20,517*	*26,113*	*78,548*	*38,412*	*40,468*	*42,231*	*NA*

NA (Not Applicable)

Gathering and Boosting – Pneumatic Controllers (Recalculation with Updated Data)

Gathering and boosting pneumatic controllers CH_4 emissions estimates are on average 0.1 percent higher across the 1990 to 2021 time series compared with the previous *Inventory*. The emissions estimate for 2021 is 2 percent lower than in the previous *Inventory*, largely because of a decrease in emissions from high-bleed pneumatic devices. These changes were due to GHGRP submission revisions.

Table 3-101: Pneumatic Controllers National Emissions (Metric Tons CH_4)

Source	1990	2005	2018	2019	2020	2021	2022
High-Bleed Pneumatic Devices	17,092	22,111	25,030	24,187	22,981	20,709	18,854
Intermittent Bleed Pneumatic Devices	78,424	101,451	173,929	184,542	171,679	156,842	145,574
Low-Bleed Pneumatic Devices	2,713	3,509	5,799	6,996	6,965	6,564	6,572
Total Emissions	**98,229**	**127,072**	**204,758**	**215,725**	**201,625**	**184,116**	**171,000**
Previous Estimate	*99,843*	*127,073*	*204,748*	*215,339*	*201,415*	*187,290*	*NA*

NA (Not Applicable)

Gathering and Boosting – Acid Gas Removal Units (Recalculation with Updated Data)

Carbon dioxide emissions estimates for acid gas removal units (AGRU) are on average 0.3 percent lower across the 1990 to 2021 time series compared with the previous *Inventory*. The emissions estimate for 2021 decreased by 4 percent compared to the previous *Inventory*. These changes were due to GHGRP submission revisions.

Table 3-102: Acid Gas Removal Units National Emissions (kt CO_2)

Source	1990	2005	2018	2019	2020	2021	2022
AGRU	241	311	707	1,191	1,629	2,222	2,044
Previous Estimate	*245*	*311*	*707*	*1,288*	*1,655*	*2,304*	*NA*

NA (Not Applicable)

Gathering and Boosting – Yard Piping (Recalculation with Updated Data)

Methane emissions estimates for yard piping are on average 0.6 percent higher across the 1990 to 2021 time series compared with the previous *Inventory*. The emissions estimate for 2021 is 4 percent higher than in the previous *Inventory*. These changes were due to GHGRP submission revisions.

Table 3-103: Yard Piping National Emissions (Metric Tons CH_4)

Source	1990	2005	2018	2019	2020	2021	2022
Yard Piping	36,319	46,984	86,270	94,306	94,463	96,785	101,777
Previous Estimate	*36,773*	*46,802*	*85,996*	*94,191*	*93,253*	*93,253*	*NA*

NA (Not Applicable)

Processing

Flares (Recalculation with Updated Data)

Processing segment flare CH_4 emission estimates are on average 0.5 percent lower across the 1993 to 2021 time series than in the previous *Inventory*. The CH_4 estimate for 2021 is 7 percent lower than in the previous Inventory. The processing segment flare CO_2 emission estimates decreased by an average of 0.4 percent over the 1993 to 2021 time series, while the CO_2 estimate for 2021 decreased by 6 percent compared to the previous *Inventory*. These changes were due to GHGRP submission revisions.

Table 3-104: Processing Segment Flares National CH_4 Emissions (Metric Tons CH_4)

Source	1990	2005	2018	2019	2020	2021	2022
Flares	NO	NA	24,173	43,887	36,985	26,807	33,586
Previous Estimate	*NO*	*NA*	*24,148*	*43,613*	*36,928*	*28,784*	*NA*

NA (Not Applicable)
NO (Not Occurring)

Table 3-105: Processing Segment Flares National CO_2 Emissions (kt CO_2)

Source	1990	2005	2018	2019	2020	2021	2022
Flares	NO	3,517	5,948	9,776	8,121	6,941	8,533
Previous Estimate	*NO*	*3,517*	*5,945*	*9,859*	*8,120*	*7,381*	*NA*

NA (Not Applicable)
NO (Not Occurring)

Transmission and Storage

Transmission Compressor Station Leaks and Venting (Methodological Update)

EPA updated the methodology to estimate national level activity data for transmission compressor stations (i.e., station and compressor counts). EPA used annual data for 1996 to 2022 from FERC and PHMSA to estimate national transmission station counts and total transmission compressor counts. FERC requires major interstate transmission compression facilities to report annual data on station counts, total compressor counts, and total transmission pipeline miles. EPA compiled annual FERC data and scaled it up to the national level using PHMSA national transmission pipeline miles for 1996 to 2022. EPA retained existing *Inventory* activity data for 1990 to 1992 and used linear interpolation to estimate national station and total compressor counts for 1993 to 1995.

Total compressor counts were apportioned to reciprocating and centrifugal compressor types using data from GHGRP's Subpart W. EPA retained existing *Inventory* activity data for 1990 to 1992 and used linear interpolation

for intermediate time series years. For more details on this update, refer to the *Transmission Station Activity* memo.

This update impacts CH_4 and CO_2 emissions from leaks (including compressor leaks), dehydrator vents, pneumatic devices, flaring, and venting at transmission compression stations. As a result of this update, CH_4 emissions estimates increased by an average of 2.6 percent across the time series and decreased by 18 percent in 2021, compared to the previous *Inventory*. Emissions estimates of CO_2 increased by an average of 2.5 percent across the time series and decreased by 16 percent in 2021, compared to the previous *Inventory*.

Table 3-106: Transmission Compressor Station National CH_4 Emissions (Metric Tons CH_4)

Source	1990	2005	2018	2019	2020	2021	2022
Station Total Emissions	1,096,527	704,651	581,117	585,617	580,273	585,666	588,497
Station + Compressor Fugitive Emissions	NE	NE	118,592	120,704	120,256	125,440	128,128
Reciprocating Compressor	NE	NE	347,685	342,485	333,385	325,130	322,725
Centrifugal Compressor (wet seals)	NE	NE	50,116	51,544	52,360	53,652	50,524
Centrifugal Compressor (dry seals)	NE	NE	64,724	70,884	74,272	81,444	87,120
Dehydrator vents	1,991	1,931	2,132	2,170	2,162	2,255	2,304
Flaring	305	296	606	432	522	364	492
Pneumatic Devices	213,081	87,701	31,749	31,640	30,120	30,585	31,170
High Bleed	NE	NE	9,781	9,797	9,119	8,951	8,350
Intermittent Bleed	NE	NE	21,132	21,074	20,222	20,882	22,157
Low Bleed	NE	NE	836	769	779	753	663
Station Venting	145,241	138,843	127,165	136,920	136,332	143,132	146,659
Total Emissions	**1,457,144**	**933,422**	**742,770**	**756,779**	**749,409**	**762,002**	**769,121**
Previous Estimate	*1,459,223*	*871,649*	*809,418*	*891,620*	*911,471*	*923,868*	*NA*

NE (Not Estimated at individual source level due to lack of data)
NA (Not Applicable)

Table 3-107: Transmission Compressor Station National CO_2 Emissions (Metric Tons CO_2)

Source	1990	2005	2018	2019	2020	2021	2022
Station Total Emissions	32,285	20,747	17,110	17,242	17,085	17,244	17,327
Station + Compressor Fugitive Emissions	NE	NE	3,492	3,554	3,541	3,693	3,773
Reciprocating Compressor	NE	NE	10,237	10,084	9,816	9,573	9,502
Centrifugal Compressor (wet seals)	NE	NE	1,476	1,518	1,542	1,580	1,488
Centrifugal Compressor (dry seals)	NE	NE	1,906	2,087	2,187	2,398	2,565
Dehydrator vents	59	57	63	64	64	66	68
Flaring	78,386	76,030	70,366	78,424	93,510	62,974	82,004
Pneumatic Devices Transmission	6,274	4,526	945	915	863	841	876
High Bleed	NE	NE	290	280	256	226	221
Intermittent Bleed	NE	NE	631	614	587	598	639
Low Bleed	NE	NE	23	21	20	17	16
Station Venting	4,276	4,148	4,580	4,662	4,645	4,845	4,949
Total Emissions	**121,281**	**105,508**	**93,065**	**101,307**	**116,166**	**85,970**	**105,224**
Previous Estimate	*121,473*	*98,281*	*101,654*	*118,915*	*140,933*	*102,280*	*NA*

NE (Not Estimated at individual source level due to lack of data)
NA (Not Applicable)

Underground Natural Gas Storage Well Events (Methodological Update)

EPA updated the *Inventory* with CO_2 and CH_4 estimates resulting from underground natural gas storage well events that occurred in several years across the inventory time series. Previously, EPA included emissions only from the Aliso Canyon event (occurring 2015 to 2016). This update incorporates emissions from 9 events identified as occurring at storage wells. For the update, emissions from individual events were added to the year in which they occurred.

EPA calculated CH_4 emissions using the reported leak size and applying inventory assumptions for CH_4 content. The CH_4 emissions estimates were then adjusted using a 60 percent combustion efficiency if there was evidence of combustion or ignition during the event. EPA calculated CO_2 emissions only for the events where combustion or ignition occurred, using the 60 percent combustion efficiency. The *Storage Well Events* memo presents additional information and considerations for this update.

One commenter provided feedback and it focused on the 60 percent combustion efficiency. The commenter suggested using 30 percent as the combustion efficiency instead of 60 percent based on research from Gvakharia et al., 2017, which lists 30 percent as the lowest flare efficiency.[83] The commenter noted the study used to justify the 60 percent combustion efficiency evaluated engineered flares which may not be representative of combustion during emergency events.

The newly incorporated events occurred in years 1992, 1998, 2001, 2002, 2003, 2004, 2006, 2010, and 2011. They emitted on average 7,085 metric tons of CH_4 and 27,056 metric tons CO_2.

Methane emissions estimates for underground natural gas storage wells increased 15 percent across the time series compared to previous estimates. The largest increase between the updates and the previous estimates occurs in 2004, which incorporates CH_4 emissions from the Moss Bluff event.

Updates to CO_2 emissions resulted in an increase of 1,693 percent across the time series compared to previous estimates. This increase is mostly due to additions for 2001 and 2004 estimates, resulting from Yaggy and Moss Bluff events, respectively. Combustion occurred at both of these events, resulting in the application of the 60 percent combustion efficiency.

Pipeline Venting (Recalculation with Updated Data)

Transmission pipeline venting CH_4 emission estimates are on average 0.1 percent lower across the 1990 to 2021 time series than in the previous *Inventory*. The CH_4 emissions estimate for 2021 is 4 percent lower than in the previous *Inventory*. These changes were due to GHGRP submission revisions.

Table 3-108: Pipeline Venting National CH_4 Emissions (Metric Tons CH_4)

Source	1990	2005	2018	2019	2020	2021	2022
Pipeline Venting	177,951	183,159	208,438	187,266	220,544	165,703	133,761
Previous Estimate	*177,951*	*183,159*	*208,438*	*187,266*	*220,560*	*172,287*	*NA*

NA (Not Applicable)

Distribution

There were no methodological updates to the distribution segment and recalculations resulted in an average decrease in CH_4 emissions across the 1990 to 2021 time series of less than 0.1 percent and an average decrease in calculated CO_2 emissions across the 1990 to 2021 time series of less than 0.1 percent, compared to the previous *Inventory*.

[83] Gvakharia et al, 2017. Methane, Black Carbon, and Ethane Emissions from Natural Gas Flares in the Bakken Shale, North Dakota. *Environmental Science & Technology.* 51: 5317-5325. https://doi.org/10.1021/acs.est.6b05183.

Post-Meter

There were no methodological updates to estimate post-meter emissions and recalculations resulted in an average decrease in CH_4 emissions across the 1990 to 2021 time series of less than 0.1 percent and an average decrease in calculated CO_2 emissions across the 1990 to 2021 time series of less than 0.1 percent, compared to the previous *Inventory*.

Planned Improvements

Planned Improvements for 2025 *Inventory*

EPA updated the Enverus data and there were notable increases in the number of wells and completions identified as being hydraulically fractured compared with previous versions of the database. EPA will assess the underlying Enverus data to determine the cause of these changes.

Upcoming Data, and Additional Data that Could Inform the *Inventory*

EPA will assess new data received by EPA's Greenhouse Gas Reporting Program and Methane Challenge Program on an ongoing basis, which may be used to validate or improve existing estimates and assumptions.

EPA continues to track studies that contain data that may be used to update the *Inventory*. EPA will also continue to assess studies that include and compare both top-down and bottom-up emission estimates, which could lead to improved understanding of unassigned high emitters (e.g., identification of emission sources and information on frequency of high emitters) as recommended in previous stakeholder comments.

3.8 Abandoned Oil and Gas Wells (CRT Source Categories 1B2a and 1B2b)

The term "abandoned wells", as used in the *Inventory*, encompasses various types of oil and gas wells, including orphaned wells and other non-producing wells:

- Wells with no recent production, and not plugged. Common terms (such as those used in state databases) might include: inactive, temporarily abandoned, shut-in, dormant, and idle.
- Wells with no recent production and no responsible operator. Common terms might include: orphaned, deserted, long-term idle, and abandoned.
- Wells that have been plugged to prevent migration of gas or fluids.

The U.S. population of abandoned oil and gas wells (including orphaned wells and other non-producing wells) is around 3.9 million (with around 3.0 million abandoned oil wells and 0.9 million abandoned gas wells). The methods to calculate emissions from abandoned wells involve calculating the total populations of plugged and unplugged abandoned oil and gas wells in the United States and the application of emission factors. An estimate of the number of orphaned wells within this population is not developed as part of the methodology. Wells that are plugged have much lower average emissions than wells that are unplugged (less than 1 kg CH_4 per well per year, versus over 100 kg CH_4 per well per year). Around 43 percent of the abandoned well population in the United States is plugged. This fraction has increased over the *Inventory* time series (from around 22 percent in 1990) as more wells fall under regulations and programs requiring or promoting plugging of abandoned wells.

Abandoned oil wells. Abandoned oil wells emitted 235 kt CH_4 and 5 kt CO_2 in 2022. Emissions of both gases increased by 3 percent from 1990, while the total population of abandoned oil wells increased 40 percent.

Abandoned gas wells. Abandoned gas wells emitted 68 kt CH_4 and 3 kt CO_2 in 2022. Emissions of both gases increased by 33 percent from 1990, while the total population of abandoned gas wells increased 83 percent.

Table 3-109: CH_4 Emissions from Abandoned Oil and Gas Wells (MMT CO_2 Eq.)

Activity	1990	2005	2018	2019	2020	2021	2022
Abandoned Oil Wells	6.4	6.6	6.6	6.6	6.6	6.6	6.6
Abandoned Gas Wells	1.4	1.6	1.8	1.8	1.9	1.9	1.9
Total	**7.8**	**8.2**	**8.4**	**8.5**	**8.5**	**8.6**	**8.5**

Note: Totals may not sum due to independent rounding.

Table 3-110: CH_4 Emissions from Abandoned Oil and Gas Wells (kt)

Activity	1990	2005	2018	2019	2020	2021	2022
Abandoned Oil Wells	228	236	237	237	237	237	235
Abandoned Gas Wells	51	58	64	65	66	69	68
Total	**279**	**294**	**301**	**302**	**303**	**306**	**303**

Note: Totals may not sum due to independent rounding.

Table 3-111: CO_2 Emissions from Abandoned Oil and Gas Wells (MMT CO_2)

Activity	1990	2005	2018	2019	2020	2021	2022
Abandoned Oil Wells	+	+	+	+	+	+	+
Abandoned Gas Wells	+	+	+	+	+	+	+
Total	**+**	**+**	**+**	**+**	**+**	**+**	**+**

+ Does not exceed 0.05 MMT CO_2 Eq.

Note: Totals may not sum due to independent rounding.

Table 3-112: CO_2 Emissions from Abandoned Oil and Gas Wells (kt)

Activity	1990	2005	2018	2019	2020	2021	2022
Abandoned Oil Wells	5	5	5	5	5	5	5
Abandoned Gas Wells	2	3	3	3	3	3	3
Total	**7**	**7**	**8**	**8**	**8**	**8**	**8**

Note: Totals may not sum due to independent rounding.

Methodology and Time-Series Consistency

EPA uses a Tier 2 method from IPCC (2019) to quantify emissions from abandoned oil and gas wells. EPA's approach is based on the number of plugged and unplugged abandoned wells in the Appalachian region and in the rest of the U.S., and emission factors for plugged and unplugged abandoned wells in Appalachia and the rest of the U.S. Methods for abandoned wells are unavailable in IPCC (2006). The details of this approach and of the data sources used are described in the memorandum *Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-2016: Abandoned Wells in Natural Gas and Petroleum Systems (2018 Abandoned Wells Memo).*

EPA developed abandoned well CH_4 emission factors using data from Kang et al. (2016) and Townsend-Small et al. (2016). Plugged and unplugged abandoned well CH_4 emission factors were developed at the national-level (using emission data from Townsend-Small et al.) and for the Appalachia region (using emission data from measurements in Pennsylvania and Ohio conducted by Kang et al. and Townsend-Small et al., respectively). The Appalachia region emissions factors were applied to abandoned wells in states in the Appalachian basin region, and the national-level emission factors were applied to abandoned wells in all other states. EPA developed abandoned well CO_2 emission factors using the CH_4 emission factors and an assumed ratio of CO_2-to-CH_4 gas content, similar to the approach used to calculate CO_2 emissions for many sources in Petroleum Systems and Natural Gas Systems. For abandoned

oil wells, EPA used the Petroleum Systems default production segment associated gas ratio of 0.020 MT CO_2/MT CH_4, which was derived through API TankCalc modeling runs. For abandoned gas wells, EPA used the Natural Gas Systems default production segment CH_4 and CO_2 gas content values (GRI/EPA 1996, GTI 2001) to develop a ratio of 0.044 MT CO_2/MT CH_4. The same respective emission factors are applied for each year of the time series.

EPA developed state-level annual counts of abandoned wells for 1990 through 2022 by summing together an annual estimate of abandoned wells in the Enverus data set (Enverus 2023), and an estimate of total abandoned wells not included the Enverus dataset (see 2018 Abandoned Wells Memo for additional information on how the value was calculated) for each state. References reviewed to develop the number of abandoned wells not included in the Enverus dataset include historical records collected by state agencies and by USGS.

The state-level abandoned well population was then split into plugged and unplugged wells by applying an assumption that all abandoned wells were unplugged in 1950 and using Enverus data to calculate the fraction of plugged abandoned wells in 2022. Linear interpolation was applied between the 1950 value and 2022 value to calculate the plugged fraction for intermediate years. See the memorandum *Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-2016: Abandoned Wells in Natural Gas and Petroleum Systems (2018 Abandoned Wells Memo)* for details.[84]

Abandoned Oil Wells

Table 3-113: Abandoned Oil Wells Activity Data, CH_4 and CO_2 Emissions (kt)

Source	1990	2005	2018	2019	2020	2021	2022
Plugged abandoned oil wells	475,939	810,564	1,156,633	1,192,282	1,227,566	1,263,583	1,281,380
Unplugged abandoned oil wells	1,697,730	1,787,095	1,781,964	1,783,807	1,784,834	1,785,340	1,767,543
Total Abandoned Oil Wells	2,173,669	2,597,659	2,938,597	2,976,089	3,012,400	3,048,923	3,048,923
Abandoned oil wells in Appalachia	22%	20%	19%	19%	18%	18%	18%
Abandoned oil wells outside of Appalachia	78%	80%	81%	81%	82%	82%	82%
CH_4 from plugged abandoned oil wells (kt)	0.17	0.25	0.34	0.35	0.36	0.36	0.37
CH_4 from unplugged abandoned oil wells(kt)	227.6	236.1	236.5	236.9	237.0	236.8	235.0
Total CH_4 from abandoned oil wells (kt)	**227.7**	**236.4**	**236.8**	**237.2**	**237.3**	**237.2**	**235.4**
Total CO_2 from abandoned oil wells (kt)	**4.6**	**4.8**	**4.8**	**4.8**	**4.8**	**4.8**	**4.8**

Abandoned Gas Wells

Table 3-114: Abandoned Gas Wells Activity Data, CH_4 and CO_2 Emissions (kt)

Source	1990	2005	2018	2019	2020	2021	2022
Plugged abandoned gas wells	110,089	210,902	348,625	359,018	372,605	389,745	395,236
Unplugged abandoned gas wells	355,620	404,960	447,374	448,504	453,988	463,119	457,628
Total Abandoned Gas Wells	465,709	615,862	795,999	807,522	826,593	852,864	852,864
Abandoned gas wells in Appalachia	28%	25%	24%	24%	24%	26%	26%

[84] See https://www.epa.gov/ghgemissions/natural-gas-and-petroleum-systems.

Abandoned gas wells outside of Appalachia	72%	75%	76%	76%	76%	74%	74%
CH_4 from plugged abandoned gas wells (kt)	0.06	0.11	0.17	0.17	0.19	0.21	0.21
CH_4 from unplugged abandoned gas wells (kt)	51.1	57.5	64.1	64.5	65.9	68.5	67.8
Total CH_4 from abandoned gas wells (kt)	**51.1**	**57.6**	**64.3**	**64.7**	**66.1**	**68.7**	**68.0**
Total CO_2 from abandoned gas wells (kt)	**2.2**	**2.5**	**2.8**	**2.8**	**2.9**	**3.0**	**3.0**

Uncertainty

To characterize uncertainty surrounding estimates of abandoned well emissions, EPA conducted a quantitative uncertainty analysis using the IPCC Approach 2 methodology (Monte Carlo simulation technique). See the 2018 Abandoned Wells Memo for details of the uncertainty analysis methods. EPA used Microsoft Excel's @RISK add-in tool to estimate the 95 percent confidence bound around total methane emissions from abandoned oil and gas wells in year 2022, then applied the calculated bounds to both CH_4 and CO_2 emissions estimates for each population. The @RISK add-in provides for the specification of probability density functions (PDFs) for key variables within a computational structure that mirrors the calculation of the inventory estimate. EPA used measurement data from the Kang et al. (2016) and Townsend-Small et al. (2016) studies to characterize the CH_4 emission factor PDFs. For activity data inputs (e.g., total count of abandoned wells, split between plugged and unplugged), EPA assigned default uncertainty bounds of ± 10 percent based on expert judgment.

The IPCC guidance notes that in using this method, "some uncertainties that are not addressed by statistical means may exist, including those arising from omissions or double counting, or other conceptual errors, or from incomplete understanding of the processes that may lead to inaccuracies in estimates developed from models." As a result, the understanding of the uncertainty of emission estimates for this category evolves and improves as the underlying methodologies and datasets improve. The uncertainty bounds reported below only reflect those uncertainties that EPA has been able to quantify and do not incorporate considerations such as modeling uncertainty, data representativeness, measurement errors, misreporting or misclassification.

The results presented below in Table 3-115 provide the 95 percent confidence bound within which actual emissions from abandoned oil and gas wells are likely to fall for the year 2022, using the recommended IPCC methodology. Abandoned oil well CH_4 emissions in 2022 were estimated to be between 1.1 and 19.7 MMT CO_2 Eq., while abandoned gas well CH_4 emissions were estimated to be between 0.3 and 5.4 MMT CO_2 Eq. at a 95 percent confidence level. Uncertainty bounds for other years of the time series have not been calculated, but uncertainty is expected to vary over the time series.

Table 3-115: Approach 2 Quantitative Uncertainty Estimates for CH_4 and CO_2 Emissions from Petroleum and Natural Gas Systems (MMT CO_2 Eq. and Percent)

Source	Gas	2022 Emission Estimate (MMT CO_2 Eq.)[b]	Uncertainty Range Relative to Emission Estimate[a] (MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Abandoned Oil Wells	CH_4	6.6	1.1	19.7	-83%	+204%
Abandoned Gas Wells	CH_4	1.9	0.3	5.4	-83%	+204%
Abandoned Oil Wells	CO_2	0.005	0.001	0.014	-83%	+204%
Abandoned Gas Wells	CO_2	0.003	0.0005	0.008	-83%	+204%

[a] Range of emission estimates estimated by applying the 95 percent confidence intervals obtained from the Monte Carlo simulation analysis conducted for total abandoned oil and gas well CH_4 emissions in year 2022.

[b] All reported values are rounded after calculation. As a result, lower and upper bounds may not be duplicable from other rounded values as shown in the table.

QA/QC and Verification Discussion

The emission estimates in the *Inventory* are continually reviewed and assessed to determine whether emission factors and activity factors accurately reflect current industry practices. In order to ensure the quality of emission estimates for abandoned wells, general (IPCC Tier 1) quality assurance/quality control (QA/QC) procedures were implemented consistent with the U.S. Inventory QA/QC plan outlined in Annex 8. Additionally, EPA reviewed the current Enverus dataset and compared it with results from the previous dataset to identify outliers and instances of significant changes to abandoned oil and gas well counts.

EPA performs a thorough review of information associated with new studies to assess whether the assumptions in the *Inventory* are consistent with industry practices and whether new data is available that could be considered for updates to the estimates. As in previous years, EPA conducted early engagement and communication with stakeholders on updates prior to public review. EPA held a stakeholder webinar on greenhouse gas data for oil and gas in October of 2023.

Recalculations Discussion

EPA updated the *Inventory* with revised abandoned oil and gas well counts developed from Enverus data (Enverus 2023). Compared to the previous *Inventory*, annual abandoned oil well counts increased by an average of 2 percent across the time series and increased by 4 percent in 2021. Annual abandoned gas well counts increased by 2 percent across the time series and 7 percent in 2021. Similarly, both plugged wells and unplugged wells increased by 2 percent across the time series. As a result of this update, calculated abandoned oil well CH_4 and CO_2 emissions increased by an average of 2 percent each year across the time series and increased by 3 percent in 2021, compared to the previous *Inventory*. Abandoned gas well CH_4 and CO_2 emissions increased by an average of 1 percent across the time series and increased by 8 percent in 2021, compared to the previous *Inventory*.

Planned Improvements

EPA will continue to assess new data and stakeholder feedback on considerations (such as potential use of emission factor data from regions not included in the measurement studies on which current emission factors are based) to improve the abandoned well count estimates and emission factors. In future Inventories, EPA will assess data that become available from Department of Interior and Department of Energy orphan well plugging programs.

3.9 International Bunker Fuels (CRT Source Category 1: Memo Items)

Emissions resulting from the combustion of fuels used for international transport activities, termed international bunker fuels under the Paris Agreement and the UNFCCC, are not included in national emission totals, but are reported separately based upon location of fuel sales. The decision to report emissions from international bunker fuels separately, instead of allocating them to a particular country, was made by the Intergovernmental

Negotiating Committee in establishing the Framework Convention on Climate Change.[85] These decisions are reflected in the IPCC methodological guidance, including IPCC (2006), in which countries are requested to report emissions from ships or aircraft that depart from their ports with fuel purchased within national boundaries and are engaged in international transport separately from national totals (IPCC 2006).[86]

Two transport modes are addressed under the IPCC definition of international bunker fuels: aviation and marine.[87] Greenhouse gases emitted from the combustion of international bunker fuels, like other fossil fuels, include CO_2, CH_4 and N_2O for marine transport modes, and CO_2 and N_2O for aviation transport modes. Emissions from ground transport activities—by road vehicles and trains—even when crossing international borders are allocated to the country where the fuel was loaded into the vehicle and, therefore, are not counted as bunker fuel emissions.

The *2006 IPCC Guidelines* distinguish between three different modes of air traffic: civil aviation, military aviation, and general aviation. Civil aviation comprises aircraft used for the commercial transport of passengers and freight, military aviation comprises aircraft under the control of national armed forces, and general aviation applies to recreational and small corporate aircraft. The *2006 IPCC Guidelines* further define international bunker fuel use from civil aviation as the fuel combusted for civil (e.g., commercial) aviation purposes by aircraft arriving or departing on international flight segments. However, as mentioned above, and in keeping with the *2006 IPCC Guidelines*, only the fuel purchased in the United States and used by aircraft taking-off (i.e., departing) from the United States are reported here. The standard fuel used for civil and military aviation is kerosene-type jet fuel, while the typical fuel used for general aviation is aviation gasoline.[88]

Emissions of CO_2 from aircraft are essentially a function of fuel consumption. Nitrous oxide emissions also depend upon engine characteristics, flight conditions, and flight phase (i.e., take-off, climb, cruise, decent, and landing). Recent data suggest that little or no CH_4 is emitted by modern engines (Anderson et al. 2011), and as a result, CH_4 emissions from this category are reported as zero. In jet engines, N_2O is primarily produced by the oxidation of atmospheric nitrogen, and the majority of emissions occur during the cruise phase.

International marine bunkers comprise emissions from fuels burned by ocean-going ships of all flags that are engaged in international transport. Ocean-going ships are generally classified as cargo and passenger carrying, military (i.e., U.S. Navy), fishing, and miscellaneous support ships (e.g., tugboats). For the purpose of estimating greenhouse gas emissions, international bunker fuels are solely related to cargo and passenger carrying vessels, which is the largest of the four categories, and military vessels. Two main types of fuels are used on sea-going vessels: distillate diesel fuel and residual fuel oil. Carbon dioxide is the primary greenhouse gas emitted from marine shipping.

Overall, aggregate greenhouse gas emissions in 2022 from the combustion of international bunker fuels from both aviation and marine activities were 99.1 MMT CO_2 Eq., or 5.2 percent below emissions in 1990 (see Table 3-116 and Table 3-117). Emissions from international flights and international shipping voyages departing from the United States have increased by 74.4 percent and decreased by 51.7 percent, respectively, since 1990. The majority of these emissions were in the form of CO_2; however, small amounts of CH_4 (from marine transport modes) and N_2O were also emitted.

[85] See report of the Intergovernmental Negotiating Committee for a Framework Convention on Climate Change on the work of its ninth session, held at Geneva from 7 to 18 February 1994 (A/AC.237/55, annex I, para. 1c).

[86] Note that the definition of international bunker fuels used by the UNFCCC differs from that used by the International Civil Aviation Organization.

[87] Most emission related international aviation and marine regulations are under the rubric of the International Civil Aviation Organization (ICAO) or the International Maritime Organization (IMO), which develop international codes, recommendations, and conventions, such as the International Convention of the Prevention of Pollution from Ships (MARPOL).

[88] Naphtha-type jet fuel was used in the past by the military in turbojet and turboprop aircraft engines.

Table 3-116: CO_2, CH_4, and N_2O Emissions from International Bunker Fuels (MMT CO_2 Eq.)

Gas/Mode	1990	2005	2018	2019	2020	2021	2022
CO_2	**103.6**	**113.3**	**124.3**	**113.6**	**69.6**	**80.2**	**98.2**
Aviation	38.2	60.2	83.0	78.3	39.8	50.8	66.6
Commercial	*30.0*	*55.6*	*79.8*	*75.1*	*36.7*	*47.6*	*63.5*
Military	*8.2*	*4.6*	*3.2*	*3.2*	*3.1*	*3.2*	*3.1*
Marine	65.4	53.1	41.3	35.4	29.9	29.4	31.6
CH_4	**0.2**	**0.1**	**0.1**	**0.1**	**0.1**	**0.1**	**0.1**
Aviation	NO	NO	NO	NO	NO	NO	NO
Marine	0.2	0.1	0.1	0.1	0.1	0.1	0.1
N_2O	**0.8**	**0.9**	**1.0**	**0.9**	**0.5**	**0.6**	**0.8**
Aviation	0.3	0.5	0.7	0.7	0.3	0.4	0.6
Marine	0.4	0.4	0.3	0.2	0.2	0.2	0.2
Total	**104.6**	**114.3**	**125.3**	**114.6**	**70.3**	**80.9**	**99.1**

NO (Not Occurring)

Notes: Totals may not sum due to independent rounding. Includes aircraft cruise altitude emissions.

Table 3-117: CO_2, CH_4, and N_2O Emissions from International Bunker Fuels (kt)

Gas/Mode	1990	2005	2018	2019	2020	2021	2022
CO_2	**103,634**	**113,328**	**124,279**	**113,632**	**69,638**	**80,180**	**98,241**
Aviation	38,205	60,221	82,953	78,280	39,781	50,812	66,646
Marine	65,429	53,107	41,325	35,351	29,857	29,369	31,595
CH_4	**7**	**5**	**4**	**4**	**3**	**3**	**3**
Aviation	NO	NO	NO	NO	NO	NO	NO
Marine	7	5	4	4	3	3	3
N_2O	**3**	**3**	**4**	**3**	**2**	**2**	**3**
Aviation	1	2	3	2	1	2	2
Marine	2	1	1	1	1	1	1

NO (Not Occurring)

Notes: Totals may not sum due to independent rounding. Includes aircraft cruise altitude emissions.

Methodology and Time-Series Consistency

Emissions of CO_2 were for the most part estimated by applying carbon content and fraction oxidized factors to fuel consumption activity data. This approach is analogous to that described under Section 3.1. Carbon content and fraction oxidized factors for jet fuel (except for commercial aviation as per below), distillate fuel oil, and residual fuel oil are the same as used for CO_2 from Fossil Fuel Combustion and are presented in Annex 2.1, Annex 2.2, and Annex 3.8 of this *Inventory*. Density conversions were taken from ASTM (1989) and USAF (1998). Heat content for distillate fuel oil and residual fuel oil were taken from EIA (2024) and USAF (1998), and heat content for jet fuel was taken from EIA (2024). See below for details on how emission estimates for commercial aviation were determined.

A complete description of the methodology and a listing of the various factors employed can be found in Annex 2.1. See Annex 3.8 for a specific discussion on the methodology used for estimating emissions from international bunker fuel use by the U.S. military.

Emission estimates for CH_4 and N_2O were calculated by multiplying emission factors by measures of fuel consumption by fuel type and mode. Emission factors used in the calculations of CH_4 and N_2O emissions were obtained from the *Revised 1996 IPCC Guidelines* (IPCC/UNEP/OECD/IEA 1997), which is also referenced in the *2006 IPCC Guidelines* (IPCC 2006). For aircraft emissions, the following value, in units of grams of pollutant per kilogram of fuel consumed (g/kg), was employed: 0.1 for N_2O (IPCC 2006). For marine vessels consuming either distillate diesel or residual fuel oil the following values (g/MJ), were employed: 0.315 for CH_4 and 0.08 for N_2O. Activity data for aviation included solely jet fuel consumption statistics, while the marine mode included both distillate diesel and residual fuel oil.

Activity data on domestic and international aircraft fuel consumption were developed by the U.S. Federal Aviation Administration (FAA) using radar-informed data from the FAA Enhanced Traffic Management System (ETMS) for 1990 and 2000 through 2022 as modeled with the Aviation Environmental Design Tool (AEDT). This bottom-up approach is built from modeling dynamic aircraft performance for each flight occurring within an individual calendar year. The analysis incorporates data on the aircraft type, date, flight identifier, departure time, arrival time, departure airport, arrival airport, ground delay at each airport, and real-world flight trajectories. To generate results for a given flight within AEDT, the radar-informed aircraft data is correlated with engine and aircraft performance data to calculate fuel burn and exhaust emissions. Information on exhaust emissions for in-production aircraft engines comes from the International Civil Aviation Organization (ICAO) Aircraft Engine Emissions Databank (EDB). This bottom-up approach is in accordance with the Tier 3B method from the *2006 IPCC Guidelines* (IPCC 2006).

International aviation CO_2 estimates for 1990 and 2000 through 2022 were obtained directly from FAA's AEDT model (FAA 2024). The radar-informed method that was used to estimate CO_2 emissions for commercial aircraft for 1990 and 2000 through 2022 was not possible for 1991 through 1999 because the radar dataset was not available for years prior to 2000. FAA developed Official Airline Guide (OAG) schedule-informed inventories modeled with AEDT and great circle trajectories for 1990, 2000, and 2010. Because fuel consumption and CO_2 emission estimates for years 1991 through 1999 are unavailable, consumption estimates for these years were calculated using fuel consumption estimates from the Bureau of Transportation Statistics (DOT 1991 through 2013), adjusted based on 2000 through 2005 data. See Annex 3.3 for more information on the methodology for estimating emissions from commercial aircraft jet fuel consumption.

Data on U.S. Department of Defense (DoD) aviation bunker fuels and total jet fuel consumed by the U.S. military was supplied by the Office of the Under Secretary of Defense (Installations and Environment), DoD. Estimates of the percentage of each Service's total operations that were international operations were developed by DoD. Military aviation bunkers included international operations, operations conducted from naval vessels at sea, and operations conducted from U.S. installations principally over international water in direct support of military operations at sea. Military aviation bunker fuel emissions were estimated using military fuel and operations data synthesized from unpublished data from DoD's Defense Logistics Agency Energy (DLA Energy 2023). Together, the data allow the quantity of fuel used in military international operations to be estimated. Densities for each jet fuel type were obtained from a report from the U.S. Air Force (USAF 1998). Final jet fuel consumption estimates are presented in Table 3-118. See Annex 3.8 for additional discussion of military data.

Table 3-118: Aviation Jet Fuel Consumption for International Transport (TBtu)

Nationality	1990	2005	2018	2019	2020	2021	2022
U.S. and Foreign Carriers	426	791	1,104	1,068	521	677	902
U.S. Military	116	64	44	44	43	44	44
Total	**542**	**854**	**1,148**	**1,112**	**564**	**721**	**946**

Note: Totals may not sum due to independent rounding.

In order to quantify the civilian international component of marine bunker fuels, activity data on distillate diesel and residual fuel oil consumption by cargo or passenger carrying marine vessels departing from U.S. ports were collected for individual shipping agents on a monthly basis by the U.S. Customs and Border Protection. This information was then reported in unpublished data collected by the Foreign Trade Division of the U.S. Department of Commerce's Bureau of the Census (DOC 1991 through 2022) for 1990 through 2001, 2007 through 2022, and the Department of Homeland Security's Bunker Report for 2003 through 2006 (DHS 2008). Fuel consumption data for 2002 was interpolated due to inconsistencies in reported fuel consumption data. Activity data on distillate diesel consumption by military vessels departing from U.S. ports were provided by DLA Energy (2023). The total amount of fuel provided to naval vessels was reduced by 21 percent to account for fuel used while the vessels were not underway (i.e., in port). Data on the percentage of steaming hours underway versus not underway were provided by the U.S. Navy. These fuel consumption estimates are presented in Table 3-119.

Table 3-119: Marine Fuel Consumption for International Transport (Million Gallons)

Fuel Type	1990	2005	2018	2019	2020	2021	2022
Residual Fuel Oil	4,781	3,881	2,790	2,246	1,964	1,953	2,172
Distillate Diesel Fuel & Other	617	444	684	702	461	437	435
U.S. Military Naval Fuels	522	471	285	281	296	285	263
Total	**5,920**	**4,796**	**3,759**	**3,229**	**2,721**	**2,674**	**2,870**

Note: Totals may not sum due to independent rounding.

Methodological recalculations were applied to the entire time series to ensure time-series consistency from 1990 through 2022.

Uncertainty

Emission estimates related to the consumption of international bunker fuels are subject to the same uncertainties as those from domestic aviation and marine mobile combustion emissions; however, additional uncertainties result from the difficulty in collecting accurate fuel consumption activity data for international transport activities separate from domestic transport activities.[89] For example, smaller aircraft on shorter routes often carry sufficient fuel to complete several flight segments without refueling in order to minimize time spent at the airport gate or take advantage of lower fuel prices at particular airports. This practice, called tankering, when done on international flights, complicates the use of fuel sales data for estimating bunker fuel emissions. Tankering is less common with the type of large, long-range aircraft that make many international flights from the United States, however. Similar practices occur in the marine shipping industry where fuel costs represent a significant portion of overall operating costs and fuel prices vary from port to port, leading to some tankering from ports with low fuel costs.

Uncertainties exist with regard to the total fuel used by military aircraft and ships. Total aircraft and ship fuel use estimates were developed from DoD records, which document fuel sold to the DoD Components (e.g., Army, Department of Navy and Air Force) from the Defense Logistics Agency Energy. These data may not include fuel used in aircraft and ships as a result of a Service procuring fuel from, selling fuel to, trading fuel with, or giving fuel to other ships, aircraft, governments, or other entities.

Additionally, there are uncertainties in historical aircraft operations and training activity data. Estimates for the quantity of fuel actually used in Navy and Air Force flying activities reported as bunker fuel emissions had to be estimated based on a combination of available data and expert judgment. Estimates of marine bunker fuel emissions were based on Navy vessel steaming hour data, which reports fuel used while underway and fuel used while not underway. This approach does not capture some voyages that would be classified as domestic for a commercial vessel. Conversely, emissions from fuel used while not underway preceding an international voyage are reported as domestic rather than international as would be done for a commercial vessel. There is uncertainty associated with ground fuel estimates for 1997 through 2022, including estimates for the quantity of jet fuel allocated to ground transportation. Small fuel quantities may have been used in vehicles or equipment other than that which was assumed for each fuel type.

There are also uncertainties in fuel end-uses by fuel type, emissions factors, fuel densities, diesel fuel sulfur content, aircraft and vessel engine characteristics and fuel efficiencies, and the methodology used to back-calculate the data set to 1990 using the original set from 1995. The data were adjusted for trends in fuel use based on a closely correlating, but not matching, data set. All assumptions used to develop the estimate were based on process knowledge, DoD data, and expert judgments. The magnitude of the potential errors related to the various uncertainties has not been calculated but is believed to be small. The uncertainties associated with future military bunker fuel emission estimates could be reduced through revalidation of assumptions based on data regarding current equipment and operational tempo, however, it is doubtful data with more fidelity exist at this time.

[89] See uncertainty discussions under section 3.1 CO_2 from Fossil Fuel Combustion.

Although aggregate fuel consumption data have been used to estimate emissions from aviation, the recommended method for estimating emissions of gases other than CO_2 in the *2006 IPCC Guidelines* (IPCC 2006) is to use data by specific aircraft type, number of individual flights and, ideally, movement data to better differentiate between domestic and international aviation and to facilitate estimating the effects of changes in technologies. The IPCC also recommends that cruise altitude emissions be estimated separately using fuel consumption data, while landing and take-off (LTO) cycle data be used to estimate near-ground level emissions of gases other than CO_2.[90]

There is also concern regarding the reliability of the existing DOC (1991 through 2022) data on marine vessel fuel consumption reported at U.S. customs stations due to the significant degree of inter-annual variation.

QA/QC and Verification

In order to ensure the quality of the emission estimates from international bunker fuels, General (IPCC Tier 1) and category-specific (Tier 2) Quality Assurance/Quality Control (QA/QC) procedures were implemented consistent with the U.S. Inventory QA/QC plan outlined in Annex 8 The Tier 2 procedures that were implemented involved checks specifically focusing on the activity data and emission factor sources and methodology used for estimating CO_2, CH_4, and N_2O emissions from international bunker fuels in the United States. Emission totals for the different sectors and fuels were compared and trends were investigated. No corrective actions were necessary.

Recalculations Discussion

No recalculations were performed for the current *Inventory*.

Planned Improvements

EPA will evaluate data availability to update the sources for densities, energy contents, and emission factors applied to estimate emissions from aviation and marine fuels. Many are from sources from the late 1990s, such as IPCC/UNEP/OECD/IEA (1997). Potential sources with more recent data include the International Maritime Organization (IMO) greenhouse gas emission inventory, International Air Transport Association (IATA)/ICAO greenhouse gas reporting system (CORSIA), and the EPA Greenhouse Gas Reporting Program (GHGRP) Technical Support Document for Petroleum Products. Specifically, EPA will evaluate data availability to support updating the heat contents and carbon contents of jet fuel with input from EIA.

A longer-term effort is underway to consider the feasibility of including data from a broader range of domestic and international sources for bunker fuels. Potential sources include the IMO greenhouse gas emission inventory, data from the U.S. Coast Guard on vehicle operation currently used in criteria pollutant modeling, data from the International Energy Agency (IEA), relevant updated FAA models to improve aviation bunker fuel estimates, and researching newly available marine bunker data.

[90] U.S. aviation emission estimates for CO, NO_x, and NMVOCs are reported by EPA's National Emission Inventory (NEI) Air Pollutant Emission Trends website, and reported under the Mobile Combustion section. It should be noted that these estimates are based solely upon LTO cycles and consequently only capture near ground-level emissions, which are more relevant for air quality evaluations. These estimates also include both domestic and international flights. Therefore, estimates reported under the Mobile Combustion section overestimate IPCC-defined domestic CO, NO_x, and NMVOC emissions by including landing and take-off (LTO) cycles by aircraft on international flights, but underestimate because they do not include emissions from aircraft on domestic flight segments at cruising altitudes.

3.10 Biomass and Biofuels Consumption (CRT Source Category 1A)

The combustion of biomass—such as wood, charcoal, the biogenic portions of MSW, and wood waste and biofuels such as ethanol, biogas, and biodiesel—generates CO_2 in addition to CH_4 and N_2O already covered in this chapter. In line with the reporting requirements for inventories submitted under the Paris Agreement and the UNFCCC, CO_2 emissions from biomass and biofuel combustion have been estimated separately from fossil fuel CO_2 emissions and are not directly included in the energy sector contributions to U.S. totals. In accordance with IPCC methodological guidelines, any such emissions are calculated by accounting for net carbon fluxes from changes in biogenic carbon reservoirs in wooded or crop lands. For a more complete description of this methodological approach, see the Land Use, Land-Use Change, and Forestry chapter (Chapter 6), which accounts for the contribution of any resulting CO_2 emissions to U.S. totals within the Land Use, Land-Use Change, and Forestry sector's approach.

Therefore, CO_2 emissions from biomass and biofuel consumption are not included specifically in summing energy sector totals. However, they are presented here for informational purposes and to provide detail on biomass and biofuels consumption.

In 2022, total CO_2 emissions from the burning of woody biomass in the industrial, residential, commercial, and electric power sectors were approximately 195.3 MMT CO_2 Eq. (195,338 kt) (see Table 3-120 and Table 3-121). As the largest consumer of woody biomass, the industrial sector was responsible for 62.9 percent of the CO_2 emissions from this source. The residential sector was the second largest emitter, constituting 22.3 percent of the total, while the electric power and commercial sectors accounted for the remainder.

Table 3-120: CO_2 Emissions from Wood Consumption by End-Use Sector (MMT CO_2 Eq.)

End-Use Sector	1990	2005	2018	2019	2020	2021	2022
Industrial	135.3	136.3	134.4	132.1	127.3	128.2	122.8
Residential	59.8	44.3	54.1	56.3	35.6	35.5	43.6
Commercial	6.8	7.2	8.7	8.7	8.6	8.5	8.6
Electric Power	13.3	19.1	22.8	20.7	19.1	20.3	20.4
Total	**215.2**	**206.9**	**220.0**	**217.7**	**190.6**	**192.5**	**195.3**

Note: Totals may not sum due to independent rounding.

Table 3-121: CO_2 Emissions from Wood Consumption by End-Use Sector (kt)

End-Use Sector	1990	2005	2018	2019	2020	2021	2022
Industrial	135,348	136,269	134,417	132,069	127,301	128,209	122,824
Residential	59,808	44,340	54,122	56,251	35,585	35,484	43,565
Commercial	6,779	7,218	8,669	8,693	8,554	8,528	8,563
Electric Power	13,252	19,074	22,795	20,677	19,115	20,288	20,385
Total	**215,186**	**206,901**	**220,003**	**217,690**	**190,554**	**192,509**	**195,338**

Note: Totals may not sum due to independent rounding.

Carbon dioxide emissions from combustion of the biogenic components of MSW by the electric power sector were an estimated 14.9 MMT CO_2 (14,864 kt) in 2022. Emissions across the time series are shown in Table 3-122 and Table 3-123. As discussed in Section 3.3, MSW is combusted to produce electricity and the CO_2 emissions from the fossil portion of the MSW (e.g., plastics, textiles, etc.) are included in the energy sector FFC estimates. The MSW also includes biogenic components (e.g., food waste, yard trimmings, natural fibers) and the CO_2 emissions associated with that biogenic portion is included here.

Table 3-122: CO_2 Emissions from Biogenic Components of MSW (MMT CO_2 Eq.)

End-Use Sector	1990	2005	2018	2019	2020	2021	2022
Electric Power	18.5	14.7	16.1	15.7	15.6	15.3	14.9

Table 3-123: CO_2 Emissions from Biogenic Components of MSW (kt)

End-Use Sector	1990	2005	2018	2019	2020	2021	2022
Electric Power	18,534	14,722	16,115	15,709	15,614	15,329	14,864

The transportation sector is responsible for most of the fuel ethanol consumption in the United States. Ethanol used for fuel is currently produced primarily from corn grown in the Midwest, but it can be produced from a variety of biomass feedstocks. Most ethanol for transportation use is blended with gasoline to create a 90 percent gasoline, 10 percent by volume ethanol blend known as E-10 or gasohol.

In 2022, the United States transportation sector consumed an estimated 1,094.9 trillion Btu of ethanol (94 percent of total), and as a result, produced approximately 75.0 MMT CO_2 Eq. (74,953 kt) (see Table 3-124 and Table 3-125) of CO_2 emissions. Smaller quantities of ethanol were also used in the industrial and commercial sectors. Ethanol fuel production and consumption has grown significantly since 1990 due to the favorable economics of blending ethanol into gasoline and federal policies that have encouraged use of renewable fuels.

Table 3-124: CO_2 Emissions from Ethanol Consumption (MMT CO_2 Eq.)

End-Use Sector	1990	2005	2018	2019	2020	2021	2022
Transportation[a]	4.1	21.6	78.6	78.7	68.1	75.4	75.0
Industrial	0.1	1.2	1.4	1.6	1.6	1.5	1.9
Commercial	0.1	0.2	1.9	2.2	2.2	2.1	2.7
Total	**4.2**	**22.9**	**81.9**	**82.6**	**71.8**	**79.1**	**79.6**

[a] See Annex 3.2, Table A-74 for additional information on transportation consumption of these fuels.
Note: Totals may not sum due to independent rounding.

Table 3-125: CO_2 Emissions from Ethanol Consumption (kt)

End-Use Sector	1990	2005	2018	2019	2020	2021	2022
Transportation[a]	4,059	21,616	78,603	78,739	68,085	75,417	74,953
Industrial	105	1,176	1,404	1,610	1,582	1,509	1,919
Commercial	63	151	1,910	2,229	2,182	2,139	2,721
Total	**4,227**	**22,943**	**81,917**	**82,578**	**71,848**	**79,064**	**79,593**

[a] See Annex 3.2, Table A-74 for additional information on transportation consumption of these fuels.
Note: Totals may not sum due to independent rounding.

The transportation sector is assumed to be responsible for all of the biodiesel consumption in the United States (EIA 2024a). Biodiesel is currently produced primarily from soybean oil, but it can be produced from a variety of biomass feedstocks including waste oils, fats, and greases. Biodiesel for transportation use appears in low-level blends (less than 5 percent) with diesel fuel, high-level blends (between 6 and 20 percent) with diesel fuel, and 100 percent biodiesel (EIA 2024b).

In 2022, the United States consumed an estimated 211.6 trillion Btu of biodiesel, and as a result, produced approximately 15.6 MMT CO_2 Eq. (15,622 kt) (see Table 3-126 and Table 3-127) of CO_2 emissions. Biodiesel production and consumption has grown significantly since 2001 due to the favorable economics of blending biodiesel into diesel and federal policies that have encouraged use of renewable fuels (EIA 2024b). There was no measured biodiesel consumption prior to 2001 EIA (2024a).

Table 3-126: CO_2 Emissions from Biodiesel Consumption (MMT CO_2 Eq.)

End-Use Sector	1990	2005	2018	2019	2020	2021	2022
Transportation[a]	NO	0.9	17.9	17.1	17.7	16.1	15.6

NO (Not Occurring)

[a] See Annex 3.2, Table A-74 for additional information on transportation consumption of these fuels.

Table 3-127: CO_2 Emissions from Biodiesel Consumption (kt)

End-Use Sector	1990	2005	2018	2019	2020	2021	2022
Transportation[a]	NO	856	17,936	17,080	17,678	16,112	15,622

NO (Not Occurring)

[a] See Annex 3.2, Table A-74 for additional information on transportation consumption of these fuels.

Methodology and Time-Series Consistency

Woody biomass emissions were estimated by applying two gross heat contents from EIA (Lindstrom 2006) to U.S. consumption data (EIA 2024a) (see Table 3-129), provided in energy units for the industrial, residential, commercial, and electric power sectors. One heat content (16.95 MMBtu/MT wood and wood waste) was applied to the industrial sector's consumption, while the other heat content (15.43 MMBtu/MT wood and wood waste) was applied to the consumption data for the other sectors. An EIA emission factor of 0.434 MT C/MT wood (Lindstrom 2006) was then applied to the resulting quantities of woody biomass to obtain CO_2 emission estimates. The woody biomass is assumed to contain black liquor and other wood wastes, have a moisture content of 12 percent, and undergo complete combustion to be converted into CO_2.

Data for total waste incinerated, excluding tires, from 1990 to 2022 was derived following the methodology described in Section 3.3. Biogenic CO_2 emissions associated with MSW combustion were obtained from EPA's GHGRP FLIGHT data for MSW combustion sources (EPA 2023). Dividing biogenic CO_2 emissions from GHGRP FLIGHT data for MSW combustors by estimated MSW tonnage combusted yielded an annual biogenic CO_2 emission factor. This approach follows the same approach used to develop the fossil CO_2 emissions from MSW combustion as discussed in Section 3.3. As this data was only available following 2011, all years prior use an average of the emission factors from 2011 through 2015.

Biogenic CO_2 emissions from MSW combustion were calculated by multiplying the annual tonnage estimates, excluding tires, by the calculated emissions factor. Calculated biogenic CO_2 emission factors are shown in Table 3-128.

Table 3-128: Calculated Biogenic CO_2 Content per Ton Waste (kg CO_2/Short Ton Combusted)

End-Use Sector	1990	2005	2018	2019	2020	2021	2022
CO_2 Emission Factors	556	556	553	558	566	550	564

The amount of ethanol allocated across the transportation, industrial, and commercial sectors was based on the sector allocations of ethanol-blended motor gasoline. The sector allocations of ethanol-blended motor gasoline were determined using a bottom-up analysis conducted by EPA, as described in the Methodology section of Fossil Fuel Combustion. Total U.S. ethanol consumption from EIA (2024a) was allocated to individual sectors using the same sector allocations as ethanol-blended motor gasoline. The emissions from ethanol consumption were calculated by applying an emission factor of 18.67 MMT C/Qbtu (EPA 2010) to adjusted ethanol consumption estimates (see Table 3-130). The emissions from biodiesel consumption were calculated by applying an emission

factor of 20.1 MMT C/Qbtu (EPA 2010) to U.S. biodiesel consumption estimates that were provided in energy units (EIA 2024a) (see Table 3-131).[91]

Table 3-129: Woody Biomass Consumption by Sector (Trillion Btu)

End-Use Sector	1990	2005	2018	2019	2020	2021	2022
Industrial	1,441.9	1,451.7	1,432.0	1,407.0	1,356.2	1,365.9	1,308.5
Residential	580.0	430.0	524.9	545.5	345.1	344.1	422.5
Commercial	65.7	70.0	84.1	84.3	83.0	82.7	83.0
Electric Power	128.5	185.0	221.1	200.5	185.4	196.7	197.7
Total	**2,216.2**	**2,136.7**	**2,262.0**	**2,237.3**	**1,969.6**	**1,989.4**	**2,011.7**

Note: Totals may not sum due to independent rounding.

Table 3-130: Ethanol Consumption by Sector (Trillion Btu)

End-Use Sector	1990	2005	2018	2019	2020	2021	2022
Transportation	59.3	315.8	1,148.2	1,150.2	994.6	1,101.7	1,094.9
Industrial	1.5	17.2	20.5	23.5	23.1	22.0	28.0
Commercial	0.9	2.2	27.9	32.6	31.9	31.2	39.7
Total	**61.7**	**335.1**	**1,196.6**	**1,206.3**	**1,049.5**	**1,155.0**	**1,162.7**

Note: Totals may not sum due to independent rounding.

Table 3-131: Biodiesel Consumption by Sector (Trillion Btu)

End-Use Sector	1990	2005	2018	2019	2020	2021	2022
Transportation	NO	11.6	242.9	231.3	239.4	218.2	211.6

NO (Not Occurring)

Methodological recalculations were applied to the entire time series to ensure time-series consistency from 1990 through 2022.

Uncertainty

It is assumed that the combustion efficiency for biomass is 100 percent, which is believed to be an overestimate of the efficiency of biomass combustion processes in the United States. Decreasing the combustion efficiency would decrease emission estimates for CO_2. Additionally, the heat content applied to the consumption of woody biomass in the residential, commercial, and electric power sectors is unlikely to be a completely accurate representation of the heat content for all the different types of woody biomass consumed within these sectors. Emission estimates from ethanol and biodiesel production are more certain than estimates from woody biomass consumption due to better activity data collection methods and uniform combustion techniques.

Recalculations Discussion

EIA (2024a) updated 2020 and 2021 wood energy consumed by the residential sector due to new underlying data collected by the Residential Energy Consumption Survey (RECS), which collects data about once every 5 years and uses Annual Energy Outlook growth rates to estimate data for other years. This caused CO_2 emissions from residential wood consumption to decrease by 9.9 MMT CO_2 Eq. (4.9 percent) in 2020 and 12.3 MMT CO_2 Eq. (6.0 percent) in 2021 compared to estimates in the previous *Inventory* for these years.

[91] CO_2 emissions from biodiesel do not include emissions associated with the carbon in the fuel that is from the methanol used in the process. Emissions from methanol use and combustion are assumed to be accounted for under Non-Energy Use of Fuels. See Annex 2.3 – Methodology for Estimating Carbon Emitted from Non-Energy Uses of Fossil Fuels.

Planned Improvements

Future research will investigate the availability of data on woody biomass heat contents and carbon emission factors to see if there are newer, improved data sources available for these factors.

Currently, emission estimates from biomass and biomass-based fuels included in this *Inventory* are limited to woody biomass, biogenic components of MSW, ethanol, and biodiesel. Additional forms of biomass-based fuel consumption include biogas, and other renewable diesel fuels. EPA will investigate additional forms of biomass-based fuel consumption, research the availability of relevant emissions factors, and integrate these into the *Inventory* as feasible. EPA will examine EIA data on biogas and other renewable diesel fuels to see if these fuel types can be included in future Inventories. EIA (2024a) natural gas data already deducts biogas used in the natural gas supply, so no adjustments are needed to the natural gas fuel consumption data to account for biogas. Distillate fuel statistics are adjusted in this *Inventory* to remove other renewable diesel fuels as well as biodiesel. Additionally, options for including "Other Renewable Fuels," as defined by EIA, will be evaluated.

The availability of facility-level combustion emissions through EPA's GHGRP will be examined to help better characterize the industrial sector's energy consumption in the United States and further classify woody biomass consumption by business establishments according to industrial economic activity type. Most methodologies used in EPA's GHGRP are consistent with IPCC, although for EPA's GHGRP, facilities collect detailed information specific to their operations according to detailed measurement standards, which may differ with the more aggregated data collected for the *Inventory* to estimate total, national U.S. emissions. In addition, and unlike the reporting requirements for this chapter under Paris Agreement and UNFCCC reporting guidelines, some facility-level fuel combustion emissions reported under EPA's GHGRP may also include industrial process emissions.[92]

In line with the Paris Agreement and UNFCCC reporting guidelines, fuel combustion emissions are included in this chapter, while process emissions are included in the Industrial Processes and Product Use chapter of this report. In examining data from EPA's GHGRP that would be useful to improve the emission estimates for the CO_2 from biomass combustion category, particular attention will also be made to ensure time-series consistency, as the facility-level reporting data from EPA's GHGRP are not available for all inventory years as reported in this *Inventory*. Additionally, analyses will focus on aligning reported facility-level fuel types and IPCC fuel types per the national energy statistics, ensuring CO_2 emissions from biomass are separated in the facility-level reported data, and maintaining consistency with national energy statistics provided by EIA. In implementing improvements and integration of data from EPA's GHGRP, the latest guidance from the IPCC on the use of facility-level data in national inventories will be relied upon.[93]

3.11 Energy Sources of Precursor Greenhouse Gases

In addition to the main greenhouse gases addressed above, energy-related activities are also sources of greenhouse gas precursors. The reporting requirements of the Paris Agreement and the UNFCCC[94] request that information should be provided on precursor emissions, which include carbon monoxide (CO), nitrogen oxides (NO_x), non-methane volatile organic compounds (NMVOCs), and sulfur dioxide (SO_2). These gases are not direct greenhouse gases, but indirectly impact Earth's radiative balance by altering the concentrations of greenhouse

[92] See https://unfccc.int/resource/docs/2013/cop19/eng/10a03.pdf#page=2.

[93] See http://www.ipcc-nggip.iges.or.jp/public/tb/TFI_Technical_Bulletin_1.pdf.

[94] See paragraph 51 of Annex to 18/CMA.1 available online at: https://unfccc.int/sites/default/files/resource/CMA2018_03a02E.pdf.

gases (e.g., tropospheric ozone) and atmospheric aerosol (e.g., particulate sulfate). Total emissions of NO_x, CO, NMVOCs, and SO_2 from energy-related activities from 1990 to 2022 are reported in Table 3-132.

Table 3-132: NO_x, CO, NMVOC, and SO_2 Emissions from Energy-Related Activities (kt)

Gas/Activity	1990	2005	2018	2019	2020	2021	2022
NO_x	**21,804**	**18,196**	**6,812**	**6,503**	**5,630**	**5,570**	**5,225**
Fossil Fuel Combustion	21,678	18,188	6,804	6,496	5,624	5,563	5,218
Transportation[a]	*12,132*	*12,628*	*4,486*	*4,322*	*3,618*	*3,546*	*3,228*
Industrial	*2,475*	*1,486*	*820*	*800*	*751*	*721*	*721*
Electric Power Sector	*6,045*	*3,440*	*1,025*	*898*	*762*	*807*	*781*
Commercial	*451*	*288*	*186*	*187*	*193*	*189*	*188*
Residential	*575*	*346*	*288*	*290*	*300*	*300*	*300*
Petroleum and Natural Gas Systems	127	8	7	7	7	6	6
International Bunker Fuels	1,953	1,699	1,456	1,280	977	1,008	1,132
CO	**124,584**	**63,891**	**30,237**	**29,854**	**27,897**	**28,283**	**27,607**
Fossil Fuel Combustion	124,353	63,686	30,050	29,660	27,703	28,098	27,426
Transportation[a]	*119,478*	*59,540*	*26,024*	*25,621*	*23,546*	*23,912*	*23,235*
Residential	*3,620*	*2,393*	*2,751*	*2,860*	*2,968*	*2,950*	*2,950*
Industrial	*705*	*976*	*620*	*600*	*670*	*658*	*655*
Electric Power Sector	*329*	*582*	*505*	*428*	*362*	*423*	*428*
Commercial	*220*	*195*	*151*	*151*	*157*	*154*	*158*
Petroleum and Natural Gas Systems	232	205	186	194	194	185	181
International Bunker Fuels	102	131	158	150	83	101	128
NMVOCs	**12,269**	**8,081**	**5,050**	**4,987**	**4,822**	**5,167**	**5,045**
Fossil Fuel Combustion	11,793	6,079	2,632	2,593	2,391	2,454	2,329
Transportation[a]	*10,932*	*5,608*	*2,127*	*2,072*	*1,846*	*1,912*	*1,786*
Residential	*693*	*322*	*382*	*397*	*431*	*429*	*429*
Commercial	*9*	*18*	*14*	*14*	*14*	*14*	*14*
Industrial	*117*	*87*	*80*	*81*	*74*	*73*	*74*
Electric Power Sector	*43*	*44*	*30*	*29*	*26*	*27*	*27*
Petroleum and Natural Gas Systems	476	2,002	2,418	2,394	2,431	2,713	2,716
International Bunker Fuels	57	54	50	45	32	34	40
SO_2	**22,638**	**13,331**	**1,827**	**1,509**	**1,288**	**1,423**	**1,327**
Fossil Fuel Combustion	21,482	13,235	1,770	1,447	1,138	1,272	1,176
Electric Power Sector	*14,432*	*9,436*	*1,189*	*921*	*758*	*898*	*819*
Industrial	*2,886*	*1,378*	*259*	*234*	*172*	*168*	*159*
Transportation[a]	*793*	*724*	*45*	*40*	*23*	*24*	*25*
Commercial	*485*	*318*	*18*	*19*	*13*	*14*	*13*
Residential	*2,886*	*1,378*	*259*	*234*	*172*	*168*	*159*
Petroleum and Natural Gas Systems	156	96	56	61	150	151	151
International Bunker Fuels	*NA*	*NA*	*NA*	*NA*	*NA*	*NA*	*NA*

NA (Not Applicable)

[a] The scope of the NEI for aircraft related precursor emissions included under the transportation is different from the Paris Agreement and UNFCCC reporting scope. The NEI precursor estimate methodology does not exclude emissions that could be considered international bunkers given local impacts from these emissions. The precursor estimates are based on modeled using FAA- and state-supplied landing and take-off data for all aircraft types (including ground support equipment and auxiliary engines) used for public, private, and military purposes.

Note: Totals may not sum due to independent rounding.

Source: (EPA 2023a). Emission categories from EPA (2023a) are aggregated into sectors and categories reported under the Paris Agreement and the UNFCCC as shown in Table ES-3.

Methodology and Time-Series Consistency

Emission estimates for 1990 through 2022 were obtained from data published on the National Emissions Inventory (NEI) Air Pollutant Emissions Trends Data website (EPA 2023a). For Table 3-132, NEI reported emissions of CO, NO_x, NMVOCs, and SO_2 were recategorized from NEI Emissions Inventory System (EIS) sectors to source categories more

closely aligned with reporting sectors and categories under the Paris Agreement and the UNFCCC, based on discussions between the EPA *Inventory* and NEI staff (see crosswalk documented in Annex 6.3).[95] EIS sectors mapped to the energy sector categories in this report include: fuel combustion for electric utilities, industrial, and other; petroleum and related industries; highway vehicles; off-highway; and other mobile sources (e.g., commercial marine vessels and rail). As described in the NEI Technical Support Documentation (TSD) (EPA 2023b), NEI emissions are estimated through a combination of emissions data submitted directly to the EPA by state, local, and tribal air agencies, as well as additional information added by the Agency from EPA emissions programs, such as the emission trading program, Toxics Release Inventory (TRI), and data collected during rule development or compliance testing.

Methodological approaches were applied to the entire time series to ensure time-series consistency from 1990 through 2022, which are described in detail in the NEI's TSD and on EPA's Air Pollutant Emission Trends website (EPA 2023a; EPA 2023b). No quantitative estimates of uncertainty were calculated for this source category.

[95] The NEI estimates and reports emissions from six criteria air pollutants (CAPs) and 187 hazardous air pollutants (HAPs) in support of National Ambient Air Quality Standards. EPA reported CAP emission trends are grouped into 60 sectors and 15 Tier 1 source categories, which broadly cover similar source categories to those presented in this chapter. For reporting precursor emissions in the common reporting tables (CRTs), EPA has mapped and regrouped emissions of greenhouse gas precursors (CO, NO_x, SO_2, and NMVOCs) from NEI's EIS sectors to better align with NIR source categories, and to ensure consistency and completeness to the extent possible. See Annex 6.3 for more information on this mapping.

4. Industrial Processes and Product Use

Industrial Processes and Product Use (IPPU) chapter includes greenhouse gas emissions occurring from industrial processes and from the use of greenhouse gases in products. The industrial processes and product use categories included in this chapter are presented in Figure 4-1 and Figure 4-2. Greenhouse gas emissions from industrial processes can occur in two different ways. First, they may be generated and emitted as the byproducts of various non-energy-related industrial activities. Second, they may be emitted due to their use in manufacturing processes or by end-consumers. Combustion-related energy use emissions from industry are reported in Chapter 3, Energy.

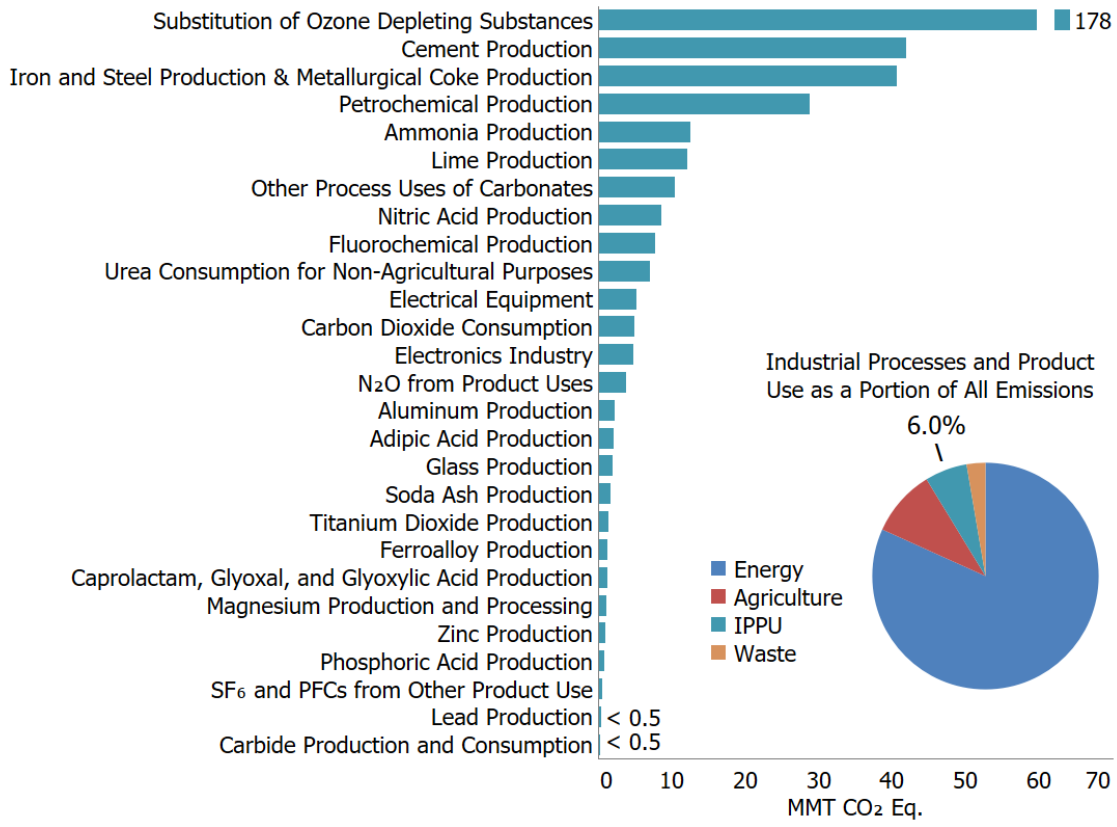
In the case of byproduct emissions, the emissions are generated by an industrial process itself and are not directly a result of energy consumed during the process. For example, raw materials can be chemically or physically transformed from one state to another. This transformation can result in the release of greenhouse gases such as carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and fluorinated greenhouse gases (e.g., HFC-23). The greenhouse gas byproduct generating processes included in this chapter include iron and steel production and metallurgical coke production, cement production, petrochemical production, ammonia production, lime production, other process uses of carbonates (e.g., flux stone, flue gas desulfurization, ceramics production, non-metallurgical magnesia production, and soda ash consumption not associated with glass manufacturing), nitric acid production, adipic acid production, urea consumption for non-agricultural purposes, aluminum production, HCFC-22 production, other fluorochemical production, glass production, soda ash production, ferroalloy production, titanium dioxide production, caprolactam production, zinc production, phosphoric acid production, lead production, and silicon carbide production and consumption.

Greenhouse gases that are used in manufacturing processes or by end-consumers include man-made compounds such as hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), sulfur hexafluoride (SF_6), and nitrogen trifluoride (NF_3). The present contribution of HFCs, PFCs, SF_6, and NF_3 gases to the radiative forcing effect of all anthropogenic greenhouse gases is small; however, because of their extremely long lifetimes, many of them will continue to persist in the atmosphere long after they were first released. In addition, many of these gases have high global warming potentials; SF_6 is the most potent greenhouse gas the Intergovernmental Panel on Climate Change (IPCC) has evaluated. Use of HFCs continues since they are the primary substitutes for ozone depleting substances (ODS), which are being phased-out under the Montreal Protocol on Substances that Deplete the Ozone Layer; however, production and consumption of HFCs are being phased down under the Kigali Amendment to the Montreal Protocol and in the United States under the American Innovation and Manufacturing Act. Hydrofluorocarbons, PFCs, SF_6, and NF_3 are employed and emitted by a number of other industrial sources in the United States, such as the electronics industry, electric power transmission and distribution, PFCs and SF_6 for other product use, and magnesium metal production and processing. Carbon dioxide is also consumed and emitted through various end-use applications. In addition, nitrous oxide is used in and emitted by the electronics industry and anesthetic and aerosol applications.

In 2022, IPPU generated emissions of 383.2 million metric tons of CO_2 equivalent (MMT CO_2 Eq.), or 6.0 percent of total U.S. greenhouse gas emissions.[1] Carbon dioxide emissions from all industrial processes were 168.9 MMT CO_2 Eq. (168,937 kt CO_2) in 2022, or 3.3 percent of total U.S. CO_2 emissions. Methane emissions from industrial processes resulted in emissions of approximately 0.04 MMT CO_2 Eq. (1 kt CH_4) in 2022, which was 0.01 percent of U.S. CH_4 emissions. Nitrous oxide emissions from IPPU were 16.1 MMT CO_2 Eq. (61 kt N_2O) in 2022, or 4.1 percent of total U.S. N_2O emissions. In 2022 combined emissions of HFCs, PFCs, SF_6, and NF_3 totaled 198.1 MMT CO_2 Eq. Total emissions from IPPU in 2022 were 3.9 percent more than 1990 emissions. Total emissions from IPPU remained relatively constant between 2021 and 2022, increasing by 0.4 percent due to offsetting trends within the sector. More information on emissions of greenhouse gas precursors emissions that also result from IPPU are presented in Section 4.27 of this chapter.

The largest source of IPPU-related emissions is the substitution of ozone depleting substances, which accounted for 46.5 percent of sector emissions in 2022. These emissions have increased by 79.1 percent since 2005, and 3.2 percent between 2021 and 2022. Cement production was the second largest source of IPPU emissions in 2022, accounting for 10.9 percent of IPPU emissions in 2022. Iron and steel production and metallurgical coke production was the third largest source of IPPU emissions, accounting for 10.6 percent of the sector total in 2022.

Figure 4-1: Industrial Processes and Product Use Sector Greenhouse Gas Sources



The increase in overall IPPU emissions since 1990 reflects a range of emission trends among the emission sources, as shown in Figure 4-2. Emissions resulting from most types of metal production have declined significantly since 1990, largely due to production shifting to other countries, but also due to transitions to less-emissive methods of

[1] Emissions reported in the IPPU chapter include those from all 50 states, including Hawaii and Alaska, as well as from U.S. Territories.

production (in the case of iron and steel) and to improved practices (in the case of PFC emissions from aluminum production). Carbon dioxide and CH_4 emissions from some chemical production sources (e.g., petrochemical production, urea consumption for non-agricultural purposes) have increased since 1990, while emissions from other chemical production sources (e.g., ammonia production, phosphoric acid production) have decreased. Emissions from mineral sources have either increased (e.g., cement production) or not changed significantly (e.g., lime production) since 1990 and largely follow economic cycles. Hydrofluorocarbon emissions from the substitution of ODS have increased drastically since 1990 and are the largest source of IPPU emissions (46.5 percent in 2022), while the emissions of HFCs, PFCs, SF_6, and NF_3 from other sources have generally declined. Nitrous oxide emissions from the production of nitric acid have decreased. Some emission sources (e.g., adipic acid) exhibit varied interannual trends. Trends are explained further within each emission source category throughout the chapter.

Figure 4-2: Trends in Industrial Processes and Product Use Sector Greenhouse Gas Sources

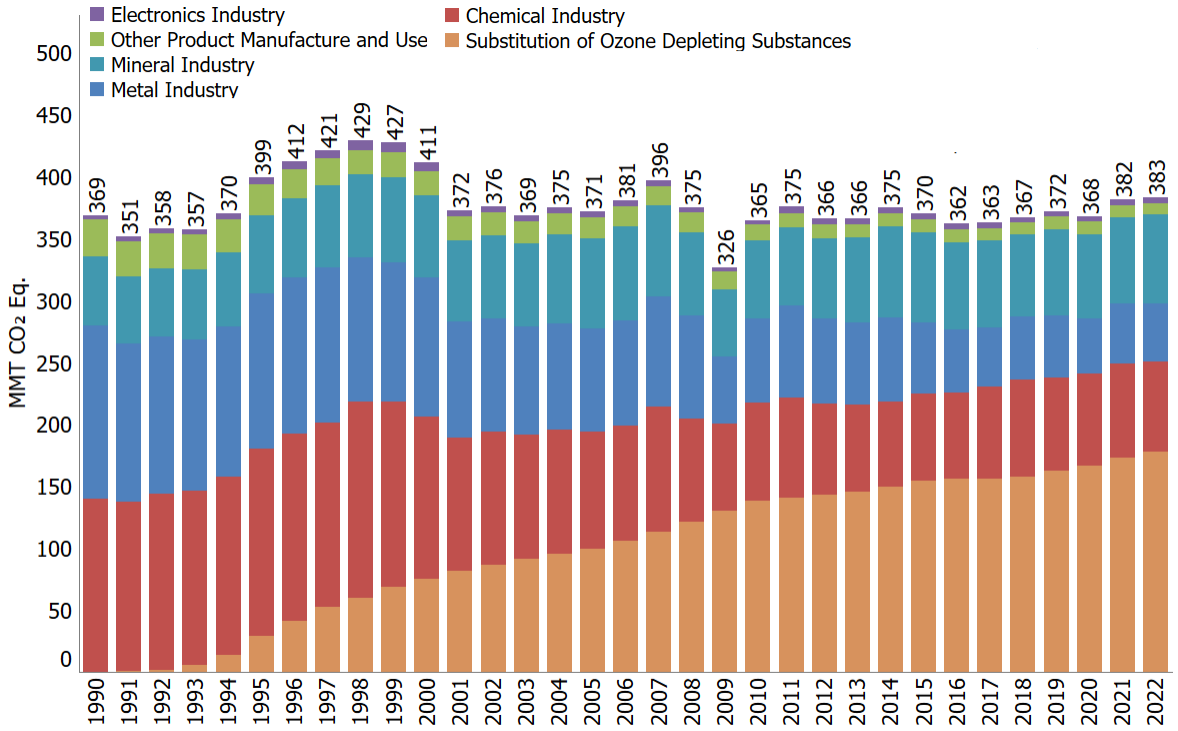


Table 4-1 summarizes emissions for the IPPU chapter in MMT CO_2 Eq. using IPCC *Fifth Assessment Report* (AR5) GWP values, following the requirements of the current United Nations Framework Convention on Climate Change (UNFCCC) reporting guidelines for national inventories (IPCC 2007).[2] Unweighted gas emissions in kt are also provided in Table 4-2. The source descriptions that follow in the chapter are presented in the order as reported to the UNFCCC in the Common Reporting Tables (CRTs), corresponding generally to: mineral industry, chemical industry, metal industry, and emissions from the uses of HFCs, PFCs, SF_6, and NF_3.

Each year, some emission and sink estimates in the IPPU sector of the *Inventory* are recalculated and revised with improved methods and/or data. In general, recalculations are made to the U.S. greenhouse gas emission estimates either to incorporate new methodologies or, most commonly, to update recent historical data. These improvements are implemented consistently across the previous *Inventory's* time series (i.e., 1990 to 2021) to

[2] See http://unfccc.int/resource/docs/2013/cop19/eng/10a03.pdf.

ensure that the trend is accurate. Key updates to this year's *Inventory* include the addition of new categories previously not estimated: CO_2 emissions from ceramics production and non-metallurgical magnesia within other process use of carbonates category; fluorinated gases from production of fluorochemicals other than HCFC-22 within the fluorochemical production category; and SF_6 and PFCs from additional product uses within the other product manufacture and use category. In addition, there were changes to the petrochemical production methodology to calculate emissions from methanol production; updates to emission estimates from urea consumption for non-agricultural purposes driven by revisions to quantities of urea applied, urea imports, and urea exports; and revisions to the method for estimating SF_6 emissions from electrical equipment for estimating using CARB data from electrical equipment in California. Together, these methodological and data updates increased IPPU sector greenhouse gas emissions by an average 20.4 MMT CO_2 Eq. (7.2 percent) across the time series. For more information on specific methodological updates, please see the Recalculations Discussion section for each category in this chapter.

Table 4-1: Emissions from Industrial Processes and Product Use (MMT CO_2 Eq.)

Gas/Source	1990	2005	2018	2019	2020	2021	2022
CO_2	**213.7**	**195.9**	**164.4**	**168.2**	**160.7**	**168.8**	**168.9**
Cement Production	33.5	46.2	39.0	40.9	40.7	41.3	41.9
Iron and Steel Production & Metallurgical Coke Production	104.7	70.1	42.9	43.1	37.7	41.9	40.7
Iron and Steel Production	*99.1*	*66.2*	*41.6*	*40.1*	*35.4*	*38.6*	*37.7*
Metallurgical Coke Production	*5.6*	*3.9*	*1.3*	*3.0*	*2.3*	*3.2*	*3.0*
Petrochemical Production	20.1	26.9	27.2	28.5	27.9	30.7	28.8
Ammonia Production	14.4	10.2	12.7	12.4	13.0	12.2	12.6
Lime Production	11.7	14.6	13.1	12.1	11.3	11.9	12.2
Other Process Uses of Carbonates	7.1	8.5	7.9	9.0	9.0	8.6	10.4
Urea Consumption for Non-Agricultural Purposes	3.8	3.7	6.1	6.2	5.8	6.6	7.1
Carbon Dioxide Consumption	1.5	1.4	4.1	4.9	5.0	5.0	5.0
Glass Production	2.3	2.4	2.0	1.9	1.9	2.0	2.0
Soda Ash Production	1.4	1.7	1.7	1.8	1.5	1.7	1.7
Titanium Dioxide Production	1.2	1.8	1.5	1.3	1.3	1.5	1.5
Aluminum Production	6.8	4.1	1.5	1.9	1.7	1.5	1.4
Ferroalloy Production	2.2	1.4	2.1	1.6	1.4	1.6	1.3
Zinc Production	0.6	1.0	1.0	1.0	1.0	1.0	0.9
Phosphoric Acid Production	1.5	1.3	0.9	0.9	0.9	0.9	0.8
Lead Production	0.5	0.6	0.5	0.5	0.5	0.4	0.4
Carbide Production and Consumption	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Substitution of Ozone Depleting Substances	+	+	+	+	+	+	+
Magnesium Production and Processing	0.1	+	+	+	+	+	+
CH_4	**0.1**	**+**	**+**	**+**	**+**	**+**	**+**
Carbide Production and Consumption	+	+	+	+	+	+	+
Ferroalloy Production	+	+	+	+	+	+	+
Iron and Steel Production & Metallurgical Coke Production	+	+	+	+	+	+	+
Petrochemical Production	+	+	+	+	+	+	+
N_2O	**29.6**	**22.2**	**23.1**	**18.7**	**20.8**	**19.7**	**16.1**
Nitric Acid Production	10.8	10.1	8.5	8.9	8.3	7.9	8.6
N_2O from Product Uses	*3.8*	*3.8*	*3.8*	*3.8*	*3.8*	*3.8*	*3.8*

Gas/Source	1990	2005	2018	2019	2020	2021	2022
Adipic Acid Production	13.5	6.3	9.3	4.7	7.4	6.6	2.1
Caprolactam, Glyoxal, and Glyoxylic Acid Production	1.5	1.9	1.3	1.2	1.1	1.2	1.3
Electronics Industry	+	0.1	0.2	0.2	0.3	0.3	0.3
HFCs	**47.7**	**121.7**	**163.9**	**168.2**	**170.3**	**177.0**	**182.8**
Substitution of Ozone Depleting Substances[a]	0.3	99.5	157.9	162.1	166.2	172.6	178.1
Fluorochemical Production	47.3	22.1	5.7	5.7	3.8	4.0	4.3
Electronics Industry	0.2	0.2	0.3	0.3	0.3	0.4	0.3
Magnesium Production and Processing	0.0	0.0	0.1	0.1	0.1	+	+
PFCs	**39.5**	**10.2**	**7.4**	**7.3**	**6.6**	**6.3**	**6.7**
Fluorochemical Production	17.5	4.0	2.9	3.0	2.5	2.6	3.0
Electronics Industry	2.5	3.0	2.9	2.6	2.5	2.6	2.7
Aluminum Production	19.3	3.1	1.4	1.4	1.4	0.9	0.8
SF_6 and PFCs from Other Product Use	0.1	0.1	0.2	0.2	0.2	0.1	0.2
Substitution of Ozone Depleting Substances[a]	NO	+	+	+	+	+	+
Electrical Equipment	+	+	0.0	+	+	+	+
SF_6	**37.9**	**20.2**	**7.6**	**8.4**	**8.1**	**8.5**	**7.6**
Electrical Equipment	24.7	11.8	5.0	6.1	5.9	6.0	5.1
Magnesium Production and Processing	5.6	3.0	1.1	0.9	0.9	1.2	1.1
Electronics Industry	0.5	0.8	0.8	0.8	0.8	0.9	0.8
SF_6 and PFCs from Other Product Use	1.3	1.3	0.8	0.6	0.5	0.4	0.6
Fluorochemical Production	5.8	3.3	+	+	+	+	+
NF_3	**0.3**	**1.0**	**0.7**	**1.1**	**1.3**	**1.1**	**1.1**
Electronics Industry	+	0.4	0.5	0.5	0.6	0.6	0.6
Fluorochemical Production	0.3	0.6	0.1	0.6	0.7	0.5	0.5
Total[b]	**368.8**	**371.3**	**367.2**	**371.9**	**367.9**	**381.6**	**383.2**

+ Does not exceed 0.05 MMT CO_2 Eq.

NO (Not Occurring)

[a] Small amounts of PFC emissions from this source are included under HFCs due to confidential business information.

[b] Total does not include other fluorinated gases, such as HFEs and PFPEs, which are reported separately in Section 4.24.

Note: Totals may not sum due to independent rounding. Emissions of F-HTFs that are not HFCs, PFCs or SF_6 are not included in *Inventory* totals and are included for informational purposes only in Section 4.24. Emissions presented for informational purposes include HFEs, PFPMIEs, perfluoroalkylmorpholines, and perfluorotrialkylamines.

Table 4-2: Emissions from Industrial Processes and Product Use (kt)

Gas/Source	1990	2005	2018	2019	2020	2021	2022
CO_2	**213,682**	**195,933**	**164,404**	**168,175**	**160,701**	**168,838**	**168,937**
Cement Production	33,484	46,194	38,971	40,896	40,688	41,312	41,884
Iron and Steel Production & Metallurgical Coke Production	104,740	70,082	42,863	43,095	37,724	41,873	40,672
Iron and Steel Production	*99,132*	*66,161*	*41,581*	*40,089*	*35,398*	*38,648*	*37,718*
Metallurgical Coke Production	*5,608*	*3,921*	*1,282*	*3,006*	*2,325*	*3,224*	*2,954*
Petrochemical Production	20,075	26,882	27,200	28,483	27,926	30,656	28,788
Ammonia Production	14,404	10,234	12,669	12,401	13,006	12,192	12,610
Lime Production	11,700	14,552	13,106	12,112	11,299	11,870	12,208
Other Process Uses of Carbonates	7,103	8,472	7,938	8,973	9,012	8,583	10,384

Gas/Source	1990	2005	2018	2019	2020	2021	2022
Urea Consumption for Non-Agricultural Purposes	3,784	3,653	6,113	6,150	5,805	6,600	7,053
Carbon Dioxide Consumption	1,472	1,375	4,130	4,870	4,970	4,990	5,000
Glass Production	2,263	2,402	1,989	1,940	1,858	1,969	1,956
Soda Ash Production	1,431	1,655	1,714	1,792	1,461	1,714	1,704
Titanium Dioxide Production	1,195	1,755	1,541	1,340	1,340	1,474	1,474
Aluminum Production	6,831	4,142	1,455	1,880	1,748	1,541	1,446
Ferroalloy Production	2,152	1,392	2,063	1,598	1,377	1,567	1,327
Zinc Production	632	1,030	999	1,026	977	1,007	947
Phosphoric Acid Production	1,529	1,342	937	909	901	874	840
Lead Production	516	553	527	531	450	439	428
Carbide Production and Consumption	243	213	184	175	154	172	210
Substitution of Ozone Depleting Substances[a]	+	1	3	3	4	4	4
Magnesium Production and Processing	129	4	2	2	3	3	3
CH_4	**3**	**2**	**2**	**1**	**1**	**1**	**1**
Carbide Production and Consumption	1	+	+	+	+	+	+
Ferroalloy Production	1	+	1	+	+	+	+
Iron and Steel Production & Metallurgical Coke Production	1	1	+	+	+	+	+
Petrochemical Production	+	+	+	+	+	+	+
N_2O	**112**	**84**	**87**	**71**	**79**	**74**	**61**
Nitric Acid Production	41	38	32	34	31	30	33
N_2O from Product Uses	*14*	*14*	*14*	*14*	*14*	*14*	*14*
Adipic Acid Production	51	24	35	18	28	25	8
Caprolactam, Glyoxal, and Glyoxylic Acid Production	6	7	5	5	4	5	5
Electronics Industry	+	+	1	1	1	1	1
HFCs	**M**	**M**	**M**	**M**	**M**	**M**	**M**
Substitution of Ozone Depleting Substances[a]	M	M	M	M	M	M	M
Fluorochemical Production	M	M	M	M	M	M	M
Electronics Industry	+	+	+	+	+	+	+
Magnesium Production and Processing	0	0	+	+	+	+	+
PFCs	**101**	**83**	**179**	**173**	**167**	**139**	**172**
Fluorochemical Production	M	M	M	M	M	M	M
Electronics Industry	+	+	+	+	+	+	+
Aluminum Production	M	M	M	M	M	M	M
SF_6 and PFCs from Other Product Use	101	83	178	173	167	138	172
Substitution of Ozone Depleting Substances[a]	NO	+	+	+	+	+	+
Electrical Equipment	+	+	0	+	+	+	+
SF_6	**2**	**1**	**+**	**+**	**+**	**+**	**+**
Electrical Equipment	1	1	+	+	+	+	+
Magnesium Production and Processing	+	+	+	+	+	+	+
Electronics Industry	+	+	+	+	+	+	+

Gas/Source	1990	2005	2018	2019	2020	2021	2022
SF_6 and PFCs from Other Product Use	0	0	+	+	+	+	+
Fluorochemical Production	0	0	+	+	+	+	+
NF_3	**+**	**0**	**+**	**0**	**0**	**0**	**0**
Electronics Industry	+	+	+	+	+	+	+
Fluorochemical Production	+	+	+	+	+	+	+

+ Does not exceed 0.5 kt.

M (Mixture of gases)

NO (Not Occurring)

[a] Small amounts of PFC emissions from this source are included under HFCs due to confidential business information.

Note: Totals by gas may not sum due to independent rounding.

This chapter presents emission estimates calculated in accordance with the *2006 IPCC Guidelines for National Greenhouse Gas Inventories* (*2006 IPCC Guidelines*) and its refinements. For additional detail on IPPU sources that are not included in this *Inventory* report, please review Annex 5, Assessment of the Sources and Sinks of Greenhouse Gas Emissions Not Included. These sources are not included due to various national circumstances, such as emissions from a source may not currently occur in the United States, data are not currently available for those emission sources (e.g., glyoxal and glyoxylic acid production, CH_4 from direct reduced iron production), emissions are included elsewhere within the *Inventory* report, or data suggest that emissions are not significant (e.g., other various fluorinated gas emissions from other product uses). In terms of geographic scope, emissions reported in the IPPU chapter include those from all 50 states, including Hawaii and Alaska, as well as from District of Columbia and U.S. Territories to the extent to which industries are occurring. While most IPPU sources do not occur in U.S. Territories (e.g., electronics manufacturing does not occur in U.S. Territories), they are estimated and accounted for where they are known to occur (e.g., cement production, lime production, electrical equipment). EPA will review this on an ongoing basis to ensure emission sources are included across all geographic areas if they occur. Information on planned improvements for specific IPPU source categories can be found in the Planned Improvements section of the individual source category.

In addition, as mentioned in the Energy chapter of this report (Box 3-5), fossil fuels consumed for non-energy uses for primary purposes other than combustion for energy (including lubricants, paraffin waxes, bitumen asphalt, and solvents) are reported in the Energy chapter. According to the *2006 IPCC Guidelines*, these non-energy uses of fossil fuels are to be reported under the IPPU, rather than the Energy sector; however, due to national circumstances regarding the allocation of energy statistics and carbon balance data, the United States reports these non-energy uses in the Energy chapter of this *Inventory*. Although emissions from these non-energy uses are reported in the Energy chapter, the methodologies used to determine emissions are compatible with the *2006 IPCC Guidelines* and are well documented and scientifically based. The methodologies used are described in Section 3.2, Carbon Emitted from Non-Energy Uses of Fossil Fuels and Annex 2.3, Methodology for Estimating Carbon Emitted from Non-Energy Uses of Fossil Fuels. The emissions are reported under the Energy chapter to improve transparency, report a more complete carbon balance, and avoid double counting. For example, only the emissions from the first use of lubricants and waxes are to be reported under the IPPU sector, and emissions from use of lubricants in 2-stroke engines and emissions from secondary use of lubricants and waxes in waste incineration with energy recovery are to be reported under the Energy sector. Reporting non-energy use emissions from only first use of lubricants and waxes under IPPU would involve making artificial adjustments to the non-energy use carbon balance and could potentially result in double counting of emissions. These artificial adjustments would also be required for asphalt and road oil and solvents (which are captured as part of petrochemical feedstock emissions) and could also potentially result in double counting of emissions. For more information, see the Methodology discussion in Section 3.1, CO_2 from Fossil Fuel Combustion, Section 3.2, Carbon Emitted from Non-Energy Uses of Fossil Fuels and Annex 2.3, Methodology for Estimating Carbon Emitted from Non-Energy Uses of Fossil Fuels.

Finally, as stated in the Energy chapter, portions of the fuel consumption data for seven fuel categories—coking coal, distillate fuel, industrial other coal, petroleum coke, natural gas, residual fuel oil, and other oil—are

reallocated to the IPPU chapter, as they are consumed during non-energy related industrial process activity. Emissions from uses of fossil fuels as feedstocks or reducing agents (e.g., petrochemical production, aluminum production, titanium dioxide, zinc production) are reported in the IPPU chapter, unless otherwise noted due to specific national circumstances. This approach is compatible with the *2006 IPCC Guidelines* and is well documented and scientifically based. The emissions from these feedstocks and reducing agents are reported under the IPPU chapter to improve transparency and to avoid double counting of emissions under both the Energy and IPPU sectors. More information on the methodology to adjust for these emissions within the Energy chapter is described in the Methodology section of CO_2 from Fossil Fuel Combustion (3.1 Fossil Fuel Combustion [CRT Source Category 1A]) and Annex 2.1 Methodology for Estimating Emissions of CO_2 from Fossil Fuel Combustion. Additional information is listed within each IPPU emission source in which this approach applies.

Box 4-1: Methodological Approach for Estimating and Reporting U.S. Emissions and Removals

Consistent with Article 13.7(a) of the Paris Agreement and Article 4.1(a) of the UNFCCC as well as relevant decisions under those agreements, the emissions and removals presented in this report and this chapter are organized by source and sink categories and calculated using internationally accepted methods provided by the Intergovernmental Panel on Climate Change (IPCC) in the *2006 IPCC Guidelines for National Greenhouse Gas Inventories* (*2006 IPCC Guidelines*) and its supplements and refinements. Additionally, the calculated emissions and removals in a given year for the United States are presented in a common format in line with the reporting guidelines for the reporting of inventories under the Paris Agreement and the UNFCCC. The Parties' use of consistent methods to calculate emissions and removals for their inventories helps to ensure that these reports are comparable. The presentation of emissions and removals provided in the IPPU chapter do not preclude alternative examinations. Rather, this chapter presents emissions and removals in a common format consistent with how Parties are to report inventories under the Paris Agreement and the UNFCCC. The report itself, and this chapter, follows this common format, and provides an explanation of the application of methods used to calculate emissions and removals from industrial processes and from the use of greenhouse gases in products.

QA/QC and Verification Procedures

The quality of IPPU source categories is assured through application of the U.S. Inventory QA/QC plan outlined in Annex 8. Two types of checks were performed using this plan: (1) general (Tier 1) procedures consistent with Volume 1, Chapter 6 of the *2006 IPCC Guidelines* that focus on annual procedures and checks to be used when gathering, maintaining, handling, documenting, checking, and archiving the data, supporting documents, and files; and (2) source category-specific (Tier 2) procedures that focus on checks and comparisons of the emission factors, activity data, and methodologies used for estimating emissions from the relevant industrial process and product use sources. Examples of these procedures include: checks to ensure that activity data and emission estimates are consistent with historical trends; that consistent, complete and data sources are used and documented; that interpolation or extrapolation techniques are consistent across sources; and that common units, and conversion factors are used where applicable. Consistent with the *2006 IPCC Guidelines*, additional category-specific QC procedures were performed for more significant emission categories or sources where significant methodological and data updates have taken place. Any significant findings and errors identified are documented and corrected. Application of these procedures, specifically category-specific QC procedures and updates/improvements as a result of QA processes (expert, public, and UNFCCC technical expert reviews), are described further within respective source categories, in the Recalculations Discussion and Planned Improvement sections.

For sources that use data from EPA's Greenhouse Gas Reporting Program (GHGRP), EPA verifies annual facility-level reports through a multi-step process (e.g., including a combination of pre-and post-submittal electronic

checks and manual reviews by staff) to identify potential errors and ensure that data submitted to EPA are accurate, complete, and consistent.[3] Based on the results of the verification process, EPA follows up with facilities to resolve mistakes that may have occurred. The post-submittals checks are consistent with the general and category-specific QC procedures including: range checks, statistical checks, algorithm checks, and year-to-year checks of reported data and emissions. See Box 4-2 below for more information on use of GHGRP data in this chapter.

For most IPPU categories, activity data are obtained via aggregation of facility-level data from EPA's GHGRP (see Box 4-2 below and Annex 9), national commodity surveys conducted by U.S. Geological Survey (USGS) National Minerals Information Center, U.S. Department of Energy (DOE), U.S. Census Bureau, and industry associations such as Air-Conditioning, Heating, and Refrigeration Institute (AHRI), American Chemistry Council (ACC), and American Iron and Steel Institute (AISI) (specified within each source category). The emission factors used include those derived from the EPA's GHGRP and application of IPCC default factors.

Box 4-2: Industrial Process and Product Use Data from EPA's Greenhouse Gas Reporting Program

EPA collects greenhouse gas emissions data from individual facilities and suppliers of certain fossil fuels and industrial gases through its Greenhouse Gas Reporting Program (GHGRP). The GHGRP applies to direct greenhouse gas emitters, fossil fuel suppliers, industrial gas suppliers, and facilities that inject CO_2 underground for sequestration or other reasons and requires reporting by sources or suppliers in 41 industrial categories. Annual reporting is at the facility level, except for certain suppliers of fossil fuels and industrial greenhouse gases.

In general, the threshold for reporting is 25,000 metric tons or more of CO_2 Eq. per year, but reporting is required for all facilities in some industries. Calendar year 2010 was the first year for which data were collected for facilities subject to 40 CFR Part 98, though some source categories first collected data for calendar year 2011. For more information, see Annex 9, Use of EPA Greenhouse Gas Reporting Program in Inventory.

EPA uses annual GHGRP data in a number of categories to improve the national estimates presented in this *Inventory*, consistent with IPCC guidelines (e.g., minerals, chemicals, product uses). Methodologies used in EPA's GHGRP are consistent with IPCC guidelines, including higher tier methods; however, it should be noted that the coverage and definitions for source categories (e.g., allocation of energy and IPPU emissions) in EPA's GHGRP may differ from those used in this *Inventory* in meeting the Paris Agreement and UNFCCC reporting guidelines (IPCC 2011) and is an important consideration when incorporating GHGRP data in the *Inventory*. In line with the Paris Agreement and UNFCCC reporting guidelines, the *Inventory* is a comprehensive accounting of all emissions from source categories identified in the *2006 IPCC Guidelines*. EPA has paid particular attention to ensuring both completeness and time-series consistency for major recalculations that have occurred from the incorporation of GHGRP data into these categories, consistent with *2006 IPCC Guidelines* and the *2019 Refinement*, Volume 1, Chapter 2, Section 2.3, *Use of Facility Data in Inventories.*[4]

For certain source categories in this *Inventory* (e.g., nitric acid production, lime production, cement production, petrochemical production, carbon dioxide consumption, ammonia production, and urea consumption for non-agricultural purposes), EPA has integrated data values that have been calculated by aggregating GHGRP data that are considered confidential business information (CBI) at the facility level. EPA, with industry engagement, has put forth criteria to confirm that a given data aggregation shields underlying CBI from public disclosure. EPA is

[3] See https://www.epa.gov/sites/production/files/2015-07/documents/ghgrp_verification_factsheet.pdf.

[4] See https://www.ipcc-nggip.iges.or.jp/public/2019rf/pdf/1_Volume1/19R_V1_Ch02_DataCollection.pdf.

only publishing data values that meet these aggregation criteria.[5] Specific uses of aggregated facility-level data are described in the respective methodological sections (e.g., including other sources using GHGRP data that is not aggregated CBI, such as aluminum, electronics industry, electrical equipment, HCFC-22 production, and magnesium production and processing). For other source categories in this chapter, as indicated in the respective planned improvements sections,[6] EPA is continuing to analyze how facility-level GHGRP data may be used to improve the national estimates presented in this *Inventory*, giving particular consideration to ensuring time-series consistency and completeness.

Additionally, EPA's GHGRP has and will continue to enhance QA/QC procedures and assessment of uncertainties within the IPPU categories (see those categories for specific QA/QC details regarding the use of GHGRP data).

4.1 Cement Production (CRT Source Category 2A1)

Cement production is an energy- and raw material-intensive process that results in the generation of carbon dioxide (CO_2) both from the energy consumed in making the clinker precursor to cement and from the chemical process to make the clinker. This reporting category (2A1) includes emissions from production of clinker and use of cement kiln dust. Per the IPCC methodological guidance, emissions from fuels consumed for energy purposes during the production of cement are accounted for as part of fossil fuel combustion in the industrial end-use sector reported under the Energy chapter.

During the clinker production process, the key reaction occurs when calcium carbonate ($CaCO_3$), in the form of limestone or similar rocks or in the form of cement kiln dust (CKD), is heated in a cement kiln at a temperature range of about 700 to 1,000 degrees Celsius (1,300 to 1,800 degrees Fahrenheit) to form lime (i.e., calcium oxide, or CaO) and CO_2 in a process known as calcination or calcining. The quantity of CO_2 emitted during clinker production is directly proportional to the lime content of the clinker. During calcination, each mole of $CaCO_3$ heated in the clinker kiln forms one mole of CaO and one mole of CO_2. The CO_2 is vented to the atmosphere as part of the kiln exhaust:

$$CaCO_3 + heat \rightarrow CaO + CO_2$$

Next, over a temperature range of 1000 to 1450 degrees Celsius, the CaO combines with alumina, iron oxide and silica that are also present in the clinker raw material mix to form hydraulically reactive compounds within white-hot semifused (sintered) nodules of clinker. These "sintering" reactions are highly exothermic and produce few CO_2 process emissions. The clinker is then rapidly cooled to maintain quality and then very finely ground with a small amount of gypsum and potentially other materials (e.g., ground granulated blast furnace slag, etc.) to make portland and similar cements.

Masonry cement consists of plasticizers (e.g., ground limestone, lime, etc.) and portland cement, and the amount of portland cement used accounts for approximately 3 percent of total clinker production (USGS 2023b; 2023c). No

[5] U.S. EPA Greenhouse Gas Reporting Program. Developments on Publication of Aggregated Greenhouse Gas Data, November 25, 2014. See http://www.epa.gov/ghgreporting/confidential-business-information-ghg-reporting.

[6] Ammonia production, glass production, lead production, and other fluorinated gas production.

additional emissions are associated with the production of masonry cement. Carbon dioxide emissions that result from the production of lime used to produce portland and masonry cement are included in Section 4.2.

Carbon dioxide emitted from the chemical process of cement production is the second largest source of industrial CO_2 emissions in the United States. Cement is produced in 34 states and Puerto Rico. Texas, Missouri, California, and Florida were the leading cement-producing states in 2022 and accounted for approximately 43 percent of total U.S. production (USGS 2023b). In 2022, shipments of cement were estimated to have increased by about 3 percent from 2021, and net imports increased by about 17 percent compared to 2021 (USGS 2023b).

In 2022, U.S. clinker production totaled 80,500 kilotons, which was an increase of 1 percent compared to 2021 and an increase of 25 percent compared to 1990 (EPA 2023). The resulting CO_2 emissions were estimated to be 41.9 MMT CO_2 Eq. (41,884 kt) (see Table 4-3 and Table 4-4). The total construction value and cement shipments increased by 11 percent and 4 percent, respectively, during the first nine months of 2022 compared to the same time period in 2021. This increase was attributed to continued economic recovery from the COVID-19 pandemic and the November 2021 passage of the Bipartisan Infrastructure Law. Despite the increases, growth was constrained by increased costs, labor and production shortages, and ongoing supply chain disruptions (USGS 2023b).

Table 4-3: CO_2 Emissions from Cement Production (MMT CO_2 Eq.)

Year	1990	2005	2018	2019	2020	2021	2022
Cement Production	33.5	46.2	39.0	40.9	40.7	41.3	41.9

Table 4-4: CO_2 Emissions from Cement Production (kt CO_2)

Year	1990	2005	2018	2019	2020	2021	2022
Cement Production	33,484	46,194	38,971	40,896	40,688	41,312	41,884

Greenhouse gas emissions from cement production, which are primarily driven by production levels, increased every year from 1991 through 2006 but decreased in the following years until 2009. Emissions from cement production were at their highest levels in 2006 and at their lowest levels in 2009. Emissions in 2009 were approximately 28 percent lower than 2008 emissions and 12 percent lower than 1990 due to the economic recession and the associated decrease in demand for construction materials. Since 2009, emissions have increased by 41 percent due to increasing demand for cement. Cement continues to be a critical component of the construction industry; therefore, the availability of public and private construction funding, as well as overall economic conditions, have considerable impact on the level of cement production.

Methodology and Time-Series Consistency

Carbon dioxide emissions from cement production are estimated using the Tier 2 method from the *2006 IPCC Guidelines* as this is a key category, in accordance with the IPCC methodological decision tree and available data. The Tier 2 methodology was used because detailed and complete data (including weights and composition) for carbonate(s) consumed in clinker production are not available,[7] and thus a rigorous Tier 3 approach is impractical. Tier 2 specifies the use of aggregated plant or national clinker production data and an emission factor, which is the product of the average lime mass fraction for clinker of 65 percent and a constant reflecting the mass of CO_2 released per unit of lime. The U.S. Geological Survey (USGS) mineral commodity expert for cement has confirmed that this is a reasonable assumption for the United States (Van Oss 2013a). This calculation yields an emission factor of 0.510 tons of CO_2 per ton of clinker produced, which was determined as follows:

[7] As discussed further under "Planned Improvements," most cement-producing facilities that report their emissions to the GHGRP use CEMS to monitor combined process and fuel combustion emissions for kilns, making it difficult to quantify the process emissions on a facility-specific basis. By the end of 2022, the percentage of facilities not using CEMS was 1 percent.

Equation 4-1: *2006 IPCC Guidelines* Tier 1 Emission Factor for Clinker (precursor to Equation 2.4)

$$EF_{clinker} = 0.650\ CaO \times \left[\left(44.01 \frac{g}{mole} CO_2\right) \div \left(56.08 \frac{g}{mole} CaO\right)\right] = 0.510 \frac{\text{tons } CO_2}{\text{ton clinker}}$$

During clinker production, some of the raw materials, partially reacted raw materials, and clinker enters the kiln line's exhaust system as non-calcinated, partially calcinated, or fully calcinated cement kiln dust (CKD). To the degree that the CKD contains carbonate raw materials which are then calcined, there are associated CO_2 emissions. At some plants, essentially all CKD is directly returned to the kiln, becoming part of the raw material feed, or is likewise returned to the kiln after first being removed from the exhaust. In either case, the returned CKD becomes a raw material, thus forming clinker, and the associated CO_2 emissions are a component of those calculated for the clinker overall. At some plants, however, the CKD cannot be returned to the kiln because it is chemically unsuitable as a raw material or chemical issues limit the amount of CKD that can be so reused. Any clinker that cannot be returned to the kiln is either used for other (non-clinker) purposes or is landfilled. The CO_2 emissions attributable to the non-returned calcinated portion of the CKD are not accounted for by the clinker emission factor and thus a CKD correction factor should be applied to account for those emissions. The USGS reports the amount of CKD used to produce clinker, but no information is currently available on the total amount of CKD produced annually.[8] Because data are not currently available to derive a country-specific CKD correction factor, a default correction factor of 1.02 (2 percent) was used to account for CKD CO_2 emissions, as recommended by the IPCC (IPCC 2006).[9] Total cement production emissions were calculated by adding the emissions from clinker production and the emissions assigned to CKD.

Small amounts of impurities (i.e., not calcium carbonate) may exist in the raw limestone used to produce clinker. The proportion of these impurities is generally minimal, although a small amount (1 to 2 percent) of magnesium oxide (MgO) may be desirable as a flux. Per the IPCC Tier 2 methodology, a correction for MgO is not used, since the amount of MgO from carbonate is likely very small and the assumption of a 100 percent carbonate source of CaO already yields an overestimation of emissions (IPCC 2006).

The 1990 through 2012 activity data for clinker production were obtained from USGS (Van Oss 2013a; Van Oss 2013b). Clinker production data for 2013 were also obtained from USGS (USGS 2014). USGS compiled the data (to the nearest ton) through questionnaires sent to domestic clinker and cement manufacturing plants, including facilities in Puerto Rico. Clinker production values in the current *Inventory* report utilize GHGRP data for the years 2014 through 2022 (EPA 2023). Clinker production data are summarized in Table 4-5. Details on how this GHGRP data compares to USGS reported data can be found in the section on QA/QC and Verification.

Table 4-5: Clinker Production (kt)

Year	1990	2005	2018	2019	2020	2021	2022
Clinker Production	64,355	88,783	74,900	78,600	78,200	79,400	80,500

Note: Clinker production from 1990 through 2022 includes Puerto Rico (relevant U.S. Territories).

Methodological approaches were applied to the entire time series to ensure time-series consistency from 1990 through 2022. The methodology for cement production spliced activity data from two different sources: USGS for

[8] The USGS *Minerals Yearbook: Cement* notes that CKD values used for clinker production are likely underreported.

[9] As stated on p. 2.12 of the *2006 IPCC Guidelines*, Vol. 3, Chapter 2: "…As data on the amount of CKD produced may be scarce (except possibly for plant-level reporting), estimating emissions from lost CKD based on a default value can be considered good practice. The amount of CO_2 from lost CKD can vary but range typically from about 1.5 percent (additional CO_2 relative to that calculated for clinker) for a modern plant to about 20 percent for a plant losing a lot of highly calcinated CKD (van Oss 2005). In the absence of data, the default CKD correction factor (CF_{ckd}) is 1.02 (i.e., add 2 percent to the CO_2 calculated for clinker). If no calcined CKD is believed to be lost to the system, the CKD correction factor will be 1.00 (van Oss 2005)…"

1990 through 2013 and GHGRP starting in 2014. Consistent with the *2006 IPCC Guidelines*, the overlap technique was applied to compare the two data sets for years where there was overlap, with findings that the data sets were consistent and adjustments were not needed.

Uncertainty

The uncertainties contained in these estimates are primarily due to uncertainties in the lime content of clinker and in the percentage of CKD recycled inside the cement kiln. Uncertainty is also associated with the assumption that all calcium-containing raw materials are $CaCO_3$, when a small percentage likely consists of other carbonate and non-carbonate raw materials. The lime content of clinker varies from 60 to 67 percent; 65 percent is used as a representative value (Van Oss 2013a). This contributes to the uncertainty surrounding the emission factor for clinker which has an uncertainty range of ±3 percent with uniform densities (Van Oss 2013b). The amount of CO_2 from CKD loss can range from 1.5 to 8 percent depending upon plant specifications, and uncertainty was estimated at ±5 percent with uniform densities (Van Oss 2013b). Additionally, some amount of CO_2 is reabsorbed when the cement is used for construction. As cement reacts with water, alkaline substances such as calcium hydroxide are formed. During this curing process, these compounds may react with CO_2 in the atmosphere to create calcium carbonate. This reaction only occurs in roughly the outer 0.2 inches of the total thickness. Because the amount of CO_2 reabsorbed is thought to be minimal, it was not estimated. EPA assigned uncertainty bounds of ±3 percent and a normal probability density function for clinker production and uncertainty bounds of ±5 percent and a uniform probability density function for the emission factor, based on expert judgment (Van Oss 2013b).

The results of the Approach 2 quantitative uncertainty analysis are summarized in Table 4-6. Based on the uncertainties associated with total U.S. clinker production, the CO_2 emission factor for clinker production, and the emission factor for additional CO_2 emissions from CKD, 2022 CO_2 emissions from cement production were estimated to be between 40.1 and 43.8 MMT CO_2 Eq. at the 95 percent confidence level. This confidence level indicates a range of approximately 4 percent below and 5 percent above the emission estimate of 41.9 MMT CO_2 Eq.

Table 4-6: Approach 2 Quantitative Uncertainty Estimates for CO_2 Emissions from Cement Production (MMT CO_2 Eq. and Percent)

Source	Gas	2022 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate [a] (MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Cement Production	CO_2	41.9	40.1	43.8	-4%	+5%

[a] Range of emission estimates predicted by Monte Carlo stochastic simulation for a 95 percent confidence interval.

QA/QC and Verification

General quality assurance/quality control (QA/QC) procedures were applied consistent with the U.S. Inventory QA/QC plan, which is in accordance with Volume 1, Chapter 6 of *2006 IPCC Guidelines* as described in the introduction of the IPPU chapter (see Annex 8 for more details).

EPA relied upon the latest guidance from the IPCC on the use of facility-level data in national inventories and applied a category-specific QC process to compare activity data from EPA's GHGRP with existing data from USGS surveys. This was to ensure time-series consistency of the emission estimates presented in the *Inventory*. Total U.S. clinker production is assumed to have low uncertainty because facilities routinely measure this for economic reasons and because both USGS and GHGRP take multiple steps to ensure that reported totals are accurate. EPA verifies annual facility-level GHGRP reports through a multi-step process that is tailored to the reporting industry (e.g., combination of electronic checks including range checks, statistical checks, algorithm checks, year-to-year

comparison checks, along with manual reviews involving outside data checks) to identify potential errors and ensure that data submitted to EPA are accurate, complete, and consistent (EPA 2015). Based on the results of the verification process, EPA follows up with facilities to resolve mistakes that may have occurred.[10] Facilities are also required to monitor and maintain records of monthly clinker production per section 98.84 of the GHGRP regulation (40 CFR 98.84).

EPA's GHGRP requires all facilities producing portland cement to report greenhouse gas emissions, including CO_2 process emissions from each kiln, CO_2 combustion emissions from each kiln, CH_4 and N_2O combustion emissions from each kiln, and CO_2, CH_4, and N_2O emissions from each stationary combustion unit other than kilns (40 CFR Part 98 Subpart H). Source-specific quality control measures for the cement production category are included in section 98.84, Monitoring and QA/QC Requirements.

As mentioned above, EPA compares GHGRP clinker production data (EPA 2023) to the USGS clinker production data (USGS 2023a; USGS 2023c). For the year 2014, 2020, and 2022, USGS and GHGRP clinker production data showed a difference of approximately 1 percent. In 2018, the difference between USGS and GHGRP clinker production data was approximately 3 percent, which resulted in a difference in emissions of about 1.2 MMT CO_2 Eq. In 2015, 2016, 2017, 2019, and 2021, that difference was less than 0.5 percent (less than 0.2 MMT CO_2 Eq.) between the two sets of activity data. The information collected by the USGS National Minerals Information Center surveys continue to be an important data source.

Recalculations Discussion

No recalculations were performed for the 1990 through 2021 portion of the time series.

Planned Improvements

EPA is continuing to evaluate and analyze data reported under EPA's GHGRP that would be useful to improve the emission estimates for the Cement Production source category. Most cement production facilities reporting under EPA's GHGRP use Continuous Emission Monitoring Systems (CEMS) to monitor and report CO_2 emissions, thus reporting combined process and combustion emissions from kilns. In implementing further improvements and integration of data from EPA's GHGRP, the latest guidance from the IPCC on the use of facility-level data in national inventories will be relied upon, in addition to category-specific QC methods recommended by the *2006 IPCC Guidelines*.[11] EPA's long-term improvement plan includes continued assessment of the feasibility of using additional GHGRP information beyond aggregation of reported facility-level clinker data, in particular disaggregating the combined process and combustion emissions reported using CEMS, to separately present national process and combustion emissions streams consistent with IPCC and UNFCCC guidelines. This long-term planned analysis is still in development and has not been applied for this current *Inventory*.

EPA continues to review methods and data used to estimate CO_2 emissions from cement production in order to account for organic material in the raw material and to discuss the carbonation that occurs across the duration of the cement product. Work includes identifying data and studies on the average carbon content for organic materials in kiln feed in the United States and on CO_2 reabsorption rates via carbonation for various cement products. This information is not reported by facilities subject to GHGRP reporting. This is a long-term improvement.

[10] See GHGRP Verification Fact Sheet https://www.epa.gov/sites/production/files/2015-07/documents/ghgrp_verification_factsheet.pdf.

[11] See IPCC Technical Bulletin on Use of Facility-Specific Data in National Greenhouse Gas Inventories http://www.ipcc-nggip.iges.or.jp/public/tb/TFI_Technical_Bulletin_1.pdf and the *2019 Refinement*, Volume 1, Chapter 2, Section 2.3, *Use of Facility Data in Inventories* at https://www.ipcc-nggip.iges.or.jp/public/2019rf/pdf/1_Volume1/19R_V1_Ch02_DataCollection.pdf.

4.2 Lime Production (CRT Source Category 2A2)

Lime is a manufactured product with many industrial, chemical, and environmental applications. This reporting category (2A2) includes process emissions from the production of lime. Per the IPCC methodological guidance, emissions from fuels consumed for energy purposes during the production of lime are accounted for as part of fossil fuel combustion in the industrial end-use sector reported under the Energy chapter.

Lime production involves three main processes: stone preparation, calcination, and hydration. Carbon dioxide (CO_2) is generated during the calcination stage, when limestone—consisting of calcium carbonate ($CaCO_3$) and/or magnesium carbonate ($MgCO_3$)—is roasted at high temperatures in a kiln to produce calcium oxide (CaO) and CO_2. The CO_2 is given off as a gas and is normally emitted to the atmosphere.

$$CaCO_3 \rightarrow CaO + CO_2$$

Some facilities, however, recover CO_2 generated during the production process for use in sugar refining and precipitated calcium carbonate (PCC) production.[12] PCC is used as a filler or coating in the paper, food, and plastic industries and is derived from reacting hydrated high-calcium quicklime with CO_2, a production process that does not result in net emissions of CO_2 to the atmosphere.

For U.S. operations, the term "lime" refers to a variety of chemical compounds. These include CaO, or high-calcium quicklime; calcium hydroxide ($Ca(OH)_2$), or hydrated lime; dolomitic quicklime ([CaO•MgO]); and dolomitic hydrate ([$Ca(OH)_2$•MgO] or [$Ca(OH)_2$•$Mg(OH)_2$]).

The current lime market is approximately distributed across six end-use categories, as follows: metallurgical uses, 35 percent; environmental uses, 29 percent; chemical and industrial uses, 21 percent; construction uses, 10 percent; miscellaneous uses, 3 percent; and refractory dolomite, 1 percent (USGS 2021). The major uses are in steel making, chemical and industrial applications (such as the manufacture of fertilizer, glass, paper and pulp, and precipitated calcium carbonate, and in sugar refining), flue gas desulfurization (FGD) systems at coal-fired electric power plants, construction, and water treatment, as well as uses in mining, pulp and paper and precipitated calcium carbonate manufacturing (USGS 2023a). Lime is also used as a CO_2 scrubber, and there has been experimentation on the use of lime to capture CO_2 from electric power plants. Both lime (CaO) and limestone ($CaCO_3$) can be used as a sorbent for FGD systems. Emissions from limestone consumption for FGD systems are reported under Section 4.4 Other Process Uses of Carbonate Production (CRT Source Category 2A4).

Emissions from lime production have fluctuated over the time series depending on lime end-use markets – primarily the steel making industry and FGD systems for utility and industrial plants – and also energy costs. One significant change to lime end-use since 1990 has been the increase in demand for lime for FGD at coal-fired electric power plants, which can be attributed to compliance with sulfur dioxide (SO_2) emission regulations of the Clean Air Act Amendments of 1990. Phase I went into effect on January 1, 1995, followed by Phase II on January 1, 2000. To supply lime for the FGD market, the lime industry installed more than 1.8 million tons per year of new capacity by the end of 1995 (USGS 2023a). The need for air pollution controls continued to drive the FGD lime market, which had doubled between 1990 and 2019 (2021, 2023a, 2023b).

The U.S. lime industry temporarily shut down some individual gas-fired kilns and, in some case, entire lime plants during 2000 and 2001, due to significant increases in the price of natural gas. Lime production continued to

[12] The amount of CO_2 captured from lime production for sugar refining and PCC production is reported under CRT Source Category 2H3 "Other", but within this report, they are included in this chapter.

decrease in 2001 and 2002, a result of lower demand from the steel making industry, lime's largest end-use market, when domestic steel producers were affected by low priced imports and slowing demand (USGS 2023a).

Emissions from lime production peaked in 2006 at approximately 30.3 percent above 1990 levels, due to strong demand from the steel and construction markets (road and highway construction projects), before dropping to its second lowest level in 2009 at approximately 2.5 percent below 1990 emissions, driven by the economic recession and downturn in major markets including construction, mining, and steel (USGS 2023a). In 2010, the lime industry began to recover as the steel, FGD, and construction markets also recovered (USGS 2023a). Fluctuation in lime production since 2015 has been driven largely by demand from the steel making industry (USGS 2021). In 2020, a significant decline in lime production occurred due to plants temporarily closing as a result of the global COVID-19 pandemic (USGS 2023a). This resulted in the lowest level of emissions in 2020 at approximately 3.4 percent below 1990 emissions. Emissions increased annually since then, with 2022 levels similar to emissions in 2019.

Lime production in the United States—including Puerto Rico—was reported to be 16,994 kilotons in 2022, an increase of about 1.3 percent compared to 2021 levels (USGS 2023a). Compared to 1990, lime production increased by about 7.3 percent. At year-end 2022, 73 primary lime plants were operating in the United States, including Puerto Rico (USGS 2023a).[13] Principal lime producing states were, in alphabetical order, Kentucky, Missouri, Ohio, and Texas (USGS 2023a).

U.S. lime production resulted in estimated net CO_2 emissions of 12.2 MMT CO_2 Eq. (12,208 kt) (see Table 4-7 and Table 4-8). Carbon dioxide emissions from lime production increased by about 2.8 percent compared to 2021 levels. Compared to 1990, CO_2 emissions have increased by about 4.3 percent. The trends in CO_2 emissions from lime production are directly proportional to trends in production, which are described above.

Table 4-7: CO_2 Emissions from Lime Production (MMT CO_2 Eq.)

Year	1990	2005	2018	2019	2020	2021	2022
Lime Production	11.7	14.6	13.1	12.1	11.3	11.9	12.2

Table 4-8: Gross, Recovered, and Net CO_2 Emissions from Lime Production (kt CO_2)

Year	1990	2005	2018	2019	2020	2021	2022
Gross	11,959	15,074	13,609	12,676	11,875	12,586	12,750
Recovered[a]	259	522	503	564	576	716	542
Net Emissions	**11,700**	**14,552**	**13,106**	**12,112**	**11,299**	**11,870**	**12,208**

Note: Totals may not sum due to independent rounding.

[a] For sugar refining and PCC production.

Methodology and Time-Series Consistency

To calculate emissions, the amounts of high-calcium and dolomitic lime produced were multiplied by their respective emission factors, consistent with Tier 2 methodology from the *2006 IPCC Guidelines* and in accordance with the IPCC methodological decision tree and available data. The emission factor is the product of the stoichiometric ratio between CO_2 and CaO, and the average CaO and MgO content for lime. The CaO and MgO content for lime is assumed to be 95 percent for both high-calcium and dolomitic lime (IPCC 2006). The emission factors were calculated as follows:

[13] In 2022, 68 operating primary lime facilities in the United States reported to the EPA Greenhouse Gas Reporting Program.

Equation 4-2: *2006 IPCC Guidelines* Tier 2 Emission Factor for Lime Production, High-Calcium Lime (Equation 2.9)

$$EF_{\text{High-Calcium Lime}} = \left[\left(44.01\frac{\text{g}}{\text{mole}}CO_2\right) \div \left(56.08\frac{\text{g}}{\text{mole}}CaO\right)\right] \times \left(0.9500\frac{CaO}{\text{lime}}\right) = 0.7455\ \frac{\text{g } CO_2}{\text{g lime}}$$

Equation 4-3: *2006 IPCC Guidelines* Tier 2 Emission Factor for Lime Production, Dolomitic Lime (Equation 2.9)

$$EF_{\text{Dolomitic Lime}} = \left[\left(88.02\frac{\text{g}}{\text{mole}}CO_2\right) \div \left(96.39\frac{\text{g}}{\text{mole}}CaO \bullet MgO\right)\right] \times \left(0.9500\ \frac{CaO \bullet MgO}{\text{lime}}\right) = 0.8675\ \frac{\text{g } CO_2}{\text{g lime}}$$

Production was adjusted to remove the mass of chemically combined water found in hydrated lime, determined according to the molecular weight ratios of H_2O to ($Ca(OH)_2$ and $[Ca(OH)_2 \bullet Mg(OH)_2]$) (IPCC 2006). These factors set the chemically combined water content to 27 percent for high-calcium hydrated lime, and 30 percent for dolomitic hydrated lime.

The *2006 IPCC Guidelines* (Tier 2 method) also recommends accounting for emissions from lime kiln dust (LKD) through application of a correction factor. LKD is a byproduct of the lime manufacturing process typically not recycled back to kilns. LKD is a very fine-grained material and is especially useful for applications requiring very small particle size. Most common LKD applications include soil reclamation and agriculture. Emissions from the application of lime for agricultural purposes are reported in the Agriculture chapter under 5.5 Liming (CRT Source Category 3G). Currently, data on annual LKD production is not readily available to develop a country-specific correction factor. Lime emission estimates were multiplied by a factor of 1.02 to account for emissions from LKD (IPCC 2006). See the Planned Improvements section associated with efforts to improve uncertainty analysis and emission estimates associated with LKD.

Lime emission estimates were further adjusted to account for the amount of CO_2 captured for use in on-site processes. All the domestic lime facilities are required to report these data to EPA under its GHGRP. The total national-level annual amount of CO_2 captured for on-site process use was obtained from EPA's GHGRP (EPA 2023) based on reported facility-level data for years 2010 through 2022. The amount of CO_2 captured/recovered for non-marketed on-site process use is deducted from the total gross emissions (i.e., from lime production and LKD). The net lime emissions are presented in Table 4-7 and Table 4-8. GHGRP data on CO_2 removals (i.e., CO_2 captured/recovered) was available only for 2010 through 2022. Since GHGRP data are not available for 1990 through 2009, IPCC "splicing" techniques were used as per the *2006 IPCC Guidelines* on time-series consistency (IPCC 2006, Volume 1, Chapter 5).

Lime production data (i.e., lime sold and non-marketed lime used by the producer) by type (i.e., high-calcium and dolomitic quicklime, high-calcium and dolomitic hydrated lime, and dead-burned dolomite) for 1990 through 2022 (see Table 4-9) were obtained from U.S. Geological Survey (USGS) *Minerals Yearbook* (USGS 2023a) and are compiled by USGS to the nearest ton. Dead-burned dolomite data are additionally rounded by USGS to no more than one significant digit to avoid disclosing company proprietary data. Production data for the individual quicklime (i.e., high-calcium and dolomitic) and hydrated lime (i.e., high-calcium and dolomitic) types were not provided prior to 1997. These were calculated based on total quicklime and hydrated lime production data from 1990 through 1996 and the three-year average ratio of the individual lime types from 1997 to 1999. Natural hydraulic lime, which is produced from CaO and hydraulic calcium silicates, is not manufactured in the United States (USGS 2023a). Total lime production was adjusted to account for the water content of hydrated lime by converting hydrate to oxide equivalent based on recommendations from the IPCC and using the water content values for high-calcium hydrated lime and dolomitic hydrated lime mentioned above, and is presented in Table 4-10 (IPCC 2006). The CaO and CaO•MgO contents of lime, both 95 percent, were obtained from the IPCC (IPCC 2006).

Table 4-9: High-Calcium- and Dolomitic-Quicklime, High-Calcium- and Dolomitic-Hydrated, and Dead-Burned-Dolomite Lime Production (kt)

Year	1990	2005	2018	2019	2020	2021	2022
High-Calcium Quicklime	11,166	14,100	12,400	11,300	10,700	11,200	11,500
Dolomitic Quicklime	2,234	2,990	2,810	2,700	2,390	2,700	2,640
High-Calcium Hydrated	1,781	2,220	2,430	2,430	2,320	2,430	2,410
Dolomitic Hydrated	319	474	265	267	252	244	244
Dead-Burned Dolomite	342	200	200	200	200	200	200

Table 4-10: Adjusted Lime Production (kt)

Year	1990	2005	2018	2019	2020	2021	2022
High-Calcium	12,466	15,721	14,174	13,074	12,394	12,974	13,259
Dolomitic	2,800	3,522	3,196	3,087	2,766	3,071	3,011

Note: Minus water content of hydrated lime.

Methodological approaches were applied to the entire time series to ensure consistency in emissions from 1990 through 2022.

Uncertainty

The uncertainties contained in these estimates can be attributed to slight differences in the chemical composition of lime products and CO_2 recovery rates for on-site process use over the time series. Although the methodology accounts for various formulations of lime, it does not account for the trace impurities found in lime, such as iron oxide, alumina, and silica. Due to differences in the limestone used as a raw material, a rigid specification of lime material is impossible. As a result, few plants produce lime with exactly the same properties.

In addition, a portion of the CO_2 emitted during lime production will actually be reabsorbed when the lime is consumed, especially at captive lime production facilities. As noted above, lime has many different chemical, industrial, environmental, and construction applications. In many processes, CO_2 reacts with the lime to create calcium carbonate (e.g., water softening). Carbon dioxide reabsorption rates vary, however, depending on the application. For example, 100 percent of the lime used to produce precipitated calcium carbonate reacts with CO_2, whereas most of the lime used in steel making reacts with impurities such as silica, sulfur, and aluminum compounds. Quantifying the amount of CO_2 that is reabsorbed would require a detailed accounting of lime use in the United States and additional information about the associated processes where both the lime and byproduct CO_2 are "reused." Research conducted thus far has not yielded the necessary information to quantify CO_2 reabsorption rates.[14] Some additional information on the amount of CO_2 consumed on site at lime facilities, however, has been obtained from EPA's GHGRP.

In some cases, lime is generated from calcium carbonate byproducts at pulp mills and water treatment plants.[15] The lime generated by these processes is included in the USGS data for commercial lime consumption. In the pulping industry, mostly using the Kraft (sulfate) pulping process, lime is consumed in order to causticize a process liquor (green liquor) composed of sodium carbonate and sodium sulfide. The green liquor results from the dilution of the smelt created by combustion of the black liquor where biogenic carbon (C) is present from the wood. Kraft

[14] Representatives of the National Lime Association estimate that CO_2 reabsorption that occurs from the use of lime may offset as much as a quarter of the CO_2 emissions from calcination (Males 2003).

[15] Some carbide producers may also regenerate lime from their calcium hydroxide byproducts, which does not result in emissions of CO_2. In making calcium carbide, quicklime is mixed with coke and heated in electric furnaces. The regeneration of lime in this process is done using a waste calcium hydroxide (hydrated lime) [$CaC_2 + 2H_2O \rightarrow C_2H_2 + Ca(OH)_2$], not calcium carbonate [$CaCO_3$]. Thus, the calcium hydroxide is heated in the kiln to simply expel the water [$Ca(OH)_2 + \text{heat} \rightarrow CaO + H_2O$], and no CO_2 is released.

mills recover the calcium carbonate "mud" after the causticizing operation and calcine it back into lime—thereby generating CO_2—for reuse in the pulping process. Although this re-generation of lime could be considered a lime manufacturing process, the CO_2 emitted during this process is mostly biogenic in origin and therefore is not included in the industrial processes totals (Miner and Upton 2002). In accordance with IPCC methodological guidelines, any such emissions are calculated by accounting for net carbon fluxes from changes in biogenic carbon reservoirs in wooded or crop lands (see the Land Use, Land-Use Change, and Forestry chapter).

In the case of water treatment plants, lime is used in the softening process. Some large water treatment plants may recover their waste calcium carbonate and calcine it into quicklime for reuse in the softening process. Further research is necessary to determine the degree to which lime recycling is practiced by water treatment plants in the United States.

Another uncertainty is the assumption that calcination emissions for LKD are around 2 percent. EPA assigned uncertainty ranges of ±2 percent and a triangular probability density function for the LKD correction factor based on expert judgment (RTI 2023). The National Lime Association (NLA) has commented that the estimates of emissions from LKD in the United States could be closer to 6 percent. They also note that additional emissions (approximately 2 percent) may also be generated through production of other byproducts/wastes (off-spec lime that is not recycled, scrubber sludge) at lime plants (Seeger 2013). Publicly available data on LKD generation rates, total quantities not used in cement production, and types of other byproducts/wastes produced at lime facilities are limited. NLA compiled and shared historical emissions information and quantities for some waste products reported by member facilities associated with generation of total calcined byproducts and LKD, as well as methodology and calculation worksheets that member facilities complete when reporting. There is uncertainty regarding the availability of data across the time series needed to generate a representative country-specific LKD factor. Uncertainty of the activity data is also a function of the reliability and completeness of voluntarily reported plant-level production data. EPA assigned uncertainty ranges of ±1 percent for lime production and a normal probability density function, based on expert judgment (USGS 2012). Further research, including discussion with NLA, and data is needed to improve understanding of additional calcination emissions to consider revising the current assumptions that are based on the *2006 IPCC Guidelines*. More information can be found in the Planned Improvements section below.

The results of the Approach 2 quantitative uncertainty analysis are summarized in Table 4-11. Lime CO_2 emissions for 2022 were estimated to be between 12.1 and 12.3 MMT CO_2 Eq. at the 95 percent confidence level. This confidence level indicates a range of approximately 1 percent below and 1 percent above the emission estimate of 12.2 MMT CO_2 Eq.

Table 4-11: Approach 2 Quantitative Uncertainty Estimates for CO_2 Emissions from Lime Production (MMT CO_2 Eq. and Percent)

Source	Gas	2022 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Lime Production	CO_2	12.2	12.1	12.3	-1%	+1%

[a] Range of emission estimates predicted by Monte Carlo stochastic simulation for a 95 percent confidence interval.

QA/QC and Verification

General quality assurance/quality control (QA/QC) procedures were applied consistent with the U.S. Inventory QA/QC plan, which is in accordance with Volume 1, Chapter 6 of *2006 IPCC Guidelines* as noted in the introduction of the IPPU chapter (see Annex 8 for more details).

More details on the greenhouse gas calculation, monitoring and QA/QC methods associated with reporting on CO_2 captured for onsite use applicable to lime manufacturing facilities can be found under Subpart S (lime

manufacturing) of the GHGRP regulation (40 CFR Part 98).[16]EPA verifies annual facility-level GHGRP reports through a multi-step process (e.g., combination of electronic checks and manual reviews) to identify potential errors and ensure that data submitted to EPA are accurate, complete, and consistent (EPA 2023).[17] Based on the results of the verification process, EPA follows up with facilities to resolve mistakes that may have occurred. The post-submittals checks are consistent with a number of general and category-specific QC procedures, including: range checks, statistical checks, algorithm checks, and year-to-year checks of reported data and emissions.

Recalculations Discussion

No recalculations were performed for the 1990 through 2021 portion of the time series.

Planned Improvements

EPA plans to review GHGRP emissions and activity data reported to EPA under Subpart S of the GHGRP regulation (40 CFR Part 98), and aggregated activity data on lime production by type in particular. In addition, initial review of data has identified that several facilities use CEMS to report emissions. Under Subpart S, if a facility is using a CEMS, they are required to report combined combustion emissions and process emissions. EPA continues to review how best to incorporate GHGRP and notes that particular attention will be made to also ensuring time-series consistency of the emissions estimates presented in future *Inventory* reports, consistent with IPCC and UNFCCC guidelines. This is required because the facility-level reporting data from EPA's GHGRP, with the program's initial requirements for reporting of emissions in calendar year 2010, are not available for all inventory years (i.e., 1990 through 2009) as required for this *Inventory*. In implementing improvements and integration of data from EPA's GHGRP, the latest guidance from the IPCC on the use of facility-level data in national inventories will be relied upon.[18]

Future improvements involve improving and/or confirming the representativeness of current assumptions associated with emissions from production of LKD and other byproducts/wastes as discussed in the Uncertainty section, per comments from the NLA provided during a prior Public Review comment period for a previous (1990 through 2018) *Inventory.* EPA met with NLA in summer of 2020 for clarification on data needs and available data and to discuss planned research into GHGRP data. Previously, EPA met with NLA in spring of 2015 to outline specific information required to apply IPCC methods to develop a country-specific correction factor to more accurately estimate emissions from production of LKD. In 2016, NLA compiled and shared historical emissions information reported by member facilities on an annual basis under voluntary reporting initiatives from 2002 through 2011 associated with generation of total calcined byproducts and LKD. Reporting of LKD was only differentiated for the years 2010 and 2011. This emissions information was reported on a voluntary basis consistent with NLA's facility-level reporting protocol, which was also provided to EPA. To reflect information provided by NLA, EPA updated the qualitative description of uncertainty. At the time of this *Inventory*, this planned improvement is in process and has not been incorporated into this current *Inventory* report.

[16] See http://www.ecfr.gov/cgi-bin/text-idx?tpl=/ecfrbrowse/Title40/40cfr98_main_02.tpl.

[17] See https://www.epa.gov/sites/production/files/2015-07/documents/ghgrp_verification_factsheet.pdf.

[18] See http://www.ipcc-nggip.iges.or.jp/public/tb/TFI_Technical_Bulletin_1.pdf and the *2019 Refinement*, Volume 1, Chapter 2, Section 2.3, *Use of Facility Data in Inventories* at https://www.ipcc-nggip.iges.or.jp/public/2019rf/pdf/1_Volume1/19R_V1_Ch02_DataCollection.pdf.

4.3 Glass Production (CRT Source Category 2A3)

Glass production is an energy and raw-material intensive process that results in the generation of carbon dioxide (CO_2) from both the energy consumed in making glass and the glass production process itself. This reporting category (2A3) includes emissions from the production of glass. Emissions from fuels consumed for energy purposes during the production of glass are accounted for as part of fossil fuel combustion in the industrial end-use sector reported under the Energy chapter.

Glass production employs a variety of raw materials in a glass-batch. These include formers, fluxes, stabilizers, and sometimes colorants. The major raw materials (i.e., fluxes and stabilizers) that emit process-related CO_2 emissions during the glass melting process are limestone, dolomite, and soda ash. The main former in all types of glass is silica (SiO_2). Other major formers in glass include feldspar and boric acid (i.e., borax). Fluxes are added to lower the temperature at which the batch melts. Most commonly used flux materials are soda ash (sodium carbonate, Na_2CO_3) and potash (potassium carbonate, K_2O). Stabilizers make glass more chemically stable and keep the finished glass from dissolving and/or falling apart. Commonly used stabilizing agents in glass production are limestone ($CaCO_3$), dolomite ($CaCO_3MgCO_3$), alumina (Al_2O_3), magnesia (MgO), barium carbonate ($BaCO_3$), strontium carbonate ($SrCO_3$), lithium carbonate (Li_2CO_3), and zirconia (ZrO_2) (DOE 2002). Glass makers also use a certain amount of recycled scrap glass (cullet), which comes from in-house return of glassware broken in the production process or other glass spillage or retention, such as recycling or from cullet broker services.

The raw materials (primarily soda ash, limestone, and dolomite) release CO_2 emissions in a complex high-temperature chemical reaction during the glass melting process. This process is not directly comparable to the calcination process used in lime manufacturing, cement manufacturing, and process uses of carbonates (i.e., limestone/dolomite use) but has the same net effect in terms of generating process CO_2 emissions (IPCC 2006).

The U.S. glass industry can be divided into four main categories: containers, flat (window) glass, fiber glass, and specialty glass. The majority of commercial glass produced is container and flat glass (EPA 2009). The United States is one of the major global exporters of glass. Domestically, demand comes mainly from the construction, auto, bottling, and container industries. There are more than 1,700 facilities that manufacture glass in the United States, with the largest companies being Corning, Guardian Industries, Owens-Illinois, and PPG Industries.[19]

The glass container sector is one of the leading soda ash consuming sectors in the United States. In 2022, glass production accounted for 49 percent of total domestic soda ash consumption (USGS 2023). Emissions from soda ash production are reported in Section 4.12.

In 2022, 2,250 kilotons of soda ash, 1,370 kilotons of limestone, 925 kilotons of dolomite, and 1.9 kilotons of other carbonates were consumed for glass production (USGS 2023; EPA 2023). Use of soda ash, limestone, dolomite, and other carbonates in glass production resulted in aggregate CO_2 emissions of 2.0 MMT CO_2 Eq. (1,956 kt), which are summarized in Table 4-12 and Table 4-13. Overall, emissions have decreased by 14 percent compared to 1990. Emissions decreased by 1 percent compared to 2021 levels.

Emissions from glass production have remained relatively consistent over the time series with some fluctuations since 1990. In general, these fluctuations were related to the behavior of the export market and the U.S. economy. Specifically, the extended downturn in residential and commercial construction and automotive industries between 2008 and 2010 resulted in reduced consumption of glass products, causing a drop in global demand for limestone, dolomite, and soda ash and resulting in lower emissions. Some commercial food and beverage package

[19] Excerpt from Glass & Glass Product Manufacturing Industry Profile, First Research. Available online at: http://www.firstresearch.com/Industry-Research/Glass-and-Glass-Product-Manufacturing.html.

manufacturers are shifting from glass containers towards lighter and more cost-effective polyethylene terephthalate (PET) based containers, putting downward pressure on domestic consumption of soda ash (USGS 1995 through 2015b). Glass production in 2022 was steady, changing by no more than 2 percent over the course of the year (Federal Reserve 2023).

Table 4-12: CO_2 Emissions from Glass Production (MMT CO_2 Eq.)

Year	1990	2005	2018	2019	2020	2021	2022
Glass Production	2.3	2.4	2.0	1.9	1.9	2.0	2.0

Table 4-13: CO_2 Emissions from Glass Production (kt CO_2)

Year	1990	2005	2018	2019	2020	2021	2022
Glass Production	2,263	2,402	1,989	1,940	1,858	1,969	1,956

Methodology and Time-Series Consistency

Carbon dioxide emissions were calculated based on Tier 3 method from the *2006 IPCC Guidelines*, in accordance with the IPCC methodological decision tree and available data, by multiplying the quantity of input carbonates (i.e., limestone, dolomite, soda ash, and other carbonates) by the carbonate-based emission factor (in metric tons CO_2/metric ton carbonate) and the average carbonate-based mineral mass fraction.

2010 through 2022

The methodology for estimating CO_2 emissions from glass production for years 2010 through 2022 used the quantities of limestone, dolomite, and a group of other carbonates (i.e., barium carbonate, potassium carbonate, lithium carbonate, and strontium carbonate) used for glass production, obtained from GHGRP (EPA 2023). USGS data on the quantity of soda ash used for glass production was used because it was obtained directly from the soda ash producers and includes use by smaller artisanal glass operations, which are excluded in the GHGRP data.

GHGRP collects data from glass production facilities with greenhouse gas emissions greater than 25,000 metric tons CO_2 Eq. The reporting threshold is used to exclude artisanal glass operations that are expected to have much lower greenhouse gas emissions than the threshold. These smaller facilities have not been accounted for yet for this portion of the time series for limestone, dolomite, or other carbonates due to limited data. Facilities report the total quantity of each type of carbonate used in glass production each year to GHGRP, with data collection starting in 2010 (EPA 2023).

Using the total quantities of each carbonate, EPA calculated the metric tons of emissions resulting from glass production by multiplying the quantity of input carbonates (i.e., limestone, dolomite, soda ash, and other carbonates) by carbonate-based emission factors in metric tons CO_2/metric ton carbonate (limestone, 0.43971; dolomite, 0.47732; soda ash, 0.41492; and other carbonates, 0.262), and by the average carbonate-based mineral mass fraction for each year. IPCC default emission factors were used for limestone, dolomite, and soda ash, and the emission factor for other carbonates is based on expert judgment (RTI 2022).

1990 through 2009

Data from GHGRP on the quantity of limestone, dolomite, and other carbonates used in glass production are not available for 1990 through 2009. Additionally, USGS does not collect data on the quantity of other carbonates used for glass production.

To address time-series consistency, total emissions from 1990 to 2009 were calculated using the Federal Reserve Industrial Production Index for glass production in the United States as a surrogate for the total quantity of carbonates used in glass production. The production index measures real output expressed as a percentage of real output in a base year, which is currently 2017 (Federal Reserve 2023). Since January 1971, the Federal Reserve has released the monthly glass production index for NAICS code 3272 (Glass and Glass Product Manufacturing) as part

of release G.17, "Industrial Production and Capacity Utilization" (Federal Reserve 2023). The monthly index values for each year were averaged to calculate an average annual glass production index value. Total annual process emissions were calculated by taking a ratio of the average annual glass production index for each year to the average annual glass production index for base year 2017, and multiplying by the calculated 2017 emissions (process-related) based on GHGRP data.

Emissions from limestone, dolomite, and other carbonate consumption were disaggregated from total annual emissions, using the average percent contribution of each to annual emissions from these three carbonates for 2010 through 2014 based on GHGRP data: 64.5 percent limestone, 35.5 percent dolomite, and 0.1 percent other carbonates.

The methodology for estimating CO_2 emissions from the use of soda ash for glass production and data sources for the amount of soda ash used in glass production are consistent with the methodology used for 2010 through 2022. The average mineral mass fractions for soda ash are only available starting in 2010. The average carbonate-based mineral mass fractions from the GHGRP, averaged across 2010 through 2014, indicate that soda ash contained 98.7 percent sodium carbonate (Na_2CO_3). This averaged value is used to estimate emissions for 1990 through 2009. The years 2010 to 2014 were used to determine the average carbonate-based mineral mass fractions because those years were deemed to better represent historic glass production from 1990 to 2009.

Data on soda ash used for glass production for 1990 through 2022 were obtained from the U.S. Bureau of Mines (1991 and 1993a), the USGS *Minerals Yearbook: Soda Ash* (USGS 1995 through 2015b), and USGS *Mineral Industry Surveys for Soda Ash* (USGS 2017 through 2023). Data on limestone, dolomite, and other carbonates used for glass production and on average carbonate-based mineral mass fraction for 2010 through 2022 were obtained from GHGRP (EPA 2023). The quantities of limestone, dolomite, and other carbonates were calculated for 1990 through 2009 using the Federal Reserve Industrial Production Index (Federal Reserve 2023).

The amount of limestone, dolomite, soda ash, and other carbonates used in glass production each year and the annual average Federal Reserve production indices for glass production are shown in Table 4-14.

Table 4-14: Limestone, Dolomite, Soda Ash, and Other Carbonates Used in Glass Production (kt) and Average Annual Production Index for Glass and Glass Product Manufacturing

Activity	1990	2005	2018	2019	2020	2021	2022
Limestone	1,409	1,690	1,442	1,370	1,334	1,397	1,370
Dolomite	714	857	871	883	824	893	925
Soda Ash	3,177	3,050	2,280	2,220	2,130	2,280	2,250
Other Carbonates	2	3	2	2	2	2	1.9
Total	**5,302**	**5,599**	**4,596**	**4,475**	**4,289**	**4,572**	**4,547**
Production Index[a]	94.3	113.1	102.5	99.8	92.4	88.3	86.8

[a] Average Annual Production Index uses 2017 as the base year.

Note: Totals may not sum due to independent rounding.

As discussed above, methodological approaches were applied to the entire time series to ensure consistency in emissions from 1990 through 2022. Consistent with the *2006 IPCC Guidelines*, the overlap technique was applied to compare USGS and GHGRP data sets for 2010 through 2022. To address the inconsistencies, adjustments were made as described above.

Uncertainty

The methodology in this *Inventory* report uses GHGRP data for the average mass fraction of each mineral used in glass production. These minerals are limestone, dolomite, soda ash, and other carbonates (barium carbonate ($BaCO_3$), potassium carbonate (K_2CO_3), lithium carbonate (Li_2CO_3), and strontium carbonate ($SrCO_3$)). The mass fractions are reported directly by the glass manufacturers, for each year from 2010 to 2022.

The methodology uses the quantities of limestone, dolomite, and other carbonates used in glass manufacturing which is reported directly by the glass manufacturers for years 2010 through 2022 and the amount of soda ash used in glass manufacturing which is reported by soda ash producers for the full time series. EPA assigned an uncertainty range of ±5 percent and a normal probability density function for all carbonate quantities and the Federal Reserve Industrial Production Index for glass production, and using this suggested uncertainty provided in Section 2.4.2.2 of the *2006 IPCC Guidelines* is appropriate based on expert judgment (RTI 2023). EPA assigned an uncertainty range of ±2 percent for the carbonate emission factors, ±2 percent for the mineral mass fractions, and ±1 percent for the calcination fraction, and using this suggested uncertainty provided in Section 2.4.2.1 of the *2006 IPCC Guidelines* is appropriate based on expert judgment (RTI 2023). Per this expert judgment, a triangular probability density function was assigned for emission factors, mineral mass fractions, and calcination fraction.

The results of the Approach 2 quantitative uncertainty analysis are summarized in Table 4-15. In 2022, glass production CO_2 emissions were estimated to be between 1.9 and 2.0 MMT CO_2 Eq. at the 95 percent confidence level. This indicates a range of approximately 2 percent below and 2 percent above the emission estimate of 2.0 MMT CO_2 Eq.

Table 4-15: Approach 2 Quantitative Uncertainty Estimates for CO_2 Emissions from Glass Production (MMT CO_2 Eq. and Percent)

Source	Gas	2022 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Glass Production	CO_2	2.0	1.9	2.0	-2%	+2%

[a] Range of emission estimates predicted by Monte Carlo stochastic simulation for a 95 percent confidence interval.

QA/QC and Verification

General quality assurance/quality control (QA/QC) procedures were applied consistent with the U.S. Inventory QA/QC plan, which is in accordance with Volume 1, Chapter 6 of *2006 IPCC Guidelines* as described in the introduction of the IPPU chapter (see Annex 8 for more details). For the GHGRP data, EPA verifies annual facility-level reports through a multi-step process (e.g., including a combination of pre-and post-submittal electronic checks and manual reviews by staff) to identify potential errors and ensure that data submitted to EPA are accurate, complete, and consistent (EPA 2015).[20] Based on the results of the verification process, EPA follows up with facilities to resolve mistakes that may have occurred. The post-submittals checks are consistent with a number of general and category-specific QC procedures, including: range checks, statistical checks, algorithm checks, and year-to-year checks of reported data and emissions.

Recalculations Discussion

During annual QC, a transcription error for the 1990 value of CO_2 emissions from glass production was identified and corrected in Table 4-12 and Table 4-13. No recalculations were needed or performed due to this transcription error, and no other recalculations were performed for the 1990 through 2021 portion of the time series.

[20] GHGRP Report Verification Factsheet. See https://www.epa.gov/sites/production/files/2015-07/documents/ghgrp_verification_factsheet.pdf.

Planned Improvements

EPA plans to evaluate updates to uncertainty levels for the activity data and mineral mass fraction values from EPA's GHGRP. This is a near-term planned improvement that is anticipated for inclusion in 2025 report.

Some glass producing facilities in the United States do not report to EPA's GHGRP because they fall below the reporting threshold for this industry. EPA will continue ongoing research on the availability of data to better assess the completeness of emission estimates from glass production and how to refine the methodology to ensure complete national coverage of this category. When reporting began in 2010, EPA received data from more facilities that were above the reporting threshold than expected, and total emissions for these reporting facilities were higher than expected for all glass production facilities in the United States (EPA 2009). Research will include reassessing previous assessments of GHGRP industry coverage using the reporting threshold of 25,000 metric tons CO_2 Eq. This is a medium-term planned improvement.

4.4 Other Process Uses of Carbonates (CRT Source Category 2A4)

Limestone ($CaCO_3$), dolomite ($CaCO_3MgCO_3$),[21] and other carbonates such as soda ash, magnesite, and siderite are basic materials used by a wide variety of industries, including construction, agriculture, chemical, metallurgy (i.e., iron and steel production, ferroalloy production, and magnesium production), glass production, environmental pollution control, ceramics production, and non-metallurgical magnesia production. This reporting category (2A4) includes emissions from other uses of limestone, dolomite, and other carbonates not included in other categories; the production of ceramics; other uses of soda ash not included elsewhere; and the production of non-metallurgical magnesia. This section addresses mineral industry use of these carbonates: limestone, dolomite, soda ash, and magnesite. Emissions from the use of these carbonates are organized into four subcategories: other process uses of carbonates (i.e., limestone and dolomite consumption), ceramics production, other uses of soda ash, and non-metallurgical magnesia production.

For industrial applications, carbonates are heated sufficiently enough to calcine the material and generate CO_2 as a byproduct.

$$CaCO_3 \rightarrow CaO + CO_2$$

$$MgCO_3 \rightarrow MgO + CO_2$$

Examples of such applications include limestone used as a flux or purifier in metallurgical furnaces, as a sorbent in flue gas desulfurization (FGD) systems for utility and industrial plants, and as a raw material for the production of glass, lime, and cement.

Emissions from limestone and dolomite used in the production of cement, lime, glass, and iron and steel are excluded from the other process uses of carbonates category and reported under their respective source categories (e.g., Section 4.3, Glass Production). Emissions from soda ash production are reported under Section 4.12, Soda Ash Production (CRT Source Category 2B7). Emissions from soda ash consumption associated with glass manufacturing are reported under Section 4.3, Glass Production (CRT Source Category 2A3). Emissions from the use of limestone and dolomite in liming of agricultural soils are included in the Agriculture chapter under Section 5.5, Liming (CRT Source Category 3G). Emissions from limestone and dolomite used in the production of iron and steel and magnesium production are reported under Section 4.18, Iron and Steel Production (CRT Source Category 2C1).

[21] Limestone and dolomite are collectively referred to as limestone by the industry, and intermediate varieties are seldom distinguished.

Emissions from dolomite used in the production of magnesium are reported under Section 4.21, Magnesium Production and Processing (CRT Source Category 2C4). As noted in Section 4.19, Ferroalloy Production (CRT Source Category 2C2), emissions from the production of ferromanganese are not included in this *Inventory* because of the small number of manufacturers of these materials in the United States. Government information disclosure rules prevent the publication of production data for these production facilities. Emissions from fuels consumed for energy purposes during these processes are accounted for as part of fossil fuel combustion in the industrial end-use sector reported under the Energy chapter in Section 3.1, Fossil Fuel Combustion (CRT Source Category 1A). Both lime (CaO) and limestone ($CaCO_3$) can be used as a sorbent for FGD systems. Emissions from lime consumption for FGD systems and from sugar refining are reported under Section 4.3, Lime Production (CRT Source Category 2A2). Emissions from the use of dolomite in primary magnesium metal production are reported under Section 4.21, Magnesium Production and Processing (CRT Source Category 2C4).

Limestone and dolomite are widely distributed throughout the world in deposits of varying sizes and degrees of purity. Large deposits of limestone occur in nearly every state in the United States, and significant quantities are extracted for industrial applications. In 2018, the leading limestone producing states were Texas, Florida, Ohio, Missouri, and Pennsylvania, which contributed 46 percent of the total U.S. output (USGS 2022a). Dolomite deposits are found in the United States, Canada, Mexico, Europe, Africa, and Brazil. In the United States, the leading dolomite producing states are Pennsylvania, New York, and Utah which currently contribute more than a third of the total U.S. output (USGS 2022a).

Ceramics include the production of bricks and roof tiles, vitrified clay pipes, refractory products, expanded clay products, wall and floor tiles, table and ornamental ware (i.e., household ceramics), sanitary ware, technical ceramics (e.g., aerospace, automotive, electronic, or biomedical applications), and inorganic bonded abrasives. Most ceramic products are made from one or more different types of clay (e.g., shales, fire clay, and ball clay) with varying carbonate contents. The process of manufacturing ceramic products, regardless of the product type or scale, is essentially the same. This process consists of raw material processing (grinding, calcining, and drying), forming (wet or dry process), firing (single or multiple stage firing process), and final processing. Process CO_2 emissions are produced during the calcination process in the kiln or dryer, where carbonates are heated to high temperatures which results in metal oxides and CO_2. In 2018, the leading clay producing states were Georgia, Wyoming, Texas, Alabama, and North Carolina, which contributed 60 percent of the total U.S. output (USGS 2022f).

Other uses of soda ash include the consumption of soda ash for non-glass purposes. Excluding glass production, soda ash consumption by end use in 2022 included chemicals, 54 percent, soap and detergent manufacturing, 9 percent; distributers, 10 percent; flue gas desulfurization, 7 percent; other uses, 17 percent; pulp and paper production, 1 percent; and water treatment, 2 percent (USGS 2023a). Chemicals produced using soda ash include sodium-based inorganic chemicals such as sodium bicarbonate, sodium chromates, sodium phosphates, and sodium silicates. (USGS 2022g). Internationally, two types of soda ash are produced: natural and synthetic. In 2019, 93 percent of the global soda ash production came from China, the United States, Russia, Germany, India, Turkey, Poland, and France. The United States only produces natural soda ash and only in two states: Wyoming and California (USGS 2021a).

Non-metallurgical magnesia production comprises of three categories of magnesia products: calcined magnesia, deadburned magnesia, and fused magnesia. Magnesia is produced by calcining magnesite ($MgCO_3$) which results in the release of CO_2. Non-metallurgical magnesia is used in agricultural, industrial, refractory, and electrical insulating applications. Specific applications include fertilizers, construction materials, plastics, and flue gas desulphurization. China, Russia, and Turkey account for 83 percent of global production capacity of magnesia from magnesite (USGS 2022e). In the United States, only one facility located in Nevada produces non-metallurgical magnesia using magnesite as the raw material.

In 2022, 18,671 kilotons (kt) of limestone, 2,052 kt of dolomite, 2,391 kt of soda ash, and 388 kt of magnesite were consumed for these emissive applications, which excludes consumption for the production of cement, lime, glass, and iron and steel (Willett 2023; USGS 2022b). Usage of limestone, dolomite, soda ash, and magnesite resulted in aggregate CO_2 emissions of 10.4 MMT CO_2 Eq. (10,384 kt) (see Table 4-16 and Table 4-17). The 2022 emissions increased 21 percent compared to 2021, primarily as a result of increased limestone consumption attributed to

sulfur oxide removal. Growth in the public and private construction markets contributed to an increase in consumption of crushed stone in 2022. Overall emissions have increased 46 percent from 1990 through 2022.

Table 4-16: CO_2 Emissions from Other Process Uses of Carbonates (MMT CO_2 Eq.)

Year	1990	2005	2018	2019	2020	2021	2022
Other Uses of Carbonates	4.8	6.2	6.3	7.4	7.4	7.0	8.8
Ceramics Production	0.8	0.8	0.4	0.4	0.4	0.4	0.4
Other Uses of Soda Ash[a]	1.4	1.3	1.1	1.0	1.0	1.0	1.0
Non-Metallurgical Magnesia Production	0.1	0.2	0.2	0.2	0.2	0.2	0.2
Total	**7.1**	**8.5**	**7.9**	**9.0**	**9.0**	**8.6**	**10.4**

[a] Soda ash consumption not associated with glass manufacturing.
Note: Totals may not sum due to independent rounding.

Table 4-17: CO_2 Emissions from Other Process Uses of Carbonates (kt CO_2)

Year	1990	2005	2018	2019	2020	2021	2022
Other Uses of Carbonates	4,843	6,155	6,283	7,386	7,441	6,972	8,781
Ceramics Production	757	822	418	399	397	400	407
Other Uses of Soda Ash[a]	1,390	1,305	1,069	1,036	958	979	992
Non-Metallurgical Magnesia Production	113	191	169	152	216	231	204
Total	**7,103**	**8,472**	**7,938**	**8,973**	**9,012**	**8,583**	**10,384**

[a] Soda ash consumption not associated with glass manufacturing.
Note: Totals may not sum due to independent rounding.

Methodology and Time-Series Consistency

Other Uses of Carbonates (Limestone and Dolomite Consumption)

Carbon dioxide emissions from other uses of carbonates, specifically limestone and dolomite consumption, were calculated using a Tier 2 method from the *2006 IPCC Guidelines*, in accordance with the IPCC methodological decision tree and available data, by multiplying the quantity of limestone or dolomite consumed by the emission factor for limestone or dolomite calcination, respectively: 0.43971 metric ton CO_2/metric ton carbonate for limestone and 0.47732 metric ton CO_2/metric ton carbonate for dolomite.[22] This methodology was used for limestone and dolomite used for flux stone, flue gas desulfurization systems, chemical stone, mine dusting or acid water treatment, and acid neutralization. Flux stone used during the production of iron and steel was deducted from the other uses of carbonates source category estimate and attributed to the iron and steel production source category estimate. Similarly, limestone and dolomite consumption for glass manufacturing, cement, and lime manufacturing are excluded from this category and attributed to their respective categories.

Consumption data for 1990 through 2022 of limestone and dolomite used for flux stone, flue gas desulfurization systems, chemical stone, mine dusting or acid water treatment, and acid neutralization (see Table 4-18) were obtained from the U.S. Geological Survey (USGS) *Minerals Yearbook: Crushed Stone Annual Report* (1995a through 2023b), preliminary data for 2022 from USGS Crushed Stone Commodity Expert (Willett 2023), American Iron and Steel Institute limestone and dolomite consumption data (AISI 2018 through 2021), and the U.S. Bureau of Mines (1991 and 1993a), which are reported to the nearest ton. In addition, the estimated values for limestone and dolomite consumption for flux stone used during the production of iron and steel were adjusted using emissions data from the EPA's Greenhouse Gas Reporting Program (GHGRP) Subpart Q for the iron and steel sector to account for the impacts of the COVID-19 pandemic in 2020 and 2021. Iron and steel GHGRP process emissions data

[22] *2006 IPCC Guidelines*, Volume 3: Chapter 2, Table 2.1.

decreased by approximately 8 percent from 2021 to 2022 (EPA 2023). This adjustment method is consistent with the method used in Section 4.18, Iron and Steel Production (CRT Source Category 2C1).

During 1990 and 1992, the USGS did not conduct a detailed survey of limestone and dolomite consumption by end-use; therefore, data on consumption by end use for 1990 was estimated by applying the 1991 ratios of total limestone and dolomite consumption by end use to total 1990 limestone and dolomite consumption values. Similarly, the 1992 consumption figures were approximated by applying an average of the 1991 and 1993 ratios of total limestone and dolomite use by end uses to the 1992 total values.

In 1991, the U.S. Bureau of Mines, now known as the USGS, began compiling production and end use information through surveys of crushed stone manufacturers. Manufacturers provided different levels of detail in survey responses, so information was divided into three categories: (1) production by end-use, as reported by manufacturers (i.e., "specified" production); (2) production reported by manufacturers without end-uses specified (i.e., "unspecified-reported" production); and (3) estimated additional production by manufacturers who did not respond to the survey (i.e., "unspecified-estimated" production). Additionally, each year the USGS withholds data on certain limestone and dolomite end-uses due to confidentiality agreements regarding company proprietary data. For the purposes of this analysis, emissive end-uses that contained withheld data were estimated using one of the following techniques: (1) the value for all the withheld data points for limestone or dolomite use was distributed evenly to all withheld end-uses; (2) the average percent of total limestone or dolomite for the withheld end-use in the preceding and succeeding years; or (3) the average fraction of total limestone or dolomite for the end-use over the entire time period.

A large quantity of crushed stone was reported to the USGS under the category "unspecified uses." A portion of this consumption is believed to be limestone or dolomite used for emissive end uses. The quantity listed for "unspecified uses" was, therefore, allocated to all other reported end-uses according to each end-use's fraction of total consumption in that year.[23]

Table 4-18: Limestone and Dolomite Consumption from Other Uses of Carbonates (kt)

Activity	1990	2005	2018	2019	2020	2021	2022
Limestone	10,016	10,465	12,816	15,146	13,707	12,788	17,891
Dolomite	919	3,254	1,356	1,520	2,962	2,826	1,915
Total	**10,935**	**13,719**	**14,172**	**16,667**	**16,669**	**15,614**	**19,806**

Note: Totals may not sum due to independent rounding.

Ceramics Production

Carbon dioxide emissions from ceramics production were calculated using a Tier 1 method from the *2006 IPCC Guidelines*, in accordance with the IPCC methodological decision tree and available data, by multiplying the quantity of clay consumed for emissive purposes by a carbonate content value of clay of 10 percent, limestone fraction of 85 percent and dolomite fraction of 15 percent, respectively, and by the emission factor for limestone or dolomite calcination, respectively: 0.43971 metric ton CO_2/metric ton of limestone and 0.47732 metric ton CO_2/metric ton of dolomite.[24] To estimate annual process CO_2 emissions, EPA evaluated the end-uses of each type of clay published by USGS to identify the emissive end-uses that fall into the ceramics production subcategory. The emissive end-uses were organized into three groups: ceramics, glass, and floor & tile; refractories; and heavy clay products. The total limestone and dolomite consumption from the three emissive groupings for ceramics production for 1990 through 2022 (see Table 4-19) were obtained from USGS (Simmons 2024).

[23] This approach was recommended by USGS, the data collection agency.

[24] *2006 IPCC Guidelines*, Volume 3: Chapter 2, Table 2.1.

Table 4-19: Limestone and Dolomite Consumption from Ceramics Production (kt)

Activity	1990	2005	2018	2019	2020	2021	2022
Limestone	1,444	1,569	797	762	758	764	776
Dolomite	255	277	141	135	134	135	137
Total	**1,699**	**1,846**	**938**	**897**	**892**	**899**	**913**

Note: Totals may not sum due to independent rounding.

Other Uses of Soda Ash

Carbon dioxide emissions from soda ash consumption were calculated using a Tier 1 method from the *2006 IPCC Guidelines*, in accordance with the IPCC methodological decision tree and available data. Excluding glass manufacturing which is reported under Section 4.3 Glass Production (CRT Source Category 2A3), most soda ash is consumed in chemical production, with smaller amounts used in soap production, pulp and paper, flue gas desulfurization, and water treatment. In these applications, it is assumed that one mole of carbon is released for every mole of soda ash used. Thus, approximately 0.113 metric tons of carbon (or 0.415 metric tons of CO_2) are released for every metric ton of soda ash consumed. The activity data for soda ash consumption for 1990 to 2022 (see Table 4-20) were obtained from the *U.S. Geological Survey (USGS) Minerals Yearbook for Soda Ash* (1994 through 2015b) and *USGS Mineral Industry Surveys for Soda Ash* (USGS 2017a, 2018, 2019, 2020b, 2021b, 2022a, 2023a). Soda ash consumption data were collected by the USGS from voluntary surveys of the U.S. soda ash industry.

Table 4-20: Other Uses of Soda Ash Consumption Not Associated with Glass Manufacturing (kt)

Activity	1990	2005	2018	2019	2020	2021	2022
Soda Ash[a]	3,351	3,144	2,576	2,497	2,310	2,360	2,391

[a] Soda ash consumption is sales reported by producers which exclude imports. Historically, imported soda ash is less than 1 percent of the total U.S. consumption (Kostick 2012).

Non-Metallurgical Magnesia Production

Carbon dioxide emissions from non-metallurgical magnesia production were calculated using a Tier 1 method from the *2006 IPCC Guidelines*, in accordance with the IPCC methodological decision tree and available data, by multiplying the quantity of magnesium ore extracted from the mine and processed at the facility by the carbonate content for magnesite or limestone, respectively, and by the emission factor for magnesite or limestone calcination, respectively: 0.52197 metric ton CO_2/metric ton carbonate for magnesite and 0.43971 metric ton CO_2/metric ton carbonate for limestone.[25] A USGS report on magnesite deposits at Gabbs, Nevada lists the carbonate content of magnesite as 98 percent magnesite and 1 percent limestone (USGS 1948). In the absence of other data, all magnesium ore extracted from the mine is assumed to be used for non-metallurgical magnesium production. Magnesium ore extracted from the mine and processed at the facility for non-metallurgical magnesia production for 2002 through 2022 (see Table 4-21) was obtained from the Nevada Department of Environmental Quality (McNeece 2023). This data was not available for 1990 through 2001. To address this gap in data availability and time-series consistency, carbonate consumption for 1990 through 2001 were estimated by multiplying the average ratio of magnesium ore consumption to production capacity for 2002 to 2004 by the production capacity of the facility in Nevada. Production capacity for 1990 through 2001 was obtained from the *USGS Minerals Yearbook for Magnesium Compounds* (USGS 1990 through 2002).

[25] *2006 IPCC Guidelines*, Volume 3: Chapter 2, Table 2.1.

Table 4-21: Magnesite and Limestone Consumption from Non-Metallurgical Magnesia Production (kt)

Activity	1990	2005	2018	2019	2020	2021	2022
Magnesite	214	363	321	289	410	439	388
Limestone	2	4	3	3	4	4	4
Total	**216**	**367**	**325**	**292**	**414**	**443**	**392**

Note: Totals may not sum due to independent rounding.

Methodological approaches were applied to the entire time series to ensure consistency in emissions from 1990 through 2022. Consistent with the *2006 IPCC Guidelines*, the overlap technique was applied for non-metallurgical magnesia production to compare the magnesium ore consumption data to production capacity data for years where there was overlap. To address inconsistencies, adjustments were made, as described above.

Uncertainty

The uncertainty levels presented in this section account for uncertainty associated with activity data. Data on limestone and dolomite consumption are collected by USGS through voluntary national surveys. USGS contacts the mines (i.e., producers of various types of crushed stone) for annual sales data. Data on other carbonate consumption are not readily available. The producers report the annual quantity sold to various end-users and industry types. USGS estimates the historical response rate for the crushed stone survey to be approximately 70 percent, and the rest is estimated by USGS. Large fluctuations in reported consumption exist, reflecting year-to-year changes in the number of survey responders. The uncertainty resulting from a shifting survey population is exacerbated by the gaps in the time series of reports. The accuracy of distribution by end use is also uncertain because this value is reported by the producer/mines and not the end user. Additionally, there is significant inherent uncertainty associated with estimating withheld data points for specific end uses of limestone and dolomite. Lastly, much of the limestone consumed in the United States is reported as "other unspecified uses;" therefore, it is difficult to accurately allocate this unspecified quantity to the correct end-uses. EPA contacted the USGS National Minerals Information Center Crushed Stone commodity expert to assess the current uncertainty ranges associated with the limestone and dolomite consumption data compiled and published by USGS. During this discussion, the expert confirmed that EPA's range of uncertainty was still reasonable (Willett 2017). EPA assigned an uncertainty range of ±10 percent for limestone and dolomite consumption, based on expert judgement (Willett 2017). EPA assigned an uncertainty range of ±5 percent for soda ash consumption, and using this suggested uncertainty provided in Volume 3, Chapter 2, Section 2.4.2.2 of the *2006 IPCC Guidelines* is appropriate based on expert judgment (RTI 2023).

Uncertainty in the estimates also arises in part due to variations in the chemical composition of limestone. In addition to calcium carbonate, limestone may contain smaller amounts of magnesia, silica, and sulfur, among other minerals. The exact specifications for limestone or dolomite used as flux stone vary with the pyrometallurgical process and the kind of ore processed. EPA assigned an uncertainty range of ±3 percent for the CO_2 emission factors for limestone and dolomite consumption, and using this suggested uncertainty provided in Volume 3, Chapter 2, Section 2.5.2.1 of the *2006 IPCC Guidelines* is appropriate based on expert judgment (RTI 2023).

For emissions from ceramics production, data on clay consumption are collected by USGS through voluntary national surveys. Large fluctuations in reported consumption exist, reflecting year-to-year changes in the number of survey responders. The accuracy of distribution by end use is also uncertain because this value is reported by the producer and not the end user. Uncertainty in the estimates also arises in part due to the variations in the carbonate content of the various clays used for the various types of ceramics. As discussed above, as no information is available on the carbonate content for each clay, fractions of limestone and dolomite consumed and a carbonate content for clay from the *2006 IPCC Guidelines* are used. EPA assigned an uncertainty range of ±10 percent for the activity data and ±3 percent for the emission factors, consistent with uncertainty ranges for limestone and dolomite activity data and emission factors for other process uses of carbonates, respectively.

For emissions from soda ash consumption, the primary source of uncertainty results from the fact that these emissions are dependent upon the type of processing employed by each end-use. Specific emission factors for each end-use are not available, so a Tier 1 default emission factor is used for all end-uses. Therefore, there is uncertainty surrounding the emission factors from the consumption of soda ash. Additional uncertainty comes from the reported consumption and allocation of consumption within sectors that is collected on a quarterly basis by the USGS. Efforts have been made to categorize company sales within the correct end-use sector. EPA assigned an uncertainty range of ±2 percent for the CO_2 emission factor for soda ash consumption. The uncertainty range is derived from the default ranges for soda ash consumption for glass production in Volume 3, Chapter 2, Section 2.4.2.1 of the *2006 IPCC Guidelines* which is representative of soda ash consumption not associated with glass production, based on expert judgment (RTI 2023).

For non-metallurgical magnesia production, uncertainties arise due to variations in the chemical composition of the carbonates used in production of caustic-calcined magnesia production. As noted, minor quantities of other carbonates beyond limestone and magnesite are also used but unknown. These other carbonates are likely small and have a minimal impact on the derived emission factor. EPA assigned an uncertainty range of ±10 percent for the activity data and ±3 percent for the emission factors, consistent with uncertainty ranges for limestone and dolomite activity data and emission factors for other process uses of carbonates, respectively. The results of the Approach 2 quantitative uncertainty analysis are summarized in Table 4-22.

A normal probability density function was assigned for all activity data, and a triangular probability density function was assigned for all emission factors (RTI 2023). Carbon dioxide emissions from other process uses of carbonates in 2022 were estimated to be between 9.2 and 12.0 MMT CO_2 Eq. at the 95 percent confidence level. This indicates a range of approximately 12 percent below and 15 percent above the emission estimate of 10.4 MMT CO_2 Eq.

Table 4-22: Approach 2 Quantitative Uncertainty Estimates for CO_2 Emissions from Other Process Uses of Carbonates (MMT CO_2 Eq. and Percent)

Source	Gas	2022 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (MMT CO_2 Eq.)		Uncertainty Range Relative to Emission Estimate[a] (%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Other Process Uses of Carbonates	CO_2	10.4	9.2	12.0	-12%	+15%

[a] Range of emission estimates predicted by Monte Carlo stochastic simulation for a 95 percent confidence interval.

QA/QC and Verification

General quality assurance/quality control (QA/QC) procedures were applied consistent with the U.S. Inventory QA/QC plan, which is in accordance with Volume 1, Chapter 6 of *2006 IPCC Guidelines* as described in the introduction of the IPPU chapter (see Annex 8 for more details).

Recalculations Discussion

For the current *Inventory*, emission estimates for new subcategories ceramics production and non-metallurgical magnesia production were incorporated across the entire time series. No other recalculations were performed for the 1990 through 2021 portion of the time series.

Planned Improvements

EPA plans to review the uncertainty ranges assigned to activity data. This planned improvement is currently planned as a medium-term improvement.

4.5 Ammonia Production (CRT Source Category 2B1)

Emissions of carbon dioxide (CO_2) occur during the production of synthetic ammonia (NH_3), primarily through the use of natural gas, petroleum coke, or naphtha as a feedstock. The natural gas-, naphtha-, and petroleum coke-based processes produce CO_2 and hydrogen (H_2), the latter of which is used in the production of ammonia. The brine electrolysis process for production of ammonia does not lead to process-based CO_2 emissions. This reporting category (2B1) includes emissions from the production of ammonia. Due to national circumstances, emissions from fuels consumed for energy purposes during the production of ammonia are accounted for as part of fossil fuel combustion in the industrial end-use sector reported under the Energy chapter. More information on this approach can be found in the Methodology section below.

Ammonia production requires a source of nitrogen (N) and hydrogen (H). Nitrogen is obtained from air through liquid air distillation or an oxidative process where air is burnt and the residual nitrogen is recovered. In the United States, the majority of ammonia is produced using a natural gas feedstock as the hydrogen source. One synthetic ammonia production plant located in Kansas is producing ammonia from petroleum coke feedstock. In some U.S. plants, some of the CO_2 produced by the process is captured and used to produce urea rather than being emitted to the atmosphere. In 2022, 16 companies operated 35 ammonia producing facilities in 16 states. Approximately 60 percent of domestic ammonia production capacity is concentrated in Louisiana, Oklahoma, and Texas (USGS 2023).

Synthetic ammonia production from natural gas feedstock consists of five principal process steps. The primary reforming step converts methane (CH_4) to CO_2, carbon monoxide (CO), and hydrogen (H_2) in the presence of a catalyst. Only 30 to 40 percent of the CH_4 feedstock to the primary reformer is converted to CO and CO_2 in this step of the process. The secondary reforming step converts the remaining CH_4 feedstock to CO and CO_2. In the shift conversion step, the CO in the process gas from the secondary reforming step (representing approximately 15 percent of the process gas) is converted to CO_2 in the presence of a catalyst, water, and air. Carbon dioxide is removed from the process gas by the shift conversion process, and the H_2 is combined with the nitrogen (N_2) gas in the process gas during the ammonia synthesis step to produce ammonia. The CO_2 is included in a waste gas stream with other process impurities and is absorbed by a scrubber solution. In regenerating the scrubber solution, CO_2 is released from the solution.

The conversion process for conventional steam reforming of CH_4, including the primary and secondary reforming and the shift conversion processes, is approximately as follows:

$$0.88CH_4 + 1.26Air + 1.24H_2O \rightarrow 0.88CO_2 + N_2 + 3H_2$$

$$N_2 + 3H_2 \rightarrow 2NH_3$$

To produce synthetic ammonia from petroleum coke, the petroleum coke is gasified and converted to CO_2 and H_2. These gases are separated, and the H_2 is used as a feedstock to the ammonia production process, where it is reacted with N_2 to form ammonia.

Not all of the CO_2 produced during the production of ammonia is emitted directly to the atmosphere. Some of the ammonia and some of the CO_2 produced by the synthetic ammonia process are used as raw materials in the production of urea [$CO(NH_2)_2$], which has a variety of agricultural and industrial applications.

The chemical reaction that produces urea is:

$$2NH_3 + CO_2 \rightarrow NH_2COONH_4 \rightarrow CO(NH_2)_2 + H_2O$$

Only the CO_2 emitted directly to the atmosphere from the synthetic ammonia production process is accounted for in determining emissions from ammonia production. The CO_2 that is captured during the ammonia production process and used to produce urea does not contribute to the CO_2 emission estimates for ammonia production

presented in this section. Instead, CO_2 emissions resulting from the consumption of urea are attributed to the urea consumption or urea application source category (under the assumption that the carbon stored in the urea during its manufacture is released into the environment during its consumption or application). Emissions of CO_2 resulting from agricultural applications of urea are accounted for in Section 5.6. Emissions of CO_2 resulting from non-agricultural applications of urea (e.g., use as a feedstock in chemical production processes) are accounted for in Section 4.6.

Emissions from fuel used for energy at ammonia plants are accounted for as part of fossil fuel combustion in the industrial end-use sector reported under the Energy chapter. The consumption of natural gas and petroleum coke as fossil fuel feedstocks for NH_3 production are adjusted for within the Energy chapter as these fuels were consumed during non-energy related activities. More information on this methodology is described in Annex 2.1, Methodology for Estimating Emissions of CO_2 from Fossil Fuel Combustion.

Total emissions of CO_2 from ammonia production in 2022 were 12.6 MMT CO_2 Eq. (12,610 kt) and are summarized in Table 4-23 and Table 4-24. Ammonia production relies on natural gas as both a feedstock and a fuel, and as such, market fluctuations and volatility in natural gas prices affect the production of ammonia. Since 1990, emissions from ammonia production have decreased by 12 percent. Emissions in 2022 increased by about 3 percent from the 2021 levels. One facility in Kansas produces ammonia from petroleum coke and began operations in 2000. All other facilities use natural gas as feedstock.

Emissions from ammonia production increased steadily from 2015 to 2018, due to the addition of new ammonia production facilities and new production units at existing facilities in 2016, 2017, and 2018. Agriculture continues to drive demand for nitrogen fertilizers, accounting for approximately 88 percent of domestic ammonia consumption (USGS 2023).

Table 4-23: CO_2 Emissions from Ammonia Production (MMT CO_2 Eq.)

Source	1990	2005	2018	2019	2020	2021	2022
Ammonia Production	14.4	10.2	12.7	12.4	13.0	12.2	12.6

Table 4-24: CO_2 Emissions from Ammonia Production (kt CO_2)

Source	1990	2005	2018	2019	2020	2021	2022
Ammonia Production	14,404	10,234	12,669	12,401	13,006	12,192	12,610

Methodology and Time-Series Consistency

Estimates of CO_2 emissions from the production of synthetic ammonia for 2010 through 2022 are estimated using a country-specific approach consistent with Tier 3 method from the *2006 IPCC Guidelines*, in accordance with the IPCC methodological decision tree and available data (IPCC 2006). The methodology for 2010 to 2022 directly uses the process CO_2 emissions reported to subpart G of the U.S. EPA Greenhouse Gas Reporting Program (GHGRP) (EPA 2018, EPA 2023). Estimates for 1990 to 2009 emissions are based on reported and calculated data on natural gas and petroleum coke feedstock used for ammonia production, consistent with IPCC Tier 2 methods and in accordance with the IPCC methodological decision tree and available data.

Emissions from fuel used for energy at ammonia plants are accounted for in the Energy chapter. This approach differs slightly from the *2006 IPCC Guidelines* which indicates that "in the case of ammonia production no distinction is made between fuel and feedstock emissions with all emissions accounted for in the IPPU Sector." Disaggregated data on fuel used for ammonia feedstock and fuel used for energy for ammonia production are not available in the United States. The Energy Information Administration (EIA), where energy use data are obtained for the *Inventory* (see the Energy chapter), does not provide data broken out by industrial category. EIA data are only available at the broad industry sector level. Furthermore, the GHGRP data used to estimate emissions are based on feedstock use and not fuel use. The method uses the same science informing the 2006 IPCC guidelines

and is consistent with avoiding double counting in the reporting of fuel use emissions under Energy and IPPU reporting. See more information in introduction to this Chapter.

Petroleum Coke Feedstock

Since 2000, one facility in the United States has produced ammonia using petroleum coke as a feedstock. For 2010 to 2022, CO_2 emissions from the production of synthetic ammonia from petroleum coke feedstock were estimated using CO_2 emissions reported by the facility to GHGRP (EPA 2018; EPA 2023).

For 2006 to 2009, CO_2 emissions from the production of synthetic ammonia from petroleum coke feedstock were estimated by multiplying the following: quantity of petroleum coke feedstock reported by the facility (CVR 2008 through 2022); the *Inventory* heating content value for petroleum coke (consistent with values used in the Energy chapter); the petroleum coke carbon content; and a stoichiometric CO_2/C factor of 44/12.

For 2000 to 2005, the quantity of petroleum coke feedstock was not available and was estimated by multiplying the average ratio of petroleum coke feedstock quantity to ammonia production quantity produced from petroleum coke from 2006 through 2010 by total ammonia production for 2000 to 2005 (ACC 2023). The years 2006 to 2010 were used to determine the average ratio of petroleum coke feedstock quantity to the ammonia quantity produced from petroleum coke because that period was deemed to better represent historic ammonia production from petroleum coke for the period from 2000 to 2005.

For 2000 to 2005, CO_2 emissions from the production of synthetic ammonia from petroleum coke feedstock were estimated by multiplying the following: the average ratio of petroleum coke feedstock quantity to ammonia production quantity; total ammonia production quantity (ACC 2023); the *Inventory* heating content value for petroleum coke (consistent with values used in the Energy chapter); the petroleum coke carbon content; and the stoichiometric ratio of CO_2 to C (44/12).

Natural Gas Feedstock

For 2017 through 2022, facilities directly reported to GHGRP the quantity of natural gas feedstock used for ammonia production along with the carbon content of the natural gas feedstock (EPA 2018; EPA 2023).

For 2010 through 2016, the quantity of natural gas feedstock was calculated using GHGRP process CO_2 emissions for 2010 through 2016, average molecular weight of the feedstock from 2017 through 2021, and average carbon content from 2017 through 2021. Data from years 2017 to 2021 were used to determine the average molecular weight and the average carbon content because that period better represents historic ammonia production from 2010 to 2016. Using all available data from 2017 to 2021 allowed for the maximum number of data points available at the time of adopting this methodology to ensure that the average was representative. The averages were not updated using later data to exclude any new facilities that might not be representative of facilities that were operating during the earlier years of the GHGRP.

For 2010 to 2022, CO_2 emissions from the production of synthetic ammonia from natural gas feedstock were estimated using the CO_2 emissions reported to the GHGRP (EPA 2018; EPA 2023) and subtracting the CO_2 emissions from the production of synthetic ammonia from petroleum coke feedstock as determined in the Petroleum Coke Feedstock section above.

For 1990 to 2009, the quantity of natural gas feedstock was not available and was estimated by multiplying the average ratio of natural gas feedstock quantity to ammonia production quantity from 2010 through 2014 by total ammonia production for each year for 1990 to 2009 (ACC 2023). The years 2010 to 2014 were used to determine the average ratio of natural gas feedstock quantity to ammonia production because that period better represents

historic ammonia production from 1990 to 2009.[26] For 1990 to 2009, CO_2 emissions from the production of synthetic ammonia from natural gas feedstock were estimated using the natural gas feedstock quantity as determined above and the *Inventory* CO_2 emissions factor and heating content value for natural gas (consistent with values used in the Energy chapter).

Urea Production Adjustments

Emissions of CO_2 from ammonia production from both feedstocks and for all years from 1990 to 2022 were adjusted to account for the use of some CO_2 emissions resulting from ammonia production as a raw material in the production of urea. The CO_2 emissions reported for ammonia production are reduced by a factor of 0.733, which corresponds to a stoichiometric CO_2/urea factor of 44/60, assuming complete conversion of ammonia (NH_3) and CO_2 to urea (IPCC 2006; EFMA 2000), and multiplied by total annual domestic urea production.

All synthetic ammonia production and subsequent urea production are assumed to be from the same process—conventional catalytic reforming of natural gas feedstock, with the exception of ammonia production from petroleum coke feedstock at the one facility located in Kansas.

Table 4-25: Total Ammonia Production, Total Urea Production, and Recovered CO_2 Consumed for Urea Production (kt)

Year	1990	2005	2018	2019	2020	2021	2022
Total Ammonia Production	15,425	10,143	16,010	16,410	17,020	15,420	16,800
Total Urea Production	7,450	5,270	10,700	11,400	11,500	10,521	11,272
Recovered CO_2 Consumed for Urea Production	5,463	3,865	7,847	8,360	8,433	7,715	8,266

Total ammonia production, total urea production, and recovered CO_2 consumed for urea production are shown in Table 4-25. Total ammonia production data for 2011 through 2022 were obtained from American Chemistry Council (ACC 2023). For years 1990 through 2011, ammonia production data were obtained from the Census Bureau of the U.S. Department of Commerce (U.S. Census Bureau 1991 through 1994, 1998 through 2011) as reported in *Current Industrial Reports Fertilizer Materials and Related Products* annual and quarterly reports. Data on facility-level process emissions for 2010 through 2022 and data on natural gas feedstock used and carbon content of the natural gas feedstock starting in 2017 were obtained from GHGRP (EPA 2018; EPA 2023). Natural gas and petroleum coke heating values come from national-level data (EIA 2023), and natural gas and petroleum coke carbon contents are the same as used in the Energy chapter calculations.

Data on urea production for 2010 through 2022 were obtained from GHGRP (EPA 2018, EPA 2023). Urea production data for 2009 through 2010 were obtained from the U.S. Census Bureau (U.S. Census Bureau 2010 and 2011). Urea production data for 1990 through 2008 were obtained from the USGS *Minerals Yearbook: Nitrogen* (USGS 1994-2009). The U.S. Census Bureau ceased collection of urea production statistics in 2011.

Methodological approaches were applied to the entire time series to ensure consistency in emissions from 1990 through 2022. The methodology for ammonia production spliced activity data from different sources: U. S. Census Bureau data for 1990 through 2010, ACC data beginning in 2011, and GHGRP data beginning in 2010 and 2017. Consistent with the *2006 IPCC Guidelines*, the overlap technique was applied to compare the two data sets for years where there was overlap, with findings that the data sets were consistent and adjustments were not needed.

[26] The number of facilities reporting to GHGRP has increased since 2010: 22 facilities reported from 2010 to 2012; 23 from 2013 to 2015; 26 in 2016; 28 in 2017 and 29 from 2018 to 2022. Using data from 2010 to 2014 excludes the newer facilities that might not be representative of facilities in earlier years.

Uncertainty

The uncertainties presented in this section are primarily due to how accurately the emission factor used represents an average across all ammonia plants using natural gas feedstock. Uncertainty in the back calculation of natural gas feedstock used for 1990 through 2009 also exists. Using the average ratio of natural gas feedstock quantity to ammonia production, determined using GHGRP data from 2010 to 2014, does not account for efficiency gains in ammonia production since 1990 (e.g., potential decreases in gas usage per ton of ammonia, manufacturing shift from steam-driven turbines to electrical-drive turbines). Uncertainties are also associated with ammonia production estimates and the assumption that all ammonia production and subsequent urea production was from the same process—conventional catalytic reforming of natural gas feedstock, with the exception of one ammonia production plant located in Kansas that is manufacturing ammonia from petroleum coke feedstock. Uncertainty is also associated with the representativeness of the emission factor used for the petroleum coke-based ammonia process. It is also assumed that ammonia and urea are produced at co-located plants from the same natural gas raw material. The uncertainty of the total urea production activity data, based on USGS *Minerals Yearbook: Nitrogen* data, is a function of the reliability of reported production data and is influenced by the completeness of the survey responses. EPA assigned an uncertainty range of ±5 percent for ammonia production and a range of ±2 percent for urea production, natural gas feedstock quantity, petroleum coke feedstock quantity, and carbon content of natural gas feedstock, and using the suggested uncertainty provided in Section 3.2.3.2 of the *2006 IPCC Guidelines* is appropriate based on expert judgment (RTI 2023). Per this expert judgement, a normal probability density function was assigned for all variables.

Recovery of CO_2 from ammonia production plants for purposes other than urea production (e.g., commercial sale, etc.) has not been considered in estimating the CO_2 emissions from ammonia production, as data concerning the disposition of recovered CO_2 are not available. Such recovery may or may not affect the overall estimate of CO_2 emissions depending upon the end use to which the recovered CO_2 is applied. Further research is required to determine whether byproduct CO_2 is being recovered from other ammonia production plants for application to end uses that are not accounted for elsewhere; however, for reporting purposes, CO_2 consumption for urea production is provided in this chapter.

The results of the Approach 2 quantitative uncertainty analysis are summarized in Table 4-26. Carbon dioxide emissions from ammonia production in 2022 were estimated to be between 12.2 and 13.1 MMT CO_2 Eq. at the 95 percent confidence level. This indicates a range of approximately 4 percent below and 4 percent above the emission estimate of 12.6 MMT CO_2 Eq.

Table 4-26: Approach 2 Quantitative Uncertainty Estimates for CO_2 Emissions from Ammonia Production (MMT CO_2 Eq. and Percent)

Source	Gas	2022 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Ammonia Production	CO_2	12.6	12.2	13.1	-4%	+4%

[a] Range of emission estimates predicted by Monte Carlo stochastic simulation for a 95 percent confidence interval.

QA/QC and Verification

General quality assurance/quality control (QA/QC) procedures were applied to ammonia production emission estimates consistent with the U.S. Inventory QA/QC plan, which is in accordance with Volume 1, Chapter 6 of *2006 IPCC Guidelines* as described in the introduction of the IPPU chapter (see Annex 8 for more details). More details on the greenhouse gas calculation, monitoring and QA/QC methods applicable to ammonia facilities can be found

under Subpart G (Ammonia Production) of the regulation (40 CFR Part 98).[27] EPA verifies annual facility-level GHGRP reports through a multi-step process (e.g., combination of electronic checks and manual reviews) to identify potential errors and ensure that data submitted to EPA are accurate, complete, and consistent.[28] Based on the results of the verification process, EPA follows up with facilities to resolve mistakes that may have occurred. The post-submittals checks are consistent with a number of general and category-specific QC procedures, including range checks, statistical checks, algorithm checks, and year-to-year checks of reported data and emissions.

More details on the greenhouse gas calculation, monitoring, and QA/QC methods applicable to reporting of urea produced at ammonia production facilities can be found under Section 4.6 Urea Consumption for Non-Agricultural Purposes.

Recalculations

For 2021, the urea consumption value was changed from a rounded value to a more precise unrounded value. As a result, recalculations were performed for emissions from ammonia for 2021. Compared to the previous *Inventory*, total CO_2 emissions from the production of ammonia production (from natural gas and petroleum coke feedstocks) decreased by less than 1 percent (15 kt) in 2021.

Planned Improvements

Currently the *Inventory* does not separately track fuel energy use for ammonia production. To be more consistent with *2006 IPCC Guidelines*, EPA is considering whether to include natural gas fuel use as part of ammonia production emissions as a future improvement. The data are still being evaluated as part of EPA's efforts to disaggregate other industrial sector categories' energy use in the Energy chapter of the *Inventory*. If possible, this will be incorporated in future *Inventory* reports. If incorporated, the fuel energy use and emissions will be removed from current reporting under Energy to avoid double counting.

4.6 Urea Consumption for Non-Agricultural Purposes (CRT Source Category 2B10)

Urea is produced using ammonia (NH_3) and carbon dioxide (CO_2) as raw materials. All urea produced in the United States is assumed to be produced at ammonia production facilities where both ammonia and CO_2 are generated. There were 35 plants producing ammonia in the United States in 2022, with two additional plants sitting idle for the entire year (USGS 2023b).

The chemical reaction that produces urea is:

$$2NH_3 + CO_2 \rightarrow NH_2COONH_4 \rightarrow CO(NH_2)_2 + H_2O$$

This section accounts for CO_2 emissions associated with urea consumed exclusively for non-agricultural purposes. This reporting category (2B10) includes emissions from IPCC assessment reports that do not fall within any other CRT source category, which includes emissions from urea consumption for non-agricultural purposes. Emissions of CO_2 resulting from agricultural applications of urea are accounted for in Section 5.6 of the Agriculture chapter.

[27] See http://www.ecfr.gov/cgi-bin/text-idx?tpl=/ecfrbrowse/Title40/40cfr98_main_02.tpl.

[28] See https://www.epa.gov/sites/production/files/2015-07/documents/ghgrp_verification_factsheet.pdf.

The industrial applications of urea include its use in adhesives, binders, sealants, resins, fillers, analytical reagents, catalysts, intermediates, solvents, dyestuffs, fragrances, deodorizers, flavoring agents, humectants and dehydrating agents, formulation components, monomers, paint and coating additives, photosensitive agents, and surface treatments agents. In addition, urea is used for abating nitrogen oxide (NO_x) emissions from coal-fired power plants and diesel transportation motors.

Emissions of CO_2 from urea consumed for non-agricultural purposes in 2022 were estimated to be 7.1 MMT CO_2 Eq. (7,053 kt) and are summarized in Table 4-27 and Table 4-28. Net CO_2 emissions from urea consumption for non-agricultural purposes have increased by approximately 86 percent from 1990 to 2022 and increased by approximately 7 percent from 2021 to 2022.

Table 4-27: CO_2 Emissions from Urea Consumption for Non-Agricultural Purposes (MMT CO_2 Eq.)

Source	1990	2005	2018	2019	2020	2021	2022
Urea Consumption	3.8	3.7	6.1	6.2	5.8	6.6	7.1

Table 4-28: CO_2 Emissions from Urea Consumption for Non-Agricultural Purposes (kt CO_2)

Source	1990	2005	2018	2019	2020	2021	2022
Urea Consumption	3,784	3,653	6,113	6,150	5,805	6,600	7,053

Methodology and Time-Series Consistency

Emissions of CO_2 resulting from urea consumption for non-agricultural purposes are estimated using a country-specific method consistent with the Tier 1 method used to estimate emissions from ammonia production in the *2006 IPCC Guidelines* which states that the "CO_2 recovered [from ammonia production] for downstream use can be estimated from the quantity of urea produced where CO_2 is estimated by multiplying urea production by 44/60, the stoichiometric ratio of CO_2 to urea" (IPCC 2006). The amount of urea consumed in the United States for non-agricultural purposes is multiplied by a factor representing the amount of CO_2 used as a raw material to produce the urea. This method is based on the assumption that all of the carbon in urea is released into the environment as CO_2 during use.

The amount of urea consumed for non-agricultural purposes in the United States is estimated by deducting the quantity of urea fertilizer applied to agricultural lands, which is obtained directly from the Agriculture chapter (see Table 5-25), from the total domestic supply of urea as reported in Table 4-29. The domestic supply of urea is estimated based on the amount of urea produced plus urea imports and minus urea exports. A factor of 0.733 tons of CO_2 per ton of urea consumed is then applied to the resulting supply of urea for non-agricultural purposes to estimate CO_2 emissions from the amount of urea consumed for non-agricultural purposes. The 0.733 tons of CO_2 per ton of urea emission factor is based on the stoichiometry of carbon in urea. This corresponds to a stoichiometric ratio of CO_2 to urea of 44/60, assuming complete conversion of carbon in urea to CO_2 (IPCC 2006; EFMA 2000).

Urea production data for 1990 through 2008 were obtained from the U.S. Geological Survey (USGS) *Minerals Yearbook: Nitrogen* (USGS 1994 through 2009a). Urea production data for 2009 through 2010 were obtained from the U.S. Census Bureau (2011). The U.S. Census Bureau ceased collection of urea production statistics in 2011. Urea production data for 2011 through 2022 were obtained from GHGRP (EPA 2018; EPA 2023a; EPA 2023b).

Urea import data for 2022 were not available at the time of publication and were estimated using 2021 values. Urea import data for 2013 to 2021 were obtained from the USGS *Minerals Yearbook: Nitrogen* (USGS 2023a). Urea import data for 2011 and 2012 were taken from U.S. Fertilizer Import/Exports from the United States Department of Agriculture (USDA) Economic Research Service Data Sets (U.S. Department of Agriculture 2012). USDA suspended updates to this data after 2012. Urea import data for the previous years were obtained from the U.S. Census Bureau *Current Industrial Reports Fertilizer Materials and Related Products* annual and quarterly reports for

1997 through 2010 (U.S. Census Bureau 2001 through 2011), The Fertilizer Institute (TFI 2002) for 1993 through 1996, and the United States International Trade Commission Interactive Tariff and Trade DataWeb (U.S. ITC 2002) for 1990 through 1992 (see Table 4-29).

Urea export data for 2022 were not available at the time of publication and were estimated using 2021 values. Urea export data for 2013 to 2021 were obtained from the USGS *Minerals Yearbook: Nitrogen* (USGS 2023a). Urea export data for 1990 through 2012 were taken from U.S. Fertilizer Import/Exports from USDA Economic Research Service Data Sets (U.S. Department of Agriculture 2012). USDA suspended updates to this data after 2012.

Table 4-29: Urea Production, Urea Applied as Fertilizer, Urea Imports, and Urea Exports (kt)

Year	1990	2005	2018	2019	2020	2021	2022
Urea Production	7,450	5,270	10,700	11,400	11,500	10,521	11,272
Urea Applied as Fertilizer	3,296	4,779	6,732	6,865	6,998	7,131	7,265
Urea Imports	1,860	5,026	5,110	4,410	4,190	5,880	5,880
Urea Exports	854	536	743	559	777	270	270
Urea Consumed for Non-Agricultural Purposes	5,160	4,981	8,335	8,386	7,915	9,000	9,617

Methodological approaches were applied to the entire time series to ensure consistency in emissions from 1990 through 2022. The methodology for urea consumption for non-agricultural purposes spliced activity data from different sources: USGS data for 1990 through 2008, U. S. Census Bureau data for 2009 and 2010, and GHGRP data beginning in 2011. Consistent with the *2006 IPCC Guidelines*, the overlap technique was applied to compare the data sets for years where there was overlap, with findings that the data sets were consistent and adjustments were not needed.

Uncertainty

There is limited publicly available data on the quantities of urea produced and consumed for non-agricultural purposes. Therefore, the amount of urea used for non-agricultural purposes is estimated based on a balance that relies on estimates of urea production, urea imports, urea exports, and the amount of urea used as fertilizer. EPA uses an uncertainty range of ±10 percent for urea production and ±5 percent for urea imports and urea exports, consistent with the ranges for activity data that are not obtained directly from plants, and using this suggested uncertainty provided in Section 3.2.3.2 of the *2006 IPCC Guidelines* is appropriate based on expert judgment (RTI 2023). Per this expert judgment, a normal probability density function was assigned for all activity data. The primary uncertainties associated with this source category are associated with the accuracy of these estimates as well as the fact that each estimate is obtained from a different data source. Because urea production estimates are no longer available from the USGS, there is additional uncertainty associated with urea produced beginning in 2011. There is also uncertainty associated with the assumption that all of the carbon in urea is released into the environment as CO_2 during use.

The results of the Approach 2 quantitative uncertainty analysis are summarized in Table 4-30. Carbon dioxide emissions associated with urea consumption for non-agricultural purposes during 2022 were estimated to be between 6.8 and 7.3 MMT CO_2 Eq. at the 95 percent confidence level. This indicates a range of approximately 4 percent below and 4 percent above the emission estimate of 7.1 MMT CO_2 Eq.

Table 4-30: Approach 2 Quantitative Uncertainty Estimates for CO_2 Emissions from Urea Consumption for Non-Agricultural Purposes (MMT CO_2 Eq. and Percent)

Source	Gas	2022 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Urea Consumption for Non-Agricultural Purposes	CO_2	7.1	6.8	7.3	-4%	+4%

[a] Range of emission estimates predicted by Monte Carlo stochastic simulation for a 95 percent confidence interval.

QA/QC and Verification

General quality assurance/quality control (QA/QC) procedures were applied consistent with the U.S. Inventory QA/QC plan, which is in accordance with Volume 1, Chapter 6 of *2006 IPCC Guidelines* as described in the introduction of the IPPU chapter (see Annex 8 for more details).

More details on the greenhouse gas calculation, monitoring and QA/QC methods applicable to reporting of urea production occurring at ammonia facilities can be found under Subpart G (Ammonia Manufacturing) of the regulation (40 CFR Part 98).[29] EPA verifies annual facility-level GHGRP reports through a multi-step process (e.g., combination of electronic checks and manual reviews) to identify potential errors and ensure that data submitted to EPA are accurate, complete, and consistent.[30] Based on the results of the verification process, EPA follows up with facilities to resolve mistakes that may have occurred. The post-submittals checks are consistent with a number of general and category-specific QC procedures, including range checks, statistical checks, algorithm checks, and year-to-year checks of reported data and emissions. EPA also conducts QA checks of GHGRP reported urea production data against external datasets including the USGS *Minerals Yearbook* data. The comparison shows consistent trends in urea production over time.

Recalculations Discussion

Based on updated quantities of urea applied for agricultural uses for 2017 through 2021, updated urea imports from USGS for 2021, and updated urea exports from USGS for 2021, recalculations were performed for 2017 through 2021. Compared to the previous *Inventory*, CO_2 emissions from urea consumption for non-agricultural purposes increased by less than 1 percent for 2017 (46 kt CO_2) and 2018 (2 kt CO_2), decreased by less than 1 percent for 2019 (4 kt CO_2) and 2020 (10 kt CO_2) and increased by 32 percent for 2021 (1,611 kt CO_2).

Planned Improvements

At this time, there are no specific planned improvements for estimating CO_2 emissions from urea consumption for non-agricultural purposes.

[29] See http://www.ecfr.gov/cgi-bin/text-idx?tpl=/ecfrbrowse/Title40/40cfr98_main_02.tpl.

[30] See https://www.epa.gov/sites/production/files/2015-07/documents/ghgrp_verification_factsheet.pdf.

4.7 Nitric Acid Production (CRT Source Category 2B2)

Nitrous oxide (N_2O) is emitted during the production of nitric acid (HNO_3), an inorganic compound used primarily to make synthetic commercial fertilizers. Nitric acid is also a major component in the production of adipic acid—a feedstock for nylon—and explosives. This reporting category (2B2) includes emissions from production of nitric acid. Emissions from fuels consumed for energy purposes during the production of nitric acid are accounted for as part of fossil fuel combustion in the industrial end-use sector reported under the Energy chapter.

There are two types of nitric acid: weak nitric acid and high-strength nitric acid. The weak nitric acid production method utilizes oxidation, condensation, and absorption to produce nitric acid at concentrations between 30 and 70 percent nitric acid. High-strength nitric acid (90 percent or greater nitric acid) can be produced by two methods: (1) through the dehydration, bleaching, condensing, and absorption of the weak nitric acid or (2) through the oxidation of ammonia into nitric oxide, which is oxidized and cooled into dinitrogen tetroxide and then pressurized and oxidized into high-strength nitric acid. Most U.S. plants were built between 1960 and 2000. As of 2022, there were 31 active nitric acid production plants that produce weak nitric acid in the United States (EPA 2023). One plant produces both weak and high-strength nitric acid (EPA 2010).

The basic process technology for producing nitric acid has not changed significantly over time. During this process, N_2O is formed as a byproduct and released from reactor vents into the atmosphere.

Nitric acid is made from the reaction of ammonia (NH_3) with oxygen (O_2) in two stages. The overall reaction is:

$$4NH_3 + 8O_2 \rightarrow 4HNO_3 + 4H_2$$

Currently, the nitric acid industry in the United States controls emissions of NO and NO_2 (i.e., NO_x), using a combination of non-selective catalytic reduction (NSCR) and selective catalytic reduction (SCR) technologies. In the process of destroying NO_x, NSCR systems are also very effective at destroying N_2O. Five nitric acid plants had NSCR systems installed between 1964 and 1977, over half due to the finalization of the Nitric Acid Plant New Source Performance Standards (NSPS) which went into effect in 1971. Four additional nitric acid plants had NSCR systems installed between 2016 and 2018, as a result of EPA Consent Decrees to control NO_X emissions more effectively. NSCR systems are used in approximately one-third of the weak acid production plants. For N_2O abatement, U.S. facilities are using both tertiary (i.e., NSCR and SCR) and secondary controls (i.e., catalysts added to the ammonia reactor to lessen potential N_2O production).

Emissions from the production of nitric acid are generally directly proportional to the annual amount of nitric acid produced because emissions are calculated as the product of the total annual production and plant-specific emission factors. There are a few instances, however, where that relationship has not been directly proportional. For example, in 2015 and 2019, nitric acid production decreased and emissions increased compared to the respective preceding years; in 2016, nitric acid production increased and emissions decreased compared to 2015. N_2O emissions for those years are calculated based on data from the GHGRP as discussed in the Methodology section below. According to data from plants reporting to GHGRP, plant-specific operations can affect the emission factor used, including: (1) site-specific fluctuations in ambient temperature and humidity, (2) catalyst age and condition, (3) process changes, such as fluctuations in process pressure or temperature and replacing the ammonia catalyst, (4) the addition, removal, maintenance, and utilization of abatement technologies, and (5) the number of nitric acid trains, which are reaction vessels where ammonia is oxidized to form nitric acid. Changes in those operating conditions for the years in question (2015, 2016, and 2019) caused changes in emission factors, which resulted in emissions changing disproportionally to production in those years.

Nitrous oxide emissions from this source were estimated to be 8.6 MMT CO_2 Eq. (33 kt of N_2O) in 2022 and are summarized in Table 4-31 and Table 4-32. Emissions from nitric acid production have decreased by 20 percent since 1990, while production has increased by 9 percent over the same time period (see Table 4-31 and Table

4-32). Emissions have decreased by 33 percent since 1997, the highest year of production in the time series. From 2021 to 2022, nitric acid production increased by 1 percent, while overall emissions from nitric acid production increased by 9.4 percent from 2021 to 2022.

Table 4-31: N_2O Emissions from Nitric Acid Production (MMT CO_2 Eq.)

Year	1990	2005	2018	2019	2020	2021	2022
Nitric Acid Production	10.8	10.1	8.5	8.9	8.3	7.9	8.6

Table 4-32: N_2O Emissions from Nitric Acid Production (kt N_2O)

Year	1990	2005	2018	2019	2020	2021	2022
Nitric Acid Production	41	38	32	34	31	30	33

Methodology and Time-Series Consistency

Emissions of N_2O from nitric acid production are estimated using methods provided by the *2006 IPCC Guidelines*, in accordance with the IPCC methodological decision tree and available data. For 2010 through 2022, a Tier 3 method was used to estimate emissions based on GHGRP data. For 1990 through 2009, a Tier 2 method was used to estimate emissions from nitric acid production based on U.S. Census Bureau data.

2010 through 2022

Process N_2O emissions and nitric acid production data were obtained directly from EPA's GHGRP for 2010 through 2022 by aggregating reported facility-level data (EPA 2018; EPA 2023).[31]

Since 2010, in the United States, all nitric acid facilities that produce weak nitric acid (30 to 70 percent) have been required to report annual greenhouse gas emissions data to EPA as per the requirements of the GHGRP (Subpart V). Beginning with 2018, the rule was changed to include facilities that produce nitric acid of any strength. The only facility that produces high-strength nitric acid also produces weak nitric acid. All N_2O emissions from nitric acid production originate from the production of weak nitric acid.

Process emissions and nitric acid production reported to the GHGRP provide complete estimates of greenhouse gas emissions for the United States because there are no reporting thresholds. While facilities are allowed to stop reporting to the GHGRP if the total reported emissions from nitric acid production are less than 25,000 metric tons CO_2 Eq. per year for five consecutive years or less than 15,000 metric tons CO_2 Eq. per year for three consecutive years, no facilities have stopped reporting as a result of these provisions.[32] All nitric acid facilities are required to either calculate process N_2O emissions using a site-specific emission factor that is the average of the emission factor determined through annual performance tests for each nitric acid train under typical operating conditions or directly measure process N_2O emissions using monitoring equipment.[33]

Emissions from facilities vary from year to year, depending on the amount of nitric acid produced with and without abatement technologies and other conditions affecting the site-specific emission factor. To maintain consistency

[31] National N_2O process emissions, national production, and national share of nitric acid production with abatement and without abatement technology were aggregated from the GHGRP facility-level data for 2010 to 2022 (i.e., percent production with and without abatement).

[32] See 40 CFR 98.2(i)(1) and 40 CFR 98.2(i)(2) for more information about these provisions.

[33] Facilities must use standard methods - either EPA Method 320 or ASTM D6348-03 for annual performance tests—and must follow associated QA/QC procedures consistent with category-specific QC of direct emission measurements during these performance tests.

across the time series and with the rounding approaches taken by other data sets, GHGRP nitric acid data are rounded and are shown in Table 4-33.

1990 through 2009

Using GHGRP data for 2010, country-specific N_2O emission factors were calculated for nitric acid production with abatement and without abatement (i.e., controlled and uncontrolled emission factors). The following 2010 emission factors were derived for production with abatement and without abatement: 3.3 kg N_2O/metric ton HNO_3 produced at plants using abatement technologies (e.g., tertiary systems such as NSCR systems) and 5.99 kg N_2O/metric ton HNO_3 produced at plants not equipped with abatement technology. Country-specific weighted emission factors were derived by weighting these emission factors by percent production with abatement and without abatement over time periods 1990 through 2008 and 2009. These weighted emission factors were used to estimate N_2O emissions from nitric acid production for years prior to the availability of GHGRP data (i.e., 1990 through 2008 and 2009). A separate weighted emission factor is included for 2009 due to data availability for that year.

EPA verified the installation dates of N_2O abatement technologies for all facilities based on GHGRP facility-level information and confirmed that all abatement technologies were accounted for in the derived emission factors (Icenhour 2020). Due to the lack of information on abatement equipment utilization, it is assumed that once abatement technology was installed in facilities, the equipment was consistently operational for the duration of the time series considered in this report (especially NSCRs).

The country-specific weighted N_2O emission factors were used in conjunction with annual production to estimate N_2O emissions for 1990 through 2009, using the following equations:

Equation 4-4: *2006 IPCC Guidelines* Tier 3: N_2O Emissions From Nitric Acid Production (Equation 3.6)

$$E_i = P_i \times EF_{weighted,i}$$

$$EF_{weighted,i} = \left[\left(\%P_{c,i} \times EF_c\right) + \left(\%P_{unc,i} \times EF_{unc}\right)\right]$$

where,

E_i	=	Annual N_2O Emissions for year i (kg/yr)
P_i	=	Annual nitric acid production for year i (metric tons HNO_3)
$EF_{weighted,i}$	=	Weighted N_2O emission factor for year i (kg N_2O/metric ton HNO_3)
$\%P_{c,i}$	=	Percent national production of HNO_3 with N_2O abatement technology (%)
EF_c	=	N_2O emission factor, with abatement technology (kg N_2O/metric ton HNO_3)
$\%P_{unc,i}$	=	Percent national production of HNO_3 without N_2O abatement technology (%)
EF_{unc}	=	N_2O emission factor, without abatement technology (kg N_2O/metric ton HNO_3)
i	=	year from 1990 through 2009

- For 2009: Weighted N_2O emission factor = 5.46 kg N_2O/metric ton HNO_3.
- For 1990 through 2008: Weighted N_2O emission factor = 5.66 kg N_2O/metric ton HNO_3.

Nitric acid production data for the United States for 1990 through 2009 were obtained from the U.S. Census Bureau (U.S. Census Bureau 2008, 2009, 2010a, 2010b) (see Table 4-33). EPA used GHGRP facility-level information to verify that all reported N_2O abatement equipment were incorporated into the estimation of N_2O emissions from nitric acid production over the full time series (EPA 2021).

Table 4-33: Nitric Acid Production (kt)

Year	1990	2005	2018	2019	2020	2021	2022
Production (kt)	7,200	6,710	8,210	8,080	7,970	7,800	7,860

Methodological approaches were applied to the entire time series to ensure consistency in emissions from 1990 through 2022. The methodology for nitric acid production spliced activity data from two different sources: U.S. Census Bureau production data for 1990 through 2009 and GHGRP production data starting in 2010. Consistent with the *2006 IPCC Guidelines*, the overlap technique was applied to compare the two data sets for years where there was overlap, with findings that the data sets were consistent and adjustments were not needed.

Uncertainty

Uncertainty associated with the parameters used to estimate N_2O emissions includes the share of U.S. nitric acid production attributable to each emission abatement technology (i.e., utilization) over the time series (especially prior to 2010), and the associated emission factors applied to each abatement technology type. While some information has been obtained through outreach with industry associations, limited information is available over the time series (especially prior to 2010) for a variety of facility level variables, including plant-specific production levels, plant production technology (e.g., low or high pressure, etc.), and abatement technology destruction and removal efficiency rates. Production data prior to 2010 were obtained from National Census Bureau, which does not provide uncertainty estimates with their data. Facilities reporting to EPA's GHGRP must measure production using equipment and practices used for accounting purposes. While emissions are often directly proportional to production, the emission factor for individual facilities can vary significantly from year to year due to site-specific fluctuations in ambient temperature and humidity, catalyst age and condition, nitric acid production process changes, the addition or removal of abatement technologies, and the number of nitric acid trains at the facility. At this time, EPA does not estimate uncertainty of the aggregated facility-level information. As noted in the QA/QC and verification section below, EPA verifies annual facility-level reports through a multi-step process (e.g., combination of electronic checks and manual reviews by staff) to identify potential errors and ensure that data submitted to EPA are accurate, complete, and consistent. The annual production reported by each nitric acid facility under EPA's GHGRP and then aggregated to estimate national N_2O emissions is assumed to have low uncertainty. EPA assigned an uncertainty range of ±5 percent for facility-reported N_2O emissions, and using this suggested uncertainty provided in section 3.4.3.2 of the *2006 IPCC Guidelines* is appropriate based on expert judgment (RTI 2023). EPA assigned an uncertainty range of ±2 percent for nitric acid production, and using this suggested uncertainty provided in section 3.3.3.2 of the *2006 IPCC Guidelines* is appropriate based on expert judgment (RTI 2023). Per this expert judgment, a normal probability density function was assigned for facility-reported N_2O emissions and nitric acid production.

The results of this Approach 2 quantitative uncertainty analysis are summarized in Table 4-34. Nitrous oxide emissions from nitric acid production were estimated to be between 8.2 and 9.0 MMT CO_2 Eq. at the 95 percent confidence level. This indicates a range of approximately 5 percent below to 5 percent above the 2022 emissions estimate of 8.6 MMT CO_2 Eq.

Table 4-34: Approach 2 Quantitative Uncertainty Estimates for N_2O Emissions from Nitric Acid Production (MMT CO_2 Eq. and Percent)

Source	Gas	2022 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Nitric Acid Production	N_2O	8.6	8.2	9.0	-5%	+5%

[a] Range of emission estimates predicted by Monte Carlo stochastic simulation for a 95 percent confidence interval.

QA/QC and Verification

General quality assurance/quality control (QA/QC) procedures were applied consistent with the U.S. Inventory QA/QC plan, which is in accordance with Volume 1, Chapter 6 of the *2006 IPCC Guidelines* as described in the introduction of the IPPU chapter (see Annex 8 for more details). More details on the greenhouse gas calculation, monitoring and QA/QC methods applicable to nitric acid facilities can be found under Subpart V: Nitric Acid Production of the GHGRP regulation (40 CFR Part 98). [34]

The main QA/QC activities are related to annual performance testing, which must follow either EPA Method 320 or ASTM D6348-03. EPA verifies annual facility-level GHGRP reports through a multi-step process that is tailored to the Subpart (e.g., combination of electronic checks including range checks, statistical checks, algorithm checks, year-to-year comparison checks, along with manual reviews) to identify potential errors and ensure that data submitted to EPA are accurate, complete, and consistent. Based on the results of the verification process, EPA follows up with facilities to resolve mistakes that may have occurred (EPA 2015). [35] EPA's review of observed trends noted that while emissions have generally mirrored production, in 2015 and 2019 nitric acid production decreased compared to the previous year and emissions increased. While review is ongoing, based on feedback from the verification process to date, these changes are due to facility-specific changes (e.g., in the nitric production process and management of abatement equipment).

Recalculations Discussion

No recalculations were performed for the 1990 through 2021 portion of the time series.

Planned Improvements

Pending resources, EPA is considering a near-term improvement to both review and refine quantitative uncertainty estimates and the associated qualitative discussion.

4.8 Adipic Acid Production (CRT Source Category 2B3)

Adipic acid is a white crystalline solid used in the manufacture of synthetic fibers, plastics, coatings, urethane foams, elastomers, and synthetic lubricants. This reporting category (2B3) includes emissions from the production of adipic acid. Emissions from fuels consumed for energy purposes during the production of adipic acid are accounted for as part of fossil fuel combustion in the industrial end-use sector reported under the Energy chapter.

Adipic acid is produced through a two-stage process during which nitrous oxide (N_2O) is generated in the second stage. The first stage of manufacturing usually involves the oxidation of cyclohexane to form a cyclohexanone/cyclohexanol mixture. The second stage involves oxidizing this mixture with nitric acid to produce

[34] See Subpart V monitoring and reporting regulation http://www.ecfr.gov/cgi-bin/text-idx?tpl=/ecfrbrowse/Title40/40cfr98_main_02.tpl.

[35] See GHGRP Verification Factsheet https://www.epa.gov/sites/production/files/2015-07/documents/ghgrp_verification_factsheet.pdf.

adipic acid. Nitrous oxide is generated as a byproduct of the nitric acid oxidation stage and is emitted in the waste gas stream (Thiemens and Trogler 1991). The second stage is represented by the following chemical reaction:

$$(CH_2)_5CO(cyclohexanone) + (CH_2)_5CHOH(cyclohexanol) + wHNO_3 \rightarrow HOOC(CH_2)_4COOH(adipic\ acid) + xN_2O + yH_2O$$

Process emissions from the production of adipic acid vary with the types of technologies and level of emission controls employed by a facility. In 1990, two major adipic acid-producing plants had N_2O abatement technologies in place and, as of 1998, three major adipic acid production facilities had control systems in place (Reimer et al. 1999). In 2022, thermal reduction was applied as an N_2O abatement measure at one adipic acid facility (EPA 2023).

Worldwide, only a few adipic acid plants exist. The United States, Europe, and China are the major producers, with the United States accounting for the largest share of global adipic acid production capacity in recent years. In 2022, the United States had two companies with a total of two adipic acid production facilities (one in Texas and one in Florida), following the ceased operations of a third major production facility at the end of 2015 (EPA 2023).

Commercially, adipic acid is the most important of the aliphatic dicarboxylic acids, which are used to manufacture polyesters. Eighty-four percent of all adipic acid produced in the United States is used in the production of nylon 6,6; 9 percent is used in the production of polyester polyols; 4 percent is used in the production of plasticizers; and the remaining 4 percent is accounted for by other uses, including unsaturated polyester resins and food applications (ICIS 2007). Food grade adipic acid is used to provide some foods with a "tangy" flavor (Thiemens and Trogler 1991).

Compared to 1990, national adipic acid production in 2022 has increased by 3 percent to approximately 780,000 metric tons (ACC 2023). Nitrous oxide emissions from adipic acid production were estimated to be 2.1 MMT CO_2 Eq. (8 kt N_2O) in 2022 and are summarized in Table 4-35 and Table 4-36. Over the period 1990 through 2022, facilities have reduced emissions by 84.5 percent due to the widespread installation of pollution control measures in the late 1990s. The main reason for the 68 percent decrease in N_2O emissions from adipic acid production between 2021 and 2022 is increased utilization of N_2O abatement equipment at one adipic acid production facility.

EPA reviewed GHGRP facility reported information on the date of abatement technology installation in order to better reflect trends and changes in emissions abatement within the industry across the time series. The facility using the facility-specific emission factor developed through annual performance testing has reported no installation and no utilization of N_2O abatement technology. The facility using direct measurement of N_2O emissions has reported the use of thermal reduction as an N_2O abatement technology; the first unit began operation in 1980, and the second unit began operation in 2023 (Ard 2024; Ascend 2023).

Significant changes in the amount of time that the N_2O abatement device at one facility was in operation has been the main cause of fluctuating emissions in recent years. These fluctuations are most evident for years where trends in emissions and adipic acid production were not directly proportional: (1) between 2016 and 2017, (2) between 2017 and 2018, (3) between 2019 and 2020, (4) between 2020 and 2021, and (5) between 2021 and 2022. As noted above, changes in control measures and abatement technologies at adipic acid production facilities, including maintenance of equipment, can result in annual emission fluctuations. Little additional information is available on drivers of trends, and the amount of adipic acid produced is not reported under EPA's GHGRP.

Table 4-35: N_2O Emissions from Adipic Acid Production (MMT CO_2 Eq.)

Year	1990	2005	2018	2019	2020	2021	2022
Adipic Acid Production	13.5	6.3	9.3	4.7	7.4	6.6	2.1

Table 4-36: N_2O Emissions from Adipic Acid Production (kt N_2O)

Year	1990	2005	2018	2019	2020	2021	2022
Adipic Acid Production	51	24	35	18	28	25	8

Methodology and Time-Series Consistency

Emissions of N_2O from adipic acid production are estimated using methods provided by the *2006 IPCC Guidelines*, in accordance with the IPCC methodological decision tree and available data. For 2010 through 2022, a Tier 3 method was used to estimate emissions. For 1990 through 2009, emissions are estimated using both Tier 2 and Tier 3 methods. Due to confidential business information (CBI), plant names are not provided in this section; therefore, the four adipic acid-producing facilities that have operated over the time series will be referred to as Plants 1 through 4. As noted above, one currently operating facility uses thermal reduction as an N_2O abatement technology.

2010 through 2022

All emission estimates for 2010 through 2022 were obtained through analysis of GHGRP data (EPA 2010 through 2023). Facility-level greenhouse gas emissions data were obtained from EPA's GHGRP for the years 2010 through 2022 (EPA 2010 through 2023) and aggregated to national N_2O emissions. Consistent with IPCC Tier 3 methods, all adipic acid production facilities are required to either calculate N_2O emissions using a facility-specific emission factor developed through annual performance testing under typical operating conditions or directly measure N_2O emissions using monitoring equipment.[36]

1990 through 2009

For years 1990 through 2009, which were prior to EPA's GHGRP reporting, for both Plants 1 and 2, emission estimates were obtained directly from the plant engineers and account for reductions due to control systems in place at these plants during the time series. These prior estimates are considered CBI and hence are not published (Desai 2010, 2011). These estimates were based on continuous process monitoring equipment installed at the two facilities.

For Plant 4, 1990 through 2009 N_2O emissions were estimated using the following Tier 2 equation from the *2006 IPCC Guidelines*:

Equation 4-5: *2006 IPCC Guidelines* Tier 2: N_2O Emissions From Adipic Acid Production (Equation 3.8)

$$E_{aa} = Q_{aa} \times EF_{aa} \times (1 - [DF \times UF])$$

where,

E_{aa}	=	N_2O emissions from adipic acid production, metric tons
Q_{aa}	=	Quantity of adipic acid produced, metric tons
EF_{aa}	=	Emission factor, metric ton N_2O/metric ton adipic acid produced
DF	=	N_2O destruction factor
UF	=	Abatement system utility factor

The adipic acid production is multiplied by an emission factor (i.e., N_2O emitted per unit of adipic acid produced), which has been estimated to be approximately 0.3 metric tons of N_2O per metric ton of product (IPCC 2006). The "N_2O destruction factor" in the equation represents the percentage of N_2O emissions that are destroyed by the installed abatement technology. The "abatement system utility factor" represents the percentage of time that the

[36] Facilities must use standard methods, either EPA Method 320 or ASTM D6348-03 for annual performance testing, and must follow associated QA/QC procedures during these performance tests consistent with category-specific QC of direct emission measurements.

abatement equipment operates during the annual production period. Plant-specific production data for Plant 4 were obtained across the time series through personal communications (Desai 2010, 2011). The plant-specific production data were then used for calculating emissions as described above.

For Plant 3, 2005 through 2009 emissions were obtained directly from the plant (Desai 2010, 2011). For 1990 through 2004, emissions were estimated using plant-specific production data and the IPCC factors as described above for Plant 4. Plant-level adipic acid production for 1990 through 2003 was estimated by allocating national adipic acid production data to the plant level using the ratio of known plant capacity to total national capacity for all U.S. plants (ACC 2023; CMR 2001, 1998; CW 1999; C&EN 1992 through 1995). For 2004, actual plant production data were obtained and used for emission calculations (CW 2005).

Plant capacities for 1990 through 1994 were obtained from *Chemical & Engineering News*, "Facts and Figures" and "Production of Top 50 Chemicals" (C&EN 1992 through 1995). Plant capacities for 1995 and 1996 were kept the same as 1994 data. The 1997 plant capacities were taken from *Chemical Market Reporter*, "Chemical Profile: Adipic Acid" (CMR 1998). The 1998 plant capacities for all four plants and 1999 plant capacities for three of the plants were obtained from *Chemical Week*, Product Focus: Adipic Acid/Adiponitrile (CW 1999). Plant capacities for the year 2000 for three of the plants were updated using *Chemical Market Reporter*, "Chemical Profile: Adipic Acid" (CMR 2001). For 2001 through 2003, the plant capacities for three plants were held constant at year 2000 capacities. Plant capacity for 1999 to 2003 for the one remaining plant was kept the same as 1998.

National adipic acid production data (see Table 4-37) from 1990 through 2022 were obtained from the American Chemistry Council (ACC 2023).

Table 4-37: Adipic Acid Production (kt)

Year	1990	2005	2018	2019	2020	2021	2022
Production (kt)	755	865	825	810	710	760	780

Methodological approaches were applied to the entire time series to ensure consistency in emissions from 1990 through 2022. The methodology for adipic acid production spliced activity data from multiple sources: plant-specific emissions data and publicly available plant capacity data for 1990 through 2009 and GHGRP emission data starting in 2010. Consistent with the *2006 IPCC Guidelines*, the overlap technique was applied to compare the two data sets for years where there was overlap, with findings that the data sets were consistent and adjustments were not needed.

Uncertainty

Uncertainty associated with N_2O emission estimates includes the methods used by companies to monitor and estimate emissions. While some information has been obtained through outreach with facilities, limited information is available over the time series on these methods, abatement technology destruction and removal efficiency rates, and plant-specific production levels. EPA assigned an uncertainty range of ±5 percent and a normal probability density function for facility-reported N_2O emissions, and using this suggested uncertainty provided in section 3.4.3.2 of the *2006 IPCC Guidelines* is appropriate based on expert judgment (RTI 2023).

The results of this Approach 2 quantitative uncertainty analysis are summarized in Table 4-38. Nitrous oxide emissions from adipic acid production for 2022 were estimated to be between 2.0 and 2.2 MMT CO_2 Eq. at the 95 percent confidence level. These values indicate a range of approximately 4 percent below to 4 percent above the 2022 emission estimate of 2.1 MMT CO_2 Eq.

Table 4-38: Approach 2 Quantitative Uncertainty Estimates for N_2O Emissions from Adipic Acid Production (MMT CO_2 Eq. and Percent)

Source	Gas	2022 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Adipic Acid Production	N_2O	2.1	2.0	2.2	-4%	+4%

[a] Range of emission estimates predicted by Monte Carlo stochastic simulation for a 95 percent confidence interval.

QA/QC and Verification

General quality assurance/quality control (QA/QC) procedures were applied consistent with the U.S. Inventory QA/QC plan, which is in accordance with Volume 1, Chapter 6 of the *2006 IPCC Guidelines* as described in the introduction of the IPPU chapter (see Annex 8 for more details).

More details on the greenhouse gas calculation, monitoring and QA/QC methods applicable to adipic acid facilities can be found under Subpart E (Adipic Acid Production) of the GHGRP regulation (40 CFR Part 98).[37] The main QA/QC activities are related to annual performance testing, which must follow either EPA Method 320 or ASTM D6348-03. EPA verifies annual facility-level GHGRP reports through a multi-step process (e.g., combination of electronic checks and manual reviews) to identify potential errors and ensure that data submitted to EPA are accurate, complete, and consistent (EPA 2015).[38] Based on the results of the verification process, EPA follows up with facilities to resolve mistakes that may have occurred. The post-submittals checks are consistent with a number of general and category-specific QC procedures, including range checks, statistical checks, algorithm checks, and year-to-year comparisons of reported data.

Recalculations Discussion

No recalculations were performed for the 1990 through 2021 portion of the time series.

Planned Improvements

EPA has no specific planned improvements related to adipic acid.

4.9 Caprolactam, Glyoxal and Glyoxylic Acid Production (CRT Source Category 2B4)

This reporting category (2B4) includes emissions from the production of caprolactam, glyoxal (ethanedial), and glyoxylic acid. Emissions from fuels consumed for energy purposes during the production of caprolactam, glyoxal,

[37] See http://www.ecfr.gov/cgi-bin/text-idx?tpl=/ecfrbrowse/Title40/40cfr98_main_02.tpl.

[38] See https://www.epa.gov/sites/production/files/2015-07/documents/ghgrp_verification_factsheet.pdf.

and glyoxylic acid are accounted for as part of fossil fuel combustion in the industrial end-use sector reported under the Energy chapter.

Caprolactam

Caprolactam ($C_6H_{11}NO$) is a colorless monomer produced for nylon-6 fibers and plastics. A substantial proportion of the fiber is used in carpet manufacturing. Most commercial processes used for the manufacture of caprolactam begin with benzene, but toluene can also be used. The production of caprolactam can give rise to emissions of nitrous oxide (N_2O).

During the production of caprolactam, emissions of N_2O can occur from the ammonia oxidation step, emissions of carbon dioxide (CO_2) from the ammonium carbonate step, emissions of sulfur dioxide (SO_2) from the ammonium bisulfite step, and emissions of non-methane volatile organic compounds (NMVOCs). Emissions of CO_2, SO_2 and NMVOCs from the conventional process are unlikely to be significant in well-managed plants. Modified caprolactam production processes are primarily concerned with elimination of the high volumes of ammonium sulfate that are produced as a byproduct of the conventional process (IPCC 2006).

In the most commonly used process where caprolactam is produced from benzene, benzene is hydrogenated to cyclohexane which is then oxidized to produce cyclohexanone ($C_6H_{10}O$). The classical route (Raschig process) and basic reaction equations for production of caprolactam from cyclohexanone are (IPCC 2006):

$$Oxidation\ of\ NH_3\ to \frac{NO}{NO_2}$$

$$\downarrow$$

$$NH_3\ reacted\ with \frac{CO_2}{H_2O} to\ yield\ ammonium\ carbonate\ (NH_4)_2CO_3$$

$$\downarrow$$

$$(NH_4)_2CO_3\ reacted\ with \frac{NO}{NO_2} (from\ NH_3\ oxidation) to\ yield\ ammonium\ nitrite\ (NH_4NO_2)$$

$$\downarrow$$

$$NH_3\ reacted\ with \frac{SO_2}{H_2O} to\ yield\ ammonium\ bisulphite\ (NH_4HSO_3)$$

$$\downarrow$$

$$NH_4NO_2\ and\ (NH_4HSO_3) reacted\ to\ yield\ hydroxylamine\ disulphonate\ (NOH(SO_3NH_4)_2)$$

$$\downarrow$$

$$(NOH(SO_3NH_4)_2)\ hydrolised\ to\ yield\ hydroxylamine\ sulphate\ ((NH_2OH)_2.H_2SO_4)\ and$$

$$ammonium\ sulphate\ ((NH_4)_2SO_4)$$

$$\downarrow$$

$$Cylohexanone\ reaction:$$

$$C_6H_{10}O\ + \frac{1}{2}(NH_2OH)_2.H_2SO_4(+NH_3\ and\ H_2SO_4) \rightarrow C_6H_{10}NOH\ + (NH_4)_2SO_4\ + H_2O$$

$$\downarrow$$

$$Beckmann\ rearrangement:$$

$$C_6H_{10}NOH\ \ (+H_2SO_4\ and\ SO_2) \rightarrow C_6H_{11}NO.H_2SO_4\ (+4NH_3\ and\ H_2O) \rightarrow C_6H_{11}NO\ + 2(NH4)_2SO_4$$

In 2004, three facilities produced caprolactam in the United States (ICIS 2004). Another facility, Evergreen Recycling, was in operation from 2000 to 2001 (ICIS 2004; Textile World 2000) and from 2007 through 2015 (Shaw

2015). Caprolactam production at Fibrant LLC (formerly DSM Chemicals) in Georgia ceased in 2018 (Cline 2019). As of 2022, two companies in the United States produced caprolactam at two facilities: AdvanSix (formerly Honeywell) in Virginia (AdvanSix 2023) and BASF in Texas (BASF 2023).

Nitrous oxide emissions from caprolactam production in the United States were estimated to be 1.3 MMT CO_2 Eq. (5 kt N_2O) in 2022 and are summarized in Table 4-39 and Table 4-40. National emissions from caprolactam production decreased by approximately 10.5 percent over the period of 1990 through 2022. Emissions in 2022 increased by approximately 9.8 percent from the 2021 levels. This annual increase returned caprolactam production to levels consistent with 2017 before the COVID-19 pandemic.

Table 4-39: N_2O Emissions from Caprolactam Production (MMT CO_2 Eq.)

Year	1990	2005	2018	2019	2020	2021	2022
Caprolactam Production	1.5	1.9	1.3	1.2	1.1	1.2	1.3

Table 4-40: N_2O Emissions from Caprolactam Production (kt N_2O)

Year	1990	2005	2018	2019	2020	2021	2022
Caprolactam Production	6	7	5	5	4	5	5

Glyoxal

Glyoxal is mainly used as a crosslinking agent for vinyl acetate/acrylic resins, disinfectant, gelatin hardening agent, textile finishing agent (permanent-press cotton, rayon fabrics), and wet-resistance additive (paper coatings) (IPCC 2006). It is also used for enhanced oil-recovery. It is produced from oxidation of acetaldehyde with concentrated nitric acid, or from the catalytic oxidation of ethylene glycol, and N_2O is emitted in the process of oxidation of acetaldehyde.

Glyoxal (ethanedial) ($C_2H_2O_2$) is produced from oxidation of acetaldehyde (ethanal) (C_2H_4O) with concentrated nitric acid (HNO_3). Glyoxal can also be produced from catalytic oxidation of ethylene glycol (ethanediol) (CH_2OHCH_2OH).

Glyoxylic Acid

Glyoxylic acid is produced by nitric acid oxidation of glyoxal. Glyoxylic acid is used for the production of synthetic aromas, agrochemicals, and pharmaceutical intermediates (IPCC 2006).

Preliminary data suggests that glyoxal and glyoxylic acid may be produced in small quantities domestically but are largely imported to the United States. EPA does not currently estimate the emissions associated with the production of glyoxal and glyoxylic acid because activity data are not available. See Annex 5 for more information.

Methodology and Time-Series Consistency

Emissions of N_2O from the production of caprolactam are calculated using the Tier 1 methodology from the *2006 IPCC Guidelines*, in accordance with the IPCC methodological decision tree and available data. The Tier 1 equation is as follows:

Equation 4-6: *2006 IPCC Guidelines* Tier 1: N_2O Emissions From Caprolactam Production (Equation 3.9)

$$E_{N_2O} = EF \times CP$$

where,

E_{N_2O} = Annual N_2O Emissions (kg)

EF = N_2O emission factor (default) (kg N_2O/metric ton caprolactam produced)

CP = Caprolactam production (metric tons)

During the caprolactam production process, N_2O is generated as a byproduct of the high temperature catalytic oxidation of ammonia (NH_3), which is the first reaction in the series of reactions to produce caprolactam. The amount of N_2O emissions can be estimated based on the chemical reaction shown above. Based on this formula, which is consistent with an IPCC Tier 1 approach, approximately 111.1 metric tons of caprolactam are required to generate one metric ton of N_2O, resulting in an emission factor of 9.0 kg N_2O per metric ton of caprolactam (IPCC 2006). When applying the Tier 1 method, the *2006 IPCC Guidelines* state that it is good practice to assume that there is no abatement of N_2O emissions and to use the highest default emission factor available in the guidelines. In addition, EPA did not find support for the use of secondary catalysts to reduce N_2O emissions, such as those employed at nitric acid plants.

The activity data for caprolactam production (see Table 4-41) from 1990 to 2022 were obtained from the American Chemistry Council's *Guide to the Business of Chemistry* (ACC 2023). EPA will continue to analyze and assess alternative sources of production data as a quality control measure.

Table 4-41: Caprolactam Production (kt)

Year	1990	2005	2018	2019	2020	2021	2022
Production (kt)	626	795	530	515	480	510	560

Carbon dioxide and methane (CH_4) emissions may also occur from the production of caprolactam, but currently the IPCC does not have methodologies for calculating these emissions associated with caprolactam production.

Methodological approaches, consistent with the *2006 IPCC Guidelines*, have been applied to the entire time series to ensure consistency in emissions from 1990 through 2022.

Uncertainty

Estimation of emissions of N_2O from caprolactam production can be treated as analogous to estimation of emissions of N_2O from nitric acid production. Both production processes involve an initial step of NH_3 oxidation, which is the source of N_2O formation and emissions (IPCC 2006). Therefore, uncertainties for the default emission factor values in the *2006 IPCC Guidelines* are an estimate based on default values for nitric acid plants. In general, default emission factors for gaseous substances have higher uncertainties because mass values for gaseous substances are influenced by temperature and pressure variations and gases are more easily lost through process leaks. The default values for caprolactam production have a relatively high level of uncertainty due to the limited information available (IPCC 2006). EPA assigned uncertainty bounds of ±5 percent for caprolactam production, based on expert judgment. EPA assigned an uncertainty range of ±40 percent for the N_2O emission factor, and using this suggested uncertainty provided in Section 3.5.2.1 of the *2006 IPCC Guidelines* is appropriate based on expert judgment (RTI 2023). Per this expert judgment, a normal probability density function was assigned for activity data, and a triangular probably density function was assigned for the emission factor.

The results of this Approach 2 quantitative uncertainty analysis are summarized in Table 4-42. Nitrous oxide emissions from caprolactam, glyoxal and glyoxylic acid production for 2022 were estimated to be between 0.9 and 1.8 MMT CO_2 Eq. at the 95 percent confidence level. These values indicate a range of approximately 31 percent below to 31 percent above the 2022 emission estimate of 1.3 MMT CO_2 Eq.

Table 4-42: Approach 2 Quantitative Uncertainty Estimates for N_2O Emissions from Caprolactam, Glyoxal and Glyoxylic Acid Production (MMT CO_2 Eq. and Percent)

Source	Gas	2022 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Caprolactam Production	N_2O	1.3	0.9	1.8	-31%	+31%

[a] Range of emission estimates predicted by Monte Carlo stochastic simulation for a 95 percent confidence interval.

QA/QC and Verification

General quality assurance/quality control (QA/QC) procedures were applied consistent with the U.S. Inventory QA/QC plan, which is in accordance with Volume 1, Chapter 6 of the *2006 IPCC Guidelines* as described in the introduction of the IPPU chapter (see Annex 8 for more details).

Recalculations Discussion

Recalculations were performed for 2020 and 2021 to reflect updated caprolactam production data from the American Chemistry Council's *Guide to the Business of Chemistry* (ACC 2023). Compared to the previous *Inventory*, annual N_2O emissions decreased by 2 percent in 2020 and 2021, with a decrease of 0.02 MMT CO_2 Eq. in 2020 and 2021.

Planned Improvements

Pending resources, EPA will research other available datasets for caprolactam production and industry trends, including facility-level data. EPA continues to research available activity data and emissions associated with the production of glyoxal and glyoxylic acid. Preliminary data suggests that glyoxal and glyoxylic acid may be produced in small quantities domestically but are largely imported to the United States. See Annex 5 for more information. This planned improvement is subject to data availability and will be implemented in the medium- to long-term.

4.10 Carbide Production and Consumption (CRT Source Category 2B5 & 2B10)

Carbon dioxide (CO_2) and methane (CH_4) are emitted from the production of silicon carbide (SiC), a material used for industrial abrasive, metallurgical, and other non-abrasive applications in the United States, and CO_2 is emitted from the consumption of SiC. Per the IPCC methodological guidance, emissions from fuels consumed for energy purposes during the production of silicon carbide are accounted for in the industrial end-use sector reported under the Energy chapter. Additionally, some metallurgical and non-abrasive applications of SiC are emissive at high temperatures due to the SiC oxidation temperature (Biscay 2021). While emissions should be accounted for where they occur based on *2006 IPCC Guidelines*, emissions from SiC consumption are accounted for here until additional data on SiC consumption by end-use are available. The reporting category (2B5) includes emissions from the production of SiC, and the reporting category (2B10) includes emissions from the consumption of SiC.

To produce SiC, silica sand or quartz (SiO_2) is reacted with carbon (C) in the form of petroleum coke. A portion (about 35 percent) of the carbon contained in the petroleum coke is retained in the SiC. The remaining carbon is

emitted as CO_2, CH_4, or carbon monoxide (CO). The overall reaction is shown below, but in practice, it does not proceed according to stoichiometry:

$$SiO_2 + 3C \rightarrow SiC + 2CO \ (+ O_2 \rightarrow 2CO_2)$$

Carbon dioxide and CH_4 are also emitted during the production of calcium carbide, a chemical used to produce acetylene. Carbon dioxide is implicitly accounted for in the storage factor calculation for the non-energy use of petroleum coke in the Energy chapter.

Markets for manufactured abrasives, including SiC, are heavily influenced by activity in the U.S. manufacturing sector, especially in the aerospace, automotive, furniture, housing, and steel manufacturing sectors. Specific applications of abrasive-grade SiC in 2018 included antislip abrasives, blasting abrasives, bonded abrasives, coated abrasives, polishing and buffing compounds, tumbling media, and wire-sawing abrasives (USGS 2021). Approximately 50 percent of SiC is used in metallurgical applications, which include primarily iron and steel production, and other non-abrasive applications, which include use in advanced or technical ceramics and refractories (USGS 2023a; Washington Mills 2023).

As a result of the economic downturn in 2008 and 2009, demand for SiC decreased in those years. Low-cost imports, particularly from China, combined with high relative operating costs for domestic producers, continue to put downward pressure on the production of SiC in the United States. Consumption of SiC in the United States has recovered somewhat from its low in 2009 to 2020; 2021 consumption data was withheld to avoid disclosing company proprietary data (USGS 1991b through 2021), and 2022 USGS data has not yet been released.

Silicon carbide was manufactured by two facilities in the United States, one of which produced primarily non-abrasive SiC (USGS 2021). USGS production values for the United States consists of SiC used for abrasives and for metallurgical and other non-abrasive applications (USGS 2021). During the COVID-19 pandemic in 2020, the U.S. Department of Homeland Security considered abrasives manufacturing part of the critical manufacturing sector, and as a result, pandemic "stay-at-home" orders issued in March 2020 did not affect the abrasives manufacturing industry. These plants remained at full operation (USGS 2021a). In 2022, imports and exports continued to recover from the negative effects of the COVID-19 pandemic (USGS 2023b). Consumption of SiC increased by approximately 27 percent from 2021 to 2022, rising above pre-pandemic levels (U.S. Census Bureau 2005 through 2022).

Carbon dioxide emissions from SiC production and consumption in 2022 were 0.2 MMT CO_2 Eq. (210 kt CO_2), which are about 14 percent lower than emissions in 1990 (see Table 4-43 and Table 4-44). Approximately 50 percent of these emissions resulted from SiC production, while the remainder resulted from SiC consumption. Methane emissions from SiC production in 2022 were 0.01 MMT CO_2 Eq. (0.5 kt CH_4) (see Table 4-43 and Table 4-44). These tables indicate minor changes in emissions in recent years.

Table 4-43: CO_2 and CH_4 Emissions from Silicon Carbide Production and Consumption (MMT CO_2 Eq.)

Year	1990	2005	2018	2019	2020	2021	2022
SiC Production							
CO_2	0.2	0.1	0.1	0.1	0.1	0.1	0.1
CH_4	+	+	+	+	+	+	+
SiC Consumption							
CO_2	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Total	**0.2**	**0.2**	**0.2**	**0.2**	**0.2**	**0.2**	**0.2**

+ Does not exceed 0.05 MMT CO_2 Eq.

Note: Totals may not sum due to independent rounding.

Table 4-44: CO_2 and CH_4 Emissions from Silicon Carbide Production and Consumption (kt)

Year	1990	2005	2018	2019	2020	2021	2022
SiC Production							
CO_2	170	92	92	92	92	92	105
CH_4	1	+	+	+	+	+	+
SiC Consumption							
CO_2	73	121	93	84	62	80	105

+ Does not exceed 0.5 kt.

Methodology and Time-Series Consistency

Emissions of CO_2 and CH_4 from the production of SiC are calculated using the Tier 1 method from the *2006 IPCC Guidelines*, in accordance with the IPCC methodological decision tree and available data. Emissions of CO_2 from the consumption of SiC are a country-specific source calculated using a country-specific methodology based on available data. The *2006 IPCC Guidelines* do not provide guidance for estimating emissions from use of SiC or SiC consumption, but the country-specific methodology used is based on the stoichiometry of SiC consumption and is compatible with the *2006 IPCC Guidelines* and consistent with a Tier 1 approach.

Annual estimates of SiC production were multiplied by the default emission factors, as shown below:

Equation 4-78: *2006 IPCC Guidelines* Tier 1: Emissions from Carbide Production (Equation 3.11)

$$E_{sc,CO2} = EF_{sc,CO2} \times Q_{sc}$$

$$E_{sc,CH4} = EF_{sc,CH4} \times Q_{sc} \times \left(\frac{1\ metric\ ton}{1000\ kg}\right)$$

where,

$E_{sc,CO2}$ = CO_2 emissions from production of SiC, metric tons

$EF_{sc,CO2}$ = Emission factor for production of SiC, metric ton CO_2/metric ton SiC

Q_{sc} = Quantity of SiC produced, metric tons

$E_{sc,CH4}$ = CH_4 emissions from production of SiC, metric tons

$EF_{sc,CH4}$ = Emission factor for production of SiC, kilogram CH_4/metric ton SiC

Emission factors were taken from the *2006 IPCC Guidelines*:

- 2.62 metric tons CO_2/metric ton SiC
- 11.6 kg CH_4/metric ton SiC

Production data includes silicon carbide manufactured for abrasive applications as well as for metallurgical and other non-abrasive applications (USGS 2021).

Silicon carbide industrial abrasives production data for 1990 through 2022 were obtained from the U.S. Geological Survey (USGS) *Minerals Yearbook: Manufactured Abrasives* (USGS 1991a through 2021; USGS 2023a). Silicon carbide production data published by USGS have been rounded to the nearest 5,000 metric tons to avoid disclosing company proprietary data. For the period 1990 through 2001, reported USGS production data include production from two facilities located in Canada that ceased operations in 1995 and 2001. Using SiC production data from Canada (ECCC 2022), U.S. SiC production for 1990 through 2001 was adjusted to reflect only U.S. production.

Emissions from SiC consumption are calculated by multiplying the annual SiC consumption for metallurgical and other non-abrasive uses by the carbon content of SiC (about 30.0 percent), which is based on the molecular weight

of SiC, and converted to CO_2. This conversion calculation equates to 1.10 and is consistent with the IPCC default emission factor to calculate CO_2 emissions from the consumption of acetylene, a calcium carbide product, and demonstrates a methodology consistent with the *2006 IPCC Guidelines*. The amount of SiC used by other non-abrasive applications is determined by multiplying the annual SiC consumption by 50 percent (the percentage that the USGS allocates as usage by metallurgical and other non-abrasive applications) and then subtracting the amount of SiC used for metallurgical applications (USGS 1991a through 2021; USGS 2023a).

Emissions from SiC consumption are estimated for the entire time series using USGS consumption data (USGS 1991b through 2021) and data from the U.S. International Trade Commission (USITC) database on net imports and exports of SiC (U.S. Census Bureau 2005 through 2022) (Table 4-45). Total annual SiC consumption (utilization) was estimated by subtracting annual exports of SiC from the total of annual national SiC production and annual imports. Data on the annual consumption of SiC for metallurgical uses were obtained from USGS *Minerals Yearbook: Silicon* (USGS 1991b-2021; USGS 2023c). USGS withheld consumption data for metallurgical uses from publication for 2017, 2018, and 2021, and 2022 due to concerns of disclosing company-specific sensitive information, SiC consumption for 2017 and 2018 were estimated using 2016 values, and SiC consumption for 2021 and 2022 were estimated using the 2020 value (USGS 2023c). Additionally, as the USGS has not yet released the 2022 data, SiC consumption for 2022 was estimated using the 2020 value.

The petroleum coke portion of the total CO_2 process emissions from silicon carbide production is adjusted for within the Energy chapter, as these fuels were consumed during non-energy related activities. Additional information on the adjustments made within the Energy sector for non-energy use of fuels is described in both the Methodology section of CO_2 from Fossil Fuel Combustion (Section 3.1) and Annex 2.1, Methodology for Estimating Emissions of CO_2 from Fossil Fuel Combustion.

Table 4-45: Production and Consumption of Silicon Carbide (Metric Tons)

Year	1990	2005	2018	2019	2020	2021	2022
SiC Production	65,000	35,000	35,000	35,000	35,000	35,000	40,000
SiC Consumption	132,465	220,149	168,526	152,412	113,756	146,312	191,133

Methodological approaches were applied to the entire time series to ensure consistency in emissions from 1990 through 2022.

Uncertainty

Silicon carbide production data published by the USGS is rounded to the nearest 5,000 tons and has been consistently reported at 35,000 tons since 2003 to avoid disclosure of company proprietary data. This translates to an uncertainty range of ±7 percent and a normal probability density function for SiC production (USGS 2021). There is uncertainty associated with the emission factors used because they are based on stoichiometry as opposed to monitoring of actual SiC production plants. An alternative is to calculate emissions based on the quantity of petroleum coke used during the production process rather than on the amount of silicon carbide produced; however, these data were not available. For CH_4, there is also uncertainty associated with the hydrogen-containing volatile compounds in the petroleum coke (IPCC 2006). EPA assigned an uncertainty of ±10 percent for the Tier 1 CO_2 and CH_4 emission factors for the SiC production processes, and using this suggested uncertainty provided in Section 3.6.3.1 of the *2006 IPCC Guidelines* is appropriate based on expert judgment (RTI 2023). Per this expert judgment, a triangular probability density function was assigned for emission factors. There is also uncertainty associated with the use or destruction of CH_4 generated from the process, in addition to uncertainty associated with levels of production, net imports, consumption levels, and the percent of total consumption that is attributed to metallurgical and other non-abrasive uses. EPA assigned an uncertainty range of ±5 percent for the primary data inputs for consumption (i.e., crude imports, ground and refined imports, crude exports, ground and refined exports, utilization [metallurgical applications]) to calculate overall uncertainty from SiC production, and using this suggested uncertainty provided in Section 3.6.3.2 of the *2006 IPCC Guidelines* is appropriate based on expert judgment (RTI 2023).

The results of the Approach 2 quantitative uncertainty analysis are summarized in Table 4-46. Silicon carbide production and consumption CO_2 emissions from 2022 were estimated to be between 10 percent below and 10 percent above the emission estimate of 0.2 MMT CO_2 Eq. at the 95 percent confidence level. Silicon carbide production CH_4 emissions were estimated to be between 10 percent below and 11 percent above the emission estimate of 0.01 MMT CO_2 Eq. at the 95 percent confidence level.

Table 4-46: Approach 2 Quantitative Uncertainty Estimates for CH_4 and CO_2 Emissions from Silicon Carbide Production and Consumption (MMT CO_2 Eq. and Percent)

Source	Gas	2022 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Silicon Carbide Production and Consumption	CO_2	0.2	0.2	0.2	-10%	+10%
Silicon Carbide Production	CH_4	+	+	+	-10%	+11%

+ Does not exceed 0.05 MMT CO_2 Eq.

[a] Range of emission estimates predicted by Monte Carlo stochastic simulation for a 95 percent confidence interval.

QA/QC and Verification

General quality assurance/quality control (QA/QC) procedures were applied consistent with the U.S. Inventory QA/QC plan, which is in accordance with Volume 1, Chapter 6 of *2006 IPCC Guidelines* as described in the introduction of the IPPU chapter (see Annex 8 for more details).

Recalculations Discussion

No recalculations were performed for the 1990 through 2021 portion of the time series.

Planned Improvements

EPA is initiating research for data on SiC consumption by end-use for consideration in updating emissions estimates from SiC consumption and to account for emissions where they occur. This planned improvement is subject to data availability and will be implemented in the medium- to long-term given significance of emissions.

EPA has not integrated aggregated facility-level GHGRP information to inform estimates of CO_2 and CH_4 from SiC production and consumption. The aggregated information (e.g., activity data and emissions) associated with silicon carbide did not meet criteria to shield underlying confidential business information (CBI) from public disclosure. EPA plans to examine the use of GHGRP silicon carbide emissions data for possible use in emission estimates consistent with both Volume 1, Chapter 6 of the *2006 IPCC Guidelines* and the latest IPCC guidance on the use of facility-level data in national inventories. This planned improvement is ongoing and has not been incorporated into this *Inventory* report. This is a long-term planned improvement.

4.11 Titanium Dioxide Production (CRT Source Category 2B6)

Titanium dioxide (TiO_2) is manufactured using one of two processes: the chloride process and the sulfate process. The chloride process uses petroleum coke and chlorine as raw materials and emits process-related carbon dioxide

(CO_2). The sulfate process does not use petroleum coke or other forms of carbon as a raw material and does not emit CO_2. The reporting category (2B6) includes emissions from production of TiO_2. In accordance with the IPCC methodological guidance, emissions from fuels consumed for energy purposes during the production of titanium dioxide are accounted for as part of fossil fuel combustion in the industrial end-use sector reported under the Energy chapter. The chloride process is based on the following chemical reactions and does emit CO_2:

$$2FeTiO_3 + 7Cl_2 + 3C \rightarrow 2TiCl_4 + 2FeCl_3 + 3CO_2$$

$$2TiCl_4 + 2O_2 \rightarrow 2TiO_2 + 4Cl_2$$

The carbon in the first chemical reaction is provided by petroleum coke, which is oxidized in the presence of the chlorine and $FeTiO_3$ (rutile ore) to form CO_2. Since 2004, all TiO_2 produced in the United States has been produced using the chloride process, and a special grade of "calcined" petroleum coke is manufactured specifically for this purpose.

The principal use of TiO_2 is as a white pigment in paint, lacquers, and varnishes. It is also used as a pigment in the manufacture of plastics, paper, and other products. In 2022, U.S. TiO_2 production totaled 1,100,000 metric tons (USGS 2023b). Five plants produced TiO_2 in the United States in 2022.

Emissions of CO_2 from titanium dioxide production in 2022 were estimated to be 1.5 MMT CO_2 Eq. (1,474 kt CO_2), which represents an increase of 23 percent since 1990 (see Table 4-47 and Table 4-48). Compared to 2021, emissions from titanium dioxide production remained the same because production was consistent from 2021 to 2022. Annual production dipped in 2019 and 2020 and increased in 2021 and 2022.

Table 4-47: CO_2 Emissions from Titanium Dioxide (MMT CO_2 Eq.)

Year	1990	2005	2018	2019	2020	2021	2022
Titanium Dioxide	1.2	1.8	1.5	1.3	1.3	1.5	1.5

Table 4-48: CO_2 Emissions from Titanium Dioxide (kt CO_2)

Year	1990	2005	2018	2019	2020	2021	2022
Titanium Dioxide	1,195	1,755	1,541	1,340	1,340	1,474	1,474

Methodology and Time-Series Consistency

Emissions of CO_2 from TiO_2 production are calculated using a Tier 1 method from the *2006 IPCC Guidelines*, in accordance with the IPCC methodological decision tree and available data. Annual national TiO_2 production is multiplied by chloride process-specific emission factors provided by IPCC (IPCC 2006). The Tier 1 equation is as follows:

Equation 4-9: *2006 IPCC Guidelines* Tier 1: CO_2 Emissions from Titanium Production (Equation 3.12)

$$E_{td} = EF_{td} \times Q_{td}$$

where,

E_{td} = CO_2 emissions from TiO_2 production, metric tons

EF_{td} = Emission factor (chloride process), metric ton CO_2/metric ton TiO_2

Q_{td} = Quantity of TiO_2 produced, metric tons

The petroleum coke portion of the total CO_2 process emissions from TiO_2 production is adjusted for within the Energy chapter as these fuels were consumed during non-energy related activities. Additional information on the adjustments made within the Energy sector for Non-Energy Use of Fuels is described in both the Methodology

section of CO_2 from Fossil Fuel Combustion (Section 3.1 Fossil Fuel Combustion) and Annex 2.1, Methodology for Estimating Emissions of CO_2 from Fossil Fuel Combustion.

Data were obtained for the total amount of TiO_2 produced each year. For years prior to 2004, it was assumed that TiO_2 was produced using the chloride process and the sulfate process in the same ratio as the ratio of the total U.S. production capacity for each process. As of 2004, the last remaining sulfate process plant in the United States closed; therefore, 100 percent of production since 2004 used the chloride process (USGS 2005). An emission factor of 1.34 metric tons CO_2/metric ton TiO_2 was applied to the estimated chloride-process production (IPCC 2006). It was assumed that all TiO_2 produced using the chloride process was produced using petroleum coke, although some TiO_2 may have been produced with graphite or other carbon inputs.

The emission factor for the TiO_2 chloride process was taken from the *2006 IPCC Guidelines*. Titanium dioxide production data and the percentage of total TiO_2 production capacity that used the chloride process for 1990 through 2018 (see Table 4-49) were obtained through the U.S. Geological Survey (USGS) *Minerals Yearbook: Titanium* (USGS 1991 through 2022). Production data for 2019 and 2020 were obtained from the USGS Minerals Yearbook: Titanium, advanced data release of the 2020 tables (USGS 2023a). Production data for 2020 and 2021 were obtained from the *Minerals Commodity Summaries: Titanium and Titanium Dioxide* (USGS 2023b).[39] Data on the percentage of total TiO_2 production capacity that used the chloride process were not available for 1990 through 1993, so data from the 1994 USGS *Minerals Yearbook* were used for these years. Because a sulfate process plant closed in September 2001, the chloride process percentage for 2001 was estimated (Gambogi 2002). By 2002, only one sulfate process plant remained online in the United States, and this plant closed in 2004 (USGS 2005).

Table 4-49: Titanium Dioxide Production (kt)

Year	1990	2005	2018	2019	2020	2021	2022
Production	979	1,310	1,150	1,000	1,000	1,100	1,100

Methodological approaches were applied to the entire time series to ensure consistency in emissions from 1990 through 2022.

Uncertainty

Each year, the USGS collects titanium industry data for titanium mineral and pigment production operations. If TiO_2 pigment plants do not respond, production from the operations is estimated based on prior year production levels and industry trends. Variability in response rates fluctuates from 67 to 100 percent of TiO_2 pigment plants over the time series. EPA currently uses an uncertainty range of ±5 percent and a normal probability density function for the primary data inputs (i.e., TiO_2 production and chloride process capacity values) to calculate overall uncertainty from TiO_2 production, and using this suggested uncertainty provided in Section 3.7.3.2 of the *2006 IPCC Guidelines* is appropriate based on expert judgment (RTI 2023). Additionally, the EPA uses an uncertainty range of ±15 percent and a triangular probability density function for the CO_2 chloride process carbon consumption rate, and using this uncertainty provided in Section 3.7.2.2 of the *2006 IPCC Guidelines* is representative of operations in the United States. based on expert judgment (RTI 2023).

Although some TiO_2 may be produced using graphite or other carbon inputs, information and data regarding these practices were not available. Titanium dioxide produced using graphite inputs, for example, may generate differing amounts of CO_2 per unit of TiO_2 produced as compared to that generated using petroleum coke in production. While the most accurate method to estimate emissions would be to base calculations on the amount of reducing

[39] EPA has not integrated aggregated facility-level GHGRP information for titanium dioxide production facilities (40 CFR Part 98 Subpart EE). The relevant aggregated information (activity data, emission factor) from these facilities did not meet criteria to shield underlying CBI from public disclosure.

agent used in each process rather than on the amount of TiO_2 produced, sufficient data were not available to do so.

As of 2004, the last remaining sulfate-process plant in the United States closed. Since annual TiO_2 production was not reported by USGS by the type of production process used (chloride or sulfate) prior to 2004 and only the percentage of total production capacity by process was reported, the percent of total TiO_2 production capacity that was attributed to the chloride process was multiplied by total TiO_2 production to estimate the amount of TiO_2 produced using the chloride process. Finally, the emission factor was applied uniformly to all chloride-process production, and no data were available to account for differences in production efficiency among chloride-process plants. In calculating the amount of petroleum coke consumed in chloride-process TiO_2 production, literature data were used for petroleum coke composition. Certain grades of petroleum coke are manufactured specifically for use in the TiO_2 chloride process; however, this composition information was not available. EPA assigned an uncertainty range of ±15 percent and a triangular probability density function for the Tier 1 CO_2 emission factor for the titanium dioxide (chloride route) production process, and using this uncertainty provided in Table 3.9 of the *2006 IPCC Guidelines* is representative of operations in the United States based on expert judgment (RTI 2023).

The results of the Approach 2 quantitative uncertainty analysis are summarized in Table 4-49. Titanium dioxide consumption CO_2 emissions from 2022 were estimated to be between 1.3 and 1.7 MMT CO_2 Eq. at the 95 percent confidence level. This indicates a range of approximately 12 percent below and 13 percent above the emission estimate of 1.5 MMT CO_2 Eq.

Table 4-50: Approach 2 Quantitative Uncertainty Estimates for CO_2 Emissions from Titanium Dioxide Production (MMT CO_2 Eq. and Percent)

Source	Gas	2022 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Titanium Dioxide Production	CO_2	1.5	1.3	1.7	-12%	+13%

[a] Range of emission estimates predicted by Monte Carlo stochastic simulation for a 95 percent confidence interval.

QA/QC and Verification

General quality assurance/quality control (QA/QC) procedures were applied consistent with the U.S. Inventory QA/QC plan, which is in accordance with Volume 1, Chapter 6 of the *2006 IPCC Guidelines* as described in the introduction of the IPPU chapter (see Annex 8 for more details).

Recalculations Discussion

Updated USGS data on TiO_2 production was available for 2019 and 2020, resulting in updated emissions estimates for those years. Compared to the previous *Inventory*, emissions for 2019 decreased by 9 percent (134 kt CO_2), and emissions for 2020 increased by 12 percent (147 kt CO_2).

Planned Improvements

EPA plans to examine the use of GHGRP titanium dioxide emissions and other data for possible use in emission estimates consistent with both Volume 1, Chapter 6 of the *2006 IPCC Guidelines* and the latest IPCC guidance on the use of facility-level data in national inventories.[40] This planned improvement is ongoing and has not been

[40] See http://www.ipcc-nggip.iges.or.jp/public/tb/TFI_Technical_Bulletin_1.pdf.

incorporated into this *Inventory* report. This is a long-term planned improvement given the significance of these emissions.

4.12 Soda Ash Production (CRT Source Category 2B7)

Carbon dioxide (CO_2) is generated as a byproduct of calcining trona ore to produce soda ash (sodium carbonate, Na_2CO_3) and is eventually emitted into the atmosphere. In addition, CO_2 may also be released when soda ash is consumed. This reporting category (2B7) includes emissions from the production of soda ash by any of four processes, of which calcining trona ore is the only emissive process used in the United States. Emissions from soda ash consumption associated with glass production are reported under Section 4.3, glass production. Emissions from soda ash consumption not associated with glass production are reported under Section 4.4, other process uses of carbonates. Emissions from fuels consumed for energy purposes during the production and consumption of soda ash are accounted for as part of fossil fuel combustion in the industrial end-use sector reported under the Energy chapter.

Calcining involves placing crushed trona ore into a kiln to convert sodium bicarbonate into crude sodium carbonate that will later be filtered into pure soda ash. The emission of CO_2 during trona-based production is based on the following reaction:

$$2Na_2CO_3 \cdot NaHCO_3 \cdot 2H_2O(Trona) \rightarrow 3Na_2CO_3(Soda\ Ash) + 5H_2O + CO_2$$

Soda ash is a white crystalline solid that is readily soluble in water and strongly alkaline. Commercial soda ash is used as a raw material in a variety of industrial processes and in many familiar consumer products such as glass, soap and detergents, paper, textiles, and food. The largest use of soda ash is for glass manufacturing. Emissions from soda ash used in glass production are reported under Section 4.3. In addition, soda ash is used primarily to manufacture many sodium-based inorganic chemicals, including sodium bicarbonate, sodium chromates, sodium phosphates, and sodium silicates (USGS 2018b). Internationally, two types of soda ash are produced: natural and synthetic. The United States produces only natural soda ash and is second only to China in total soda ash production. Trona is the principal ore from which natural soda ash is made.

The United States represents about one-fifth of total world soda ash output (USGS 2023a). Only two states produce natural soda ash: Wyoming and California. Of these two states, net emissions of CO_2 from soda ash production were only calculated for Wyoming where trona ore is used.[41] Soda ash end uses in 2022 (excluding glass production) consisted of chemical production, 54 percent; other uses, 17 percent; wholesale distributors (e.g., for use in agriculture, water treatment, and grocery wholesale), 10 percent; soap and detergent manufacturing, 9 percent; flue gas desulfurization, 7 percent; water treatment, 2 percent; and pulp and paper production, 1 percent (USGS 2023b).[42]

[41] In California, soda ash is manufactured using sodium carbonate-bearing brines instead of trona ore. To extract the sodium carbonate, the complex brines are first treated with CO_2 in carbonation towers to convert the sodium carbonate into sodium bicarbonate, which then precipitates from the brine solution. The precipitated sodium bicarbonate is then calcined back into sodium carbonate. Although CO_2 is generated as a byproduct, the CO_2 is recovered and recycled for use in the carbonation stage and is not emitted. A facility in a third state, Colorado, produced soda ash until the plant was idled in 2004. The lone producer of sodium bicarbonate no longer mines trona ore in the state. For a brief time, sodium bicarbonate was produced using soda ash feedstocks mined in Wyoming and shipped to Colorado. Prior to 2004, because the trona ore was mined in Wyoming, the production numbers given by the USGS included the feedstocks mined in Wyoming and shipped to Colorado. In this way, the sodium bicarbonate production that took place in Colorado was accounted for in the Wyoming numbers.

[42] Percentages may not add up to 100 percent due to independent rounding.

U.S. natural soda ash is competitive in world markets because it is generally considered a better-quality raw material than synthetically produced soda ash, and most of the world's soda ash is synthetic. Although the United States continues to be a major supplier of soda ash, China surpassed the United States in soda ash production in 2003, becoming the world's leading producer.

In 2022, CO_2 emissions from the production of soda ash from trona ore were 1.7 MMT CO_2 Eq. (1,704 kt CO_2) (see Table 4-51 and Table 4-52). Total emissions from soda ash production in 2022 decreased by approximately 1 percent compared to emissions in 2021, as soda ash production returned to 2018 levels observed before the COVID-19 pandemic. Emissions have increased by approximately 19 percent from 1990 levels.

Trends in emissions have remained relatively constant over the time series with some fluctuations since 1990. In general, these fluctuations were related to the behavior of the export market and the U.S. economy. The U.S. soda ash industry saw a decline in domestic and export sales caused by adverse global economic conditions in 2009, followed by a steady increase in production through 2019 before a significant decrease in 2020 due to the COVID-19 pandemic.

Table 4-51: CO_2 Emissions from Soda Ash Production (MMT CO_2 Eq.)

Year	1990	2005	2018	2019	2020	2021	2022
Soda Ash Production	1.4	1.7	1.7	1.8	1.5	1.7	1.7

Table 4-52: CO_2 Emissions from Soda Ash Production (kt CO_2)

Year	1990	2005	2018	2019	2020	2021	2022
Soda Ash Production	1,431	1,655	1,714	1,792	1,461	1,714	1,704

Methodology and Time-Series Consistency

Carbon dioxide emissions from soda ash production are calculated using a Tier 1 method from the *2006 IPCC Guidelines*, in accordance with the IPCC methodological decision tree and available data. During the soda ash production process, trona ore is calcined in a rotary kiln and chemically transformed into a crude soda ash that requires further processing. Carbon dioxide and water are generated as byproducts of the calcination process. Carbon dioxide emissions from the calcination of trona ore can be estimated based on the chemical reaction shown above. Based on this formula and the IPCC default emission factor of 0.0974 metric tons CO_2 per metric ton of trona ore, both of which are consistent with an IPCC Tier 1 approach, one metric ton of CO_2 is emitted when approximately 10.27 metric tons of trona ore are processed (IPCC 2006).

Data is not currently available for the quantity of trona used in soda ash production. Because trona ore is used primarily for soda ash production, EPA assumes that all trona ore production was used in soda ash production. The activity data for trona ore production (see Table 4-53) for 1990 through 2022 were obtained from the U.S. Geological Survey (USGS) *Minerals Yearbook for Soda Ash* (1994 through 2015b) and USGS *Mineral Industry Surveys for Soda Ash* (USGS 2016 through 2017, 2018a, 2019, 2020, 2021, 2022b, 2023b). Soda ash production[43] data were collected by the USGS from voluntary surveys of the U.S. soda ash industry. EPA will continue to analyze and assess opportunities to use facility-level data from EPA's GHGRP to improve the emission estimates for the soda ash production source category consistent with IPCC[44] and UNFCCC guidelines.

[43] EPA has assessed the feasibility of using emissions information (including activity data) from EPA's GHGRP program. At this time, the aggregated information associated with production of soda ash did not meet criteria to shield underlying confidential business information (CBI) from public disclosure.

[44] See http://www.ipcc-nggip.iges.or.jp/public/tb/TFI_Technical_Bulletin_1.pdf.

Table 4-53: Trona Ore Used in Soda Ash Production (kt)

Year	1990	2005	2018	2019	2020	2021	2022
Trona Ore Use[a]	14,700	17,000	17,600	18,400	15,000	17,600	17,500

[a] Trona ore use is assumed to be equal to trona ore production.

Methodological approaches were applied to the entire time series to ensure consistency in emissions estimates from 1990 through 2022.

Uncertainty

Emission estimates from soda ash production have relatively low associated uncertainty levels because reliable and accurate data sources are available for the emission factor and activity data for trona-based soda ash production. One source of uncertainty is the purity of the trona ore used for manufacturing soda ash. The emission factor used for this estimate assumes the ore is 100 percent pure and likely overestimates the emissions from soda ash manufacture. The average water-soluble sodium carbonate-bicarbonate content for ore mined in Wyoming ranges from 85.5 to 93.8 percent (USGS 1995c).

EPA is aware of one facility producing soda ash from a liquid alkaline feedstock process, based on EPA's GHGRP. Soda ash production data was collected by the USGS from voluntary surveys. A survey request was sent to each of the five soda ash producers, all of which responded, representing 100 percent of the total production data (USGS 2023b). EPA assigned an uncertainty range of ±5 percent for trona production, and using the suggested uncertainty provided in Section 3.8.2.2 of the *2006 IPCC Guidelines* is appropriate based on expert judgment (RTI 2023). EPA assigned an uncertainty range of -15 percent to 0 percent range for the trona emission factor, based on expert judgment on the purity of mined trona (USGS 1995c). Per this expert judgment, a normal probability density function was assigned for activity data, and a triangular probability density function was assigned for the emission factor.

The results of the Approach 2 quantitative uncertainty analysis are summarized in Table 4-54. Soda ash production CO_2 emissions for 2022 were estimated to be between 1.5 and 1.7 MMT CO_2 Eq. at the 95 percent confidence level. This indicates a range of approximately 9 percent below and 8 percent above the emission estimate of 1.7 MMT CO_2 Eq.

Table 4-54: Approach 2 Quantitative Uncertainty Estimates for CO_2 Emissions from Soda Ash Production (MMT CO_2 Eq. and Percent)

Source	Gas	2022 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Soda Ash Production	CO_2	1.7	1.5	1.7	-9%	+8%

[a] Range of emission estimates predicted by Monte Carlo stochastic simulation for a 95 percent confidence interval.

QA/QC and Verification

General quality assurance/quality control (QA/QC) procedures were applied consistent with the U.S. Inventory QA/QC plan, which is in accordance with Volume 1, Chapter 6 of *2006 IPCC Guidelines* as described in the introduction of the IPPU chapter (see Annex 8 for more details).

Recalculations Discussion

No recalculations were performed for the 1990 through 2021 portion of the time series.

Planned Improvements

EPA is assessing planned improvements for future reports, but at this time has no specific planned improvements for estimating CO_2 emissions from soda ash production.

4.13 Petrochemical Production (CRT Source Category 2B8)

The production of some petrochemicals results in carbon dioxide (CO_2) and methane (CH_4) emissions. Petrochemicals are chemicals isolated or derived from petroleum or natural gas. This reporting category (2B8) includes CO_2 emissions from the production of acrylonitrile, carbon black, ethylene, ethylene dichloride, ethylene oxide, and methanol, and CH_4 emissions from the production of acrylonitrile. The petrochemical industry uses primary fossil fuels (i.e., natural gas, coal, petroleum, etc.) for non-fuel purposes in the production of carbon black and other petrochemicals. Per the IPCC methodological guidance, emissions from fuels and feedstocks transferred out of the system for use in energy purposes (e.g., indirect or direct process heat or steam production) are currently accounted for as part of fossil fuel combustion in the industrial end-use sector reported under the Energy chapter.

Worldwide, more than 90 percent of acrylonitrile (vinyl cyanide, C_3H_3N) is made by way of direct ammoxidation of propylene with ammonia (NH_3) and oxygen over a catalyst. This process is referred to as the SOHIO process, named after the Standard Oil Company of Ohio (SOHIO) (IPCC 2006). The primary use of acrylonitrile is as the raw material for the manufacture of acrylic and modacrylic fibers. Other major uses include the production of plastics (acrylonitrile-butadiene-styrene [ABS] and styrene-acrylonitrile [SAN]), nitrile rubbers, nitrile barrier resins, adiponitrile, and acrylamide. All U.S. acrylonitrile facilities use the SOHIO process (AN 2014). The SOHIO process involves a fluidized bed reaction of chemical-grade propylene, ammonia, and oxygen over a catalyst. The process produces acrylonitrile as its primary product, and the process yield depends on the type of catalyst used and the process configuration. The ammoxidation process produces byproduct CO_2, carbon monoxide (CO), and water from the direct oxidation of the propylene feedstock and produces other hydrocarbons from side reactions.

Carbon black is a black powder generated by the incomplete combustion of an aromatic petroleum- or coal-based feedstock at a high temperature. Most carbon black produced in the United States is added to rubber to impart strength and abrasion resistance, and the tire industry is by far the largest consumer. The other major use of carbon black is as a pigment. The predominant process used in the United States to produce carbon black is the furnace black (or oil furnace) process. In the furnace black process, carbon black oil (a heavy aromatic liquid) is continuously injected into the combustion zone of a natural gas-fired furnace. Furnace heat is provided by the natural gas and a portion of the carbon black feedstock; the remaining portion of the carbon black feedstock is pyrolyzed to carbon black. The resultant CO_2 and uncombusted CH_4 are released from thermal incinerators used as control devices, process dryers, and equipment leaks. Three facilities in the United States use other types of carbon black processes. Specifically, one facility produces carbon black by the thermal cracking of acetylene-containing feedstocks (i.e., acetylene black process), a second facility produces carbon black by the thermal cracking of other hydrocarbons (i.e., thermal black process), and a third facility produces carbon black by the open burning of carbon black feedstock (i.e., lamp black process) (EPA 2000).

Ethylene (C_2H_4) is consumed in the production processes of the plastics industry including polymers such as high, low, and linear low density polyethylene (HDPE, LDPE, LLDPE); polyvinyl chloride (PVC); ethylene dichloride; ethylene oxide; and ethylbenzene. Virtually all ethylene is produced from steam cracking of ethane, propane, butane, naphtha, gas oil, and other feedstocks. The representative chemical equation for steam cracking of ethane to ethylene is shown below:

$$C_2H_6 \rightarrow C_2H_4 + H_2$$

Small amounts of CH_4 are also generated from the steam cracking process. In addition, CO_2 and CH_4 emissions result from combustion units.

Ethylene dichloride ($C_2H_4Cl_2$) is used to produce vinyl chloride monomer, which is the precursor to polyvinyl chloride (PVC). Ethylene dichloride was also used as a fuel additive until 1996 when leaded gasoline was phased out. Ethylene dichloride is produced from ethylene by either direct chlorination, oxychlorination, or a combination of the two processes (i.e., the "balanced process"); most U.S. facilities use the balanced process. The direct chlorination and oxychlorination reactions are shown below:

$$C_2H_4 + Cl_2 \rightarrow C_2H_4Cl_2 \text{ (direct chlorination)}$$

$$C_2H_4 + \tfrac{1}{2}O_2 + 2HCl \rightarrow C_2H_4Cl_2 + 2H_2O \text{ (oxychlorination)}$$

$$C_2H_4 + 3O_2 \rightarrow 2CO_2 + 2H_2O \text{ (direct oxidation of ethylene during oxychlorination)}$$

In addition to the byproduct CO_2 produced from the direct oxidation of the ethylene feedstock, CO_2 and CH_4 emissions are also generated from combustion units.

Ethylene oxide (C_2H_4O) is used in the manufacture of glycols, glycol ethers, alcohols, and amines. Approximately 70 percent of ethylene oxide produced worldwide is used in the manufacture of glycols, including monoethylene glycol. Ethylene oxide is produced by reacting ethylene with oxygen over a catalyst. The oxygen may be supplied to the process through either an air (air process) or a pure oxygen stream (oxygen process). The byproduct CO_2 from the direct oxidation of the ethylene feedstock is removed from the process vent stream using a recycled carbonate solution, and the recovered CO_2 may be vented to the atmosphere or recovered for further utilization in other sectors, such as food production (IPCC 2006). The combined ethylene oxide reaction and byproduct CO_2 reaction is exothermic and generates heat, which is recovered to produce steam for the process. The ethylene oxide process also produces other liquid and off-gas byproducts (e.g., ethane that may be burned for energy recovery within the process. Almost all facilities, except one in Texas, use the oxygen process to manufacture ethylene oxide (EPA 2008).

Methanol (CH_3OH) is a chemical feedstock most often converted into formaldehyde, acetic acid and olefins. It is also an alternative transportation fuel, as well as an additive used by municipal wastewater treatment facilities in the denitrification of wastewater. Methanol is most commonly synthesized from a synthesis gas (i.e., "syngas" – a mixture containing H_2, CO, and CO_2) using a heterogeneous catalyst. There are a number of process techniques that can be used to produce syngas. Worldwide, steam reforming of natural gas is the most common method; most methanol producers in the United States also use steam reforming of natural gas to produce syngas. Other syngas production processes in the United States include partial oxidation of natural gas and coal gasification.

Emissions of CO_2 and CH_4 from petrochemical production in 2022 were 28.8 MMT CO_2 Eq. (28,788 kt CO_2) and 0.005 MMT CO_2 Eq. (0.17 kt CH_4), respectively (see Table 4-55 and Table 4-56). Carbon dioxide emissions from petrochemical production are driven primarily from ethylene production, while CH_4 emissions are only from acrylonitrile production. Since 1990, total CO_2 emissions from petrochemical production increased by 43 percent, and CH_4 emissions declined by 22 percent. Emissions of CO_2 were 6 percent lower in 2022 than in 2021, and emissions of CH_4 were 12 percent higher in 2022 than in 2021. The increase in CO_2 emissions since 1990 is due primarily to increased ethylene and methanol production, which have been driven by the increased natural gas production in the United States. The reduction in CO_2 emissions since 2021 is due to a reduction in emissions from ethylene production, despite an increase in ethylene production. Since CH_4 emissions from acrylonitrile are calculated using a Tier 1 approach based on production as the activity data, the decrease in CH_4 emissions since 1990 and the increase since 2021 correspond with changes in the production levels for acrylonitrile.

Table 4-55: CO_2 and CH_4 Emissions from Petrochemical Production (MMT CO_2 Eq.)

Year	1990	2005	2018	2019	2020	2021	2022
CO_2	**20.1**	**26.9**	**27.2**	**28.5**	**27.9**	**30.7**	**28.8**
Carbon Black	3.4	4.3	3.4	3.3	2.6	3.0	3.1
Ethylene	13.1	19.0	19.4	20.7	20.7	22.8	20.7

Ethylene Dichloride	0.3	0.5	0.4	0.5	0.5	0.4	0.4
Ethylene Oxide	1.1	1.5	1.3	1.4	1.7	1.9	1.7
Methanol	1.0	0.3	1.4	1.6	1.6	1.7	2.0
Acrylonitrile	1.2	1.3	1.3	1.0	0.9	0.9	1.0
CH_4	**+**	**+**	**+**	**+**	**+**	**+**	**+**
Acrylonitrile	+	+	+	+	+	+	+
Total	**20.1**	**26.9**	**27.2**	**28.5**	**27.9**	**30.7**	**28.8**

+ Does not exceed 0.05 MMT CO_2 Eq.

Note: Totals may not sum due to independent rounding.

Table 4-56: CO_2 and CH_4 Emissions from Petrochemical Production (kt)

Year	1990	2005	2018	2019	2020	2021	2022
CO_2	**20,075**	**26,882**	**27,200**	**28,483**	**27,926**	**30,656**	**28,788**
Carbon Black	3,381	4,269	3,440	3,300	2,610	3,000	3,060
Ethylene	13,126	19,024	19,400	20,700	20,700	22,800	20,700
Ethylene Dichloride	254	455	440	503	456	376	428
Ethylene Oxide	1,123	1,489	1,300	1,370	1,680	1,930	1,650
Methanol	977	319	1,370	1,620	1,630	1,700	2,000
Acrylonitrile	1,214	1,325	1,250	990	850	850	950
CH_4	**+**	**+**	**+**	**+**	**+**	**+**	**+**
Acrylonitrile	+	+	+	+	+	+	+

+ Does not exceed 0.5 kt CH_4.

Note: Totals by gas may not sum due to independent rounding.

Methodology and Time-Series Consistency

Emissions of CO_2 and CH_4 were calculated using the estimation methods provided by the *2006 IPCC Guidelines*, in accordance with the IPCC methodological decision tree and available data, and country-specific methods from EPA's GHGRP. The *2006 IPCC Guidelines* Tier 1 method was used to estimate CO_2 and CH_4 emissions from production of acrylonitrile,[45] and a country-specific approach similar to the IPCC Tier 2 method was used to estimate CO_2 emissions from production of carbon black, ethylene oxide, ethylene, ethylene dichloride, and methanol, as CO_2 emissions from petrochemical production is a key category. The Tier 2 method for petrochemicals is a total feedstock carbon mass balance method used to estimate total CO_2 emissions, but it is not applicable for estimating CH_4 emissions.

As noted in the *2006 IPCC Guidelines*, the Tier 2 total feedstock carbon mass balance method is based on the assumption that all of the carbon input to the process is converted either into primary and secondary products or into CO_2. Further, the guideline states that while the total carbon mass balance method estimates total carbon emissions from the process, it does not directly provide an estimate of the amount of the total carbon emissions emitted as CO_2, CH_4, or non-CH_4 volatile organic compounds (NMVOCs). This method accounts for all the carbon as CO_2, including CH_4.

A methodology refinement for emissions from methanol production was implemented in this *Inventory* to transition from a Tier 1 method to a country-specific approach similar to a Tier 2 method, using the process CO_2 emissions reported to Subpart X of the GHGRP. As part of this refinement, CH_4 emissions from methanol production for every year in the time series are now included in the CO_2 emissions estimates to avoid double counting because the GHGRP reporting method is a mass balance method under which all carbon input to the process is assumed to be converted either into primary and secondary products or into CO_2.

[45] EPA has not integrated aggregated facility-level GHGRP information for acrylonitrile production. The aggregated information associated with production of these petrochemicals did not meet criteria to shield underlying CBI from public disclosure.

Note, a subset of facilities reporting under EPA's GHGRP use Continuous Emission Monitoring Systems (CEMS) to monitor CO_2 emissions from process vents and/or stacks from stationary combustion units or use the optional combustion methodology for ethylene production facilities. These facilities are required to also report CO_2, CH_4 and N_2O emissions from combustion of process off-gas in flares. The CO_2 emissions from flares are included in aggregated CO_2 results. Analysis of aggregated annual reports from those facilities shows that flared CH_4 and N_2O emissions are less than 300 kt CO_2 Eq./year. Since data is only available from a subset of facilities and not consistently reported over time and since CH_4 and N_2O emissions are shown to be insignificant, they are excluded from this analysis. See the planned improvements section below and Annex 5.

Carbon Black, Ethylene, Ethylene Dichloride, and Ethylene Oxide

2010 through 2022

Carbon dioxide emissions and national production for carbon black, ethylene, ethylene dichloride, and ethylene oxide were aggregated directly from EPA's GHGRP dataset for 2010 through 2022 (EPA 2023).

These emissions reflect application of a country-specific approach similar to the IPCC Tier 2 method and were used to estimate CO_2 emissions from the production of carbon black, ethylene, ethylene dichloride, ethylene oxide. In 2022, data reported to the GHGRP included 3,060,000 metric tons of CO_2 emissions from carbon black production; 20,700,000 metric tons of CO_2 from ethylene production; 428,000 metric tons of CO_2 from ethylene dichloride production; and 1,650,000 metric tons of CO_2 from ethylene oxide production.

Since 2010, EPA's GHGRP requires all domestic producers of petrochemicals to report annual emissions and supplemental emissions information (e.g., production data, etc.) under Subpart X to facilitate verification of reported emissions. Most petrochemical production facilities are required to use either a mass balance approach or CEMS to measure and report emissions for each petrochemical process unit to estimate facility-level process CO_2 emissions; ethylene production facilities also have a third option. The mass balance method is used by most facilities[46] and assumes that all the carbon input is converted into primary and secondary products or is emitted to the atmosphere as CO_2. To apply the mass balance, facilities must measure the volume or mass of each gaseous and liquid feedstock and product, mass rate of each solid feedstock and product, and carbon content of each feedstock and product for each process unit and sum for their facility. To apply the optional combustion methodology, ethylene production facilities must measure the quantity, carbon content, and molecular weight of the fuel to a stationary combustion unit when that fuel includes any ethylene process off-gas. These data are used to calculate the total CO_2 emissions from the combustion unit. The facility must also estimate the fraction of the emissions that is attributable to burning the ethylene process off-gas portion of the fuel. This fraction is multiplied by the total emissions to estimate the emissions from ethylene production. The QA/QC and Verification section below has a discussion of non-CO_2 emissions from ethylene production facilities.

All non-energy uses of residual fuel and some non-energy uses of "other oil" are assumed to be used in the production of carbon black; therefore, consumption of these fuels is adjusted for within the Energy chapter to avoid double-counting of emissions from fuel used in the carbon black production presented here within IPPU sector. Additional information on the adjustments made within the Energy sector for non-energy use of fuels is described in both the Methodology section of CO_2 from Section 3.1 and Annex 2.1.

1990 through 2009

Prior to 2010, for carbon black, ethylene, ethylene dichloride, and ethylene oxide processes, an average national CO_2 emission factor was calculated based on the GHGRP data and applied to production for earlier years in the time series (i.e., 1990 through 2009) to estimate CO_2 emissions. For these 4 types of petrochemical processes, CO_2 emission factors were derived from EPA's GHGRP data by dividing annual CO_2 emissions for petrochemical type "i"

[46] A few facilities producing ethylene dichloride, ethylene, and methanol used CO_2 CEMS; those CO_2 emissions have been included in the aggregated GHGRP emissions presented here.

with annual production for petrochemical type "i" and then averaging the derived emission factors obtained for each calendar year 2010 through 2013 (EPA 2023). The years 2010 through 2013 were used in the development of carbon dioxide emission factors as these years are more representative of operations in 1990 through 2009 for these facilities. The average emission factors for each petrochemical type were applied across all prior years because petrochemical production processes in the United States have not changed significantly since 1990, though some operational efficiencies have been implemented at facilities over the time series.

The average country-specific CO_2 emission factors that were calculated from the GHGRP data are as follows:

- 2.59 metric tons CO_2/metric ton carbon black produced
- 0.79 metric tons CO_2/metric ton ethylene produced
- 0.040 metric tons CO_2/metric ton ethylene dichloride produced
- 0.46 metric tons CO_2/metric ton ethylene oxide produced

Annual production data for carbon black for 1990 through 2009 were obtained from the International Carbon Black Association (Johnson 2003 and 2005 through 2010). Annual production data for ethylene, ethylene dichloride, and ethylene oxide for 1990 through 2009 were obtained from the American Chemistry Council's (ACC) *Business of Chemistry* (ACC 2023).

Methanol

2015 through 2022

Carbon dioxide emissions and national production for methanol were aggregated directly from EPA's GHGRP data for 2015 through 2022 (EPA 2023). These emissions reflect application of a country-specific approach similar to the IPCC Tier 2 method and were used to estimate CO_2 emissions from the production of methanol. In 2022, data reported to the GHGRP included 2,000,000 metric tons of CO_2 emissions from methanol production.

As noted above, since 2010, EPA's GHGRP requires all domestic producers of petrochemicals to report annual emissions and supplemental emissions information (e.g., production data, etc.) under Subpart X to facilitate verification of reported emissions. Methanol production facilities are required to use either a mass balance approach or CEMS to measure and report emissions for each methanol process unit to estimate facility-level process CO_2 emissions. Most methanol production facilities use the mass balance method. As noted above, when using the mass balance method, facilities must measure the volume or mass of each gaseous and liquid feedstock and product, mass rate of each solid feedstock and product, and carbon content of each feedstock and product for each process unit and sum for their facility. For 2010 to 2014, the methanol data reported to GHGRP is considered CBI; therefore, the direct use of the GHGRP data starts with the 2015 reported information.

1990 through 2014

In this *Inventory*, similar to the methodology for other petrochemicals that utilize GHGRP data, an average national CO_2 emission factor for years prior to 2015 was calculated for methanol production based on the GHGRP data and applied to production for earlier years in the time series (i.e., 1990 through 2014) to estimate CO_2 emissions. Methanol CO_2 emission factors were derived from EPA's GHGRP data by dividing annual CO_2 emissions for methanol with annual production for methanol and then averaging the derived emission factors obtained for each year 2015 through 2022. The average country-specific CO_2 emission factor from the GHGRP data for these years was determined to be 0.26 metric tons CO_2/metric ton methanol produced. Annual methanol production data for 1990 through 2014 were obtained from the ACC's *Business of Chemistry* (ACC 2023). The average country-specific CO_2 emission factor from the GHGRP data is lower than the IPCC Tier 1 emission factor of 0.67 metric tons CO_2/metric ton methanol produced value that was used in previous versions of the *Inventory*. The main difference between the IPCC Tier 1 emission factor and the GHGRP emission factor is that the IPCC emission factor includes emissions from combustion of natural gas fuel in the reformer as well as vented CO_2 from the process; therefore, the use of the IPCC Tier 1 emission factor would double count emissions from natural gas combustion in the IPPU

chapter and the Energy chapter. EPA already accounts for emissions from combustion of natural gas fuel in the reformer as part of fossil fuel combustion in the industrial end-use sector reported under the Energy chapter.

Acrylonitrile

Carbon dioxide and methane emissions from acrylonitrile production were estimated using the Tier 1 method in the *2006 IPCC Guidelines*. Acrylonitrile emissions represent about 3 percent of total petrochemical emissions in 2022 so a Tier 1 approach is deemed acceptable, and higher Tier methods could not be used due to data sensitivities which are described below. Annual acrylonitrile production data were used with IPCC default Tier 1 CO_2 and CH_4 emission factors to estimate emissions for 1990 through 2022. Emission factors used to estimate acrylonitrile production emissions are as follows:

- 0.18 kg CH_4/metric ton acrylonitrile produced
- 1.00 metric tons CO_2/metric ton acrylonitrile produced

Annual acrylonitrile production data for 1990 through 2022 were obtained from ACC's *Business of Chemistry* (ACC 2023). EPA is unable to apply the aggregated facility-level GHGRP information for acrylonitrile production needed for a Tier 2 approach due to sensitive nature of reported data. The aggregated information associated with production of these petrochemicals did not meet criteria to shield underlying CBI from public disclosure.

Production of each type of petrochemical are shown in Table 4-57.

Table 4-57: Production of Selected Petrochemicals (kt)

Chemical	1990	2005	2018	2019	2020	2021	2022
Carbon Black	1,307	1,651	1,280	1,210	990	1,140	1,170
Ethylene	16,542	23,975	30,500	32,400	33,500	34,700	35,400
Ethylene Dichloride	6,283	11,260	12,500	12,600	11,900	11,500	12,100
Ethylene Oxide	2,429	3,220	3,310	3,800	4,680	4,860	5,310
Methanol	3,750	1,225	5,830	6,460	6,580	7,110	8,030
Acrylonitrile	1,214	1,325	1,250	990	850	850	950

As noted earlier in the introduction section of the Petrochemical Production section, the allocation and reporting of emissions from both fuels and feedstocks transferred out of the system for use in energy purposes to the Energy chapter differs slightly from the *2006 IPCC Guidelines*. According to the *2006 IPCC Guidelines*, emissions from fuel combustion from petrochemical production should be allocated to this source category within the IPPU chapter. Due to national circumstances, EIA data on primary fuel for feedstock use within the energy balance are presented by commodity only, with no resolution on data by industry sector (i.e., petrochemical production). In addition, under EPA's GHGRP, reporting facilities began reporting in 2014 on annual feedstock quantities for mass balance and CEMS methodologies (79 FR 63794), as well as the annual average carbon content of each feedstock (and molecular weight for gaseous feedstocks) for the mass balance methodology beginning in reporting year 2017 (81 FR 89260).[47] The United States is currently unable to report non-energy fuel use from petrochemical production under the IPPU chapter due to CBI issues. Therefore, consistent with *2006 IPCC Guidelines*, fuel consumption data reported by EIA are adjusted to account for these overlaps to avoid double-counting. More information on the non-energy use of fossil fuel feedstocks for petrochemical production can be found in Annex 2.3.

Methodological approaches were applied to the entire time series to ensure consistency in emissions from 1990 through 2022. The methodology for ethylene production, ethylene dichloride production, and ethylene oxide production spliced activity data from two different sources: ACC for 1990 through 2009 and GHGRP for 2010 through 2022. The methodology for methanol production spliced activity data from two different sources: ACC for 1990 through 2014 and GHGRP for 2015 through 2022. Consistent with the *2006 IPCC Guidelines*, the overlap

[47] See https://www.epa.gov/ghgreporting/historical-rulemakings.

technique was applied to compare the two data sets for years where there was overlap. For ethylene production, the data sets were determined to be consistent, and adjustments were not needed. For ethylene dichloride production, ethylene oxide production, and methanol production, the data sets were determined to be inconsistent. The GHGRP data includes production of ethylene dichloride and ethylene oxide as intermediates, while it is unclear if the ACC data does. Methanol production data from GHGRP are significantly higher than the ACC data for every year since 2015; the reason for the difference is not clear. Therefore, no adjustments were made to the ethylene dichloride, ethylene oxide, and methanol activity data for 1990 through 2009 because the *2006 IPCC Guidelines* indicate that it is not good practice to use the overlap technique when the data sets are inconsistent. The methodology for carbon black production also spliced activity data from two different sources: ICBA for 1990 through 2009 and GHGRP for 2010 through 2022. The overlap technique was applied to these data for 2010 and 2011. The data sets were determined to be consistent, and adjustments were not needed.

Uncertainty

The CO_2 and CH_4 emission factors used for acrylonitrile production are based on a limited number of studies. Using plant-specific factors instead of default or average factors could increase the accuracy of the emission estimates; however, such data were not available for the current *Inventory* report. For acrylonitrile, EPA assigned an uncertainty range of ±60 percent for the CO_2 emission factor, ±10 percent for the CH_4 emission factor, and a normal probability density function for both, and using the suggested uncertainty provided in Table 3.27 of the *2006 IPCC Guidelines* is appropriate based on expert judgment, (RTI 2023). The results of the quantitative uncertainty analysis for the CO_2 emissions from carbon black production, ethylene, ethylene dichloride, ethylene oxide, and methanol are based on reported GHGRP data. Refer to the Methodology section for more details on how these emissions were calculated and reported to EPA's GHGRP. EPA assigned an uncertainty range of ±5 percent and a normal probability density function for CO_2 emissions from carbon black, ethylene, ethylene dichloride, and ethylene oxide production, and using the suggested uncertainty provided in Table 3.27 of the *2006 IPCC Guidelines* is appropriate based on expert judgment (RTI 2023). There is some uncertainty in the applicability of the average emission factors for each petrochemical type across all prior years. While petrochemical production processes in the United States have not changed significantly since 1990, some operational efficiencies have been implemented at facilities over the time series.

The results of the Approach 2 quantitative uncertainty analysis are summarized in Table 4-58. Petrochemical production CO_2 emissions from 2022 were estimated to be between 27.6 and 30.0 MMT CO_2 Eq. at the 95 percent confidence level. This indicates a range of approximately 4 percent below to 4 percent above the emission estimate of 28.8 MMT CO_2 Eq. Petrochemical production CH_4 emissions from 2022 were estimated to be between 0.0 and 0.01 MMT CO_2 Eq. at the 95 percent confidence level. This indicates a range of approximately 14 percent below to 14 percent above the emission estimate of 0.005 MMT CO_2 Eq.

Table 4-58: Approach 2 Quantitative Uncertainty Estimates for CH_4 Emissions from Petrochemical Production and CO_2 Emissions from Petrochemical Production (MMT CO_2 Eq. and Percent)

Source	Gas	2022 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Petrochemical Production	CO_2	28.8	27.6	30.0	-4%	+4%
Petrochemical Production	CH_4	+	0.0	0.01	-14%	+14%

+ Does not exceed 0.05 MMT CO_2 Eq.

[a] Range of emission estimates predicted by Monte Carlo stochastic simulation for a 95 percent confidence interval.

QA/QC and Verification

For petrochemical production, QA/QC activities were conducted consistent with the U.S. Inventory QA/QC plan, as described in the QA/QC and Verification Procedures section of the IPPU chapter and Annex 8. Source-specific quality control measures for this category included the QA/QC requirements and verification procedures of EPA's GHGRP. More details on the greenhouse gas calculation, monitoring and QA/QC methods applicable to petrochemical facilities can be found under Subpart X (Petrochemical Production) of the regulation (40 CFR Part 98).[48] EPA verifies annual facility-level GHGRP reports through a multi-step process (e.g., combination of electronic checks and manual reviews) to identify potential errors and ensure that data submitted to EPA are accurate, complete, and consistent (EPA 2015).[49] Based on the results of the verification process, EPA follows up with facilities to resolve mistakes that may have occurred. The post-submittals checks are consistent with a number of general and category-specific QC procedures, including range checks, statistical checks, algorithm checks, and year-to-year checks of reported data and emissions. EPA also conducts QA checks of GHGRP reported production data by petrochemical type against external datasets.

For ethylene, ethylene dichloride and ethylene oxide, it is possible to compare CO_2 emissions calculated using the GHGRP data to the CO_2 emissions that would have been calculated using the Tier 1 approach if GHGRP data were not available. For ethylene, the GHGRP emissions were within ±8 percent of the emissions calculated using the Tier 1 approach prior to 2018; for 2018 through 2022, the GHGRP emissions were between 76 percent and 87 percent of what would be calculated using the Tier 1 approach. For ethylene dichloride, the GHGRP emissions are typically higher than the Tier 1 emissions by up to 25 percent, but in 2010 and 2021, GHGRP emissions were slightly lower than the Tier 1 emissions. For ethylene oxide, GHGRP emissions typically vary from the Tier 1 emissions by up to ±20 percent, but in 2021 and 2022, the GHGRP emissions were significantly higher than the Tier 1 emissions. This was likely due to GHGRP data capturing the production of ethylene oxide as an intermediate in the onsite production of ethylene glycol.

For methanol, GHGRP production data was consistently higher than ACC production data in all years between 2015 and 2022. Even though the GHGRP production was higher than the ACC production, the GHGRP CO_2 emissions estimated using the methodology refinement in this *Inventory* are significantly lower than the emissions calculated using the Tier 1 approach in all years between 2015 and 2022. Additionally, there is a trend towards increasing differences over these years starting with an 873 kt CO_2 difference in 2015 and increasing to a 3,000 kt CO_2 difference in 2022. GHGRP emissions were between 43 percent and 61 percent of the Tier 1 emissions in 2015 and 2018, respectively. As discussed in the Methodology and Time-Series Consistency section above, EPA has determined that using the IPCC Tier 1 emissions factor to calculate methanol emissions results in double counting of natural gas combustion emissions in both this chapter and in the Energy chapter; therefore, use of the GHGRP derived emissions is deemed appropriate. For the years 1990 through 2014, the use of the GHGRP derived emission factor also results in lower emissions than those calculated using the IPCC Tier 1 emission factor. While this avoids the double counting of emissions with the Energy chapter, as described below in the Planned Improvements section, EPA intends to examine the emissions from methanol facilities that report to the GHGRP and may have been operating prior to 2010 to assess whether a more specific process-only emission factor can be developed from the GHGRP data for use in estimating CO_2 emissions from methanol production in 1990 through 2014.

EPA's GHGRP mandates that all petrochemical production facilities report their annual emissions of CO_2, CH_4, and N_2O from each of their petrochemical production processes. Source-specific quality control measures for the Petrochemical Production category included the QA/QC requirements and verification procedures of EPA's GHGRP. The QA/QC requirements differ depending on the calculation methodology used.

[48] See http://www.ecfr.gov/cgi-bin/text-idx?tpl=/ecfrbrowse/Title40/40cfr98_main_02.tpl.

[49] See https://www.epa.gov/sites/production/files/2015-07/documents/ghgrp_verification_factsheet.pdf.

As part of a planned improvement effort, EPA has assessed the potential of using GHGRP data to estimate CH_4 emissions from ethylene production. As discussed in the Methodology section above, CO_2 emissions from ethylene production in this chapter are based on data reported under the GHGRP, and these emissions are calculated using a Tier 2 approach that assumes all of the carbon in the fuel (i.e., ethylene process off-gas) is converted to CO_2. Ethylene production facilities also calculate and report CH_4 emissions under the GHGRP when they use the optional combustion methodology. The facilities calculate CH_4 emissions from each combustion unit that burns off-gas from an ethylene production process unit using a Tier 1 approach based on the total quantity of fuel burned, a default or measured higher heating value, and a default emission factor. Because multiple other types of fuel in addition to the ethylene process unit off-gas may be burned in these combustion units, the facilities also report an estimate of the fraction of emissions that is due to burning the ethylene process off-gas component of the total fuel. Multiplying the total emissions by the estimated fraction provides an estimate of the CH_4 emissions from the ethylene production process unit. These ethylene production facilities also calculate CH_4 emissions from flares that burn process vent emissions from ethylene processes. The CO_2 emissions are calculated using either a Tier 2 approach based on measured gas volumes and measured carbon content or higher heating value, or a Tier 1 approach based on the measured gas flow and a default emission factor; the CH_4 emissions are calculated based on a Tier 1 approach using the CO_2 emissions and default emission factors. Nearly all ethylene production facilities use the optional combustion methodology under the GHGRP. The CH_4 emissions from ethylene production under the GHGRP have not been included in this chapter because this approach double counts carbon (i.e., all of the carbon in the CH_4 emissions is also included in the CO_2 emissions from the ethylene process units). EPA continues to assess the GHGRP data for ways to better disaggregate the data and incorporate it into the *Inventory*.

These facilities are also required to report emissions of N_2O from combustion of ethylene process off-gas in both stationary combustion units and flares. Facilities using CEMS (consistent with a Tier 3 approach) are also required to report emissions of CH_4 and N_2O from combustion of petrochemical process-off gases in flares. Preliminary analysis of the aggregated reported CH_4 and N_2O emissions from facilities using CEMS and N_2O emissions from facilities using the optional combustion methodology suggests that these annual emissions are less than 0.4 percent of total petrochemical emissions, which is not significant enough to prioritize for inclusion in the report at this time. Pending resources and significance, EPA may include these N_2O emissions in future reports to enhance completeness. Future QC efforts to validate the use of Tier 1 default emission factors and report on the comparison of Tier 1 emission estimates and GHGRP data are described below in the Planned Improvements section.

Recalculations Discussion

A methodology refinement for calculating emissions from methanol production was implemented in this *Inventory*. As discussed in the Methodology and Time-Series Consistency section, the previously used Tier 1 approach was replaced with a country-specific approach similar to a Tier 2 method based on emissions aggregated directly from EPA's GHGRP data for 2015 through 2022 (EPA 2023) and an average country-specific CO_2 emission factor from the GHGRP data applied to production data from ACC's *Business of Chemistry* for 1990 through 2014 (ACC 2023). For 2015 through 2021, these changes resulted in a reduction in the reported CO_2 emissions between 43 percent (873 kt) in 2015 to 61 percent (2,110 kt) in 2018. For 1990 through 2014, the refinement resulted in a reduction of 61 percent each year (287 kt in 2011 to 2,449 kt in 1997).

Additionally, CH_4 emissions previously reported from methanol production were reduced to zero for all years of the time series because, as noted above in the Methodology and Time Series Consistency section, the methodology refinement is based on the assumption that all carbon input to the process is converted either to primary and secondary products or to CO_2.

Planned Improvements

Improvements include completing category-specific QC of activity data and emission factors, along with further assessment of CH_4 and N_2O emissions to enhance completeness in reporting of emissions from U.S. petrochemical

production, pending resources, significance and time-series consistency considerations. For example, EPA is planning additional assessment of fuel combustion emissions data reported by methanol production facilities for ways to estimate process-based emissions in the *Inventory* separately from combustion emissions for 1990 through 2014. If the GHGRP data can be categorized by type of methanol process design, it may be possible to use GHGRP data for single reformer process units to develop a ratio of process-to-total emissions to adjust the IPCC emission factor. Potential difficulties with this analysis are that some of the methanol producing facilities also produce other chemicals and the combustion unit names may not clearly identify the process unit to which they apply, and some combustion unit data may be aggregated for multiple combustion units. The EPA is also planning additional assessment of ways to use CH_4 data from the GHGRP in the *Inventory*. One possible approach EPA is assessing would be to adjust the CO_2 emissions from the GHGRP downward by subtracting the carbon that is also included in the reported CH_4 emissions, per the discussion in the Petrochemical Production QA/QC and Verification section, above. As of this current report, timing and resources have not allowed EPA to complete these analyses of activity data, emissions, and emission factors but they remain priority improvements within the IPPU chapter.

Pending resources, a secondary potential improvement for this source category would focus on continuing to analyze the fuel and feedstock data from EPA's GHGRP to better disaggregate energy-related emissions and allocate them more accurately between the Energy and IPPU sectors of the *Inventory*. EPA will continue to look for ways to incorporate this data into future Inventories that will allow for easier data integration between the non-energy uses of fuels category and the petrochemicals category presented in this chapter. This planned improvement is still under development and has not been completed to report on progress in this current *Inventory*.

4.14 HCFC-22 Production (CRT Source Category 2B9a)

This reporting category (2B9a) includes by-product emissions of HCFC-23 (trifluoromethane or CHF_3) from production of HCFC-22 (chlorodifluoromethane). HFC-23 is generated as a byproduct during the manufacture of HCFC-22, which is primarily employed in refrigeration and air conditioning systems and as a chemical feedstock for manufacturing synthetic polymers. Between 1990 and 2000, U.S. production of HCFC-22 increased significantly as HCFC-22 replaced chlorofluorocarbons (CFCs) in many applications. Between 2000 and 2007, U.S. production fluctuated but generally remained above 1990 levels. In 2008 and 2009, U.S. production declined markedly and has remained near 2009 levels since. Because HCFC-22 depletes stratospheric ozone, its production for non-feedstock uses was phased out in 2020 under the U.S. Clean Air Act.[50] Feedstock production, however, is permitted to continue indefinitely. Per the IPCC methodological guidance, emissions from energy use are currently accounted for as part of fossil fuel combustion in the industrial end-use sector reported under the Energy chapter.

HCFC-22 is produced by the reaction of chloroform ($CHCl_3$) and hydrogen fluoride (HF) in the presence of a catalyst, $SbCl_5$. The reaction of the catalyst and HF produces $SbCl_xF_y$, (where x + y = 5), which reacts with chlorinated hydrocarbons to replace chlorine atoms with fluorine. The HF and chloroform are introduced by submerged piping into a continuous-flow reactor that contains the catalyst in a hydrocarbon mixture of chloroform and partially fluorinated intermediates. The vapors leaving the reactor contain HCFC-21 ($CHCl_2F$), HCFC-22 ($CHClF_2$), HFC-23 (CHF_3), HCl, chloroform, and HF. The under-fluorinated intermediates (HCFC-21) and chloroform are then condensed and returned to the reactor, along with residual catalyst, to undergo further fluorination. The final vapors leaving the condenser are primarily HCFC-22, HFC-23, HCl and residual HF. The HCl is recovered as a useful

[50] As construed, interpreted, and applied in the terms and conditions of the *Montreal Protocol on Substances that Deplete the Ozone Layer* [42 U.S.C. §7671m(b), CAA §614].

byproduct, and the HF is removed. Once separated from HCFC-22, the HFC-23 may be released to the atmosphere, recaptured for use in a limited number of applications, or destroyed.

Two facilities produced HCFC-22 in the United States in 2022. Emissions of HFC-23 from this activity in 2022 were estimated to be 1.8 MMT CO_2 Eq. (0.1 kt) (see Table 4-59 and Table 4-60). This quantity represents an 18 percent increase from 2021 emissions and a 95 percent decrease from 1990 emissions. The decrease from 1990 emissions was caused primarily by changes in the HFC-23 emission rate (kg HFC-23 emitted/kg HCFC-22 produced). The decrease from 2021 emissions was caused by both a decrease in the HFC-23 emission rate at one plant and a decrease in the total quantity of HCFC-22 produced. The long-term decrease in the emission rate is primarily attributable to six factors: (a) five plants that did not capture and destroy the HFC-23 generated have ceased production of HCFC-22 since 1990; (b) one plant that captures and destroys the HFC-23 generated began to produce HCFC-22; (c) one plant implemented and documented a process change that reduced the amount of HFC-23 generated; (d) the same plant began recovering HFC-23, primarily for destruction and secondarily for sale; (e) another plant began destroying HFC-23; and (f) the same plant, whose emission rate was higher than that of the other two plants, ceased production of HCFC-22 in 2013.

Emissions from HCFC-22 production are reported under fluorochemical production (CRT category 2B9) in this *Inventory*, which also includes the production of fluorochemicals other than HCFC-22 described further in section 4.15 of this chapter.

Table 4-59: HFC-23 Emissions from HCFC-22 Production (MMT CO_2 Eq.)

Year	1990	2005	2018	2019	2020	2021	2022
HCFC-22 Production	38.6	16.8	2.7	3.1	1.8	2.2	1.8

Table 4-60: HFC-23 Emissions from HCFC-22 Production (kt HFC-23)

Year	1990	2005	2018	2019	2020	2021	2022
HCFC-22 Production	3	1	+	+	+	+	+

+ Does not exceed 0.5 kt.

Methodology and Time-Series Consistency

To estimate HFC-23 emissions for five of the eight HCFC-22 plants that have operated in the United States since 1990, methods comparable to the Tier 3 methods in the *2006 IPCC Guidelines* (IPCC 2006) were used throughout the time series. Emissions for 2010 through 2022 were obtained through reports submitted by U.S. HCFC-22 production facilities to EPA's Greenhouse Gas Reporting Program (GHGRP). EPA's GHGRP mandates that all HCFC-22 production facilities report their annual emissions of HFC-23 from HCFC-22 production processes and HFC-23 destruction processes. Previously, data were obtained by EPA through collaboration with an industry association that received voluntarily reported HCFC-22 production and HFC-23 emissions annually from all U.S. HCFC-22 producers from 1990 through 2009. These emissions were aggregated and reported to EPA on an annual basis.

For the other three plants, the last of which closed in 1993, methods comparable to the Tier 1 method in the *2006 IPCC Guidelines* were used. Emissions from these three plants have been calculated using the recommended emission factor for unoptimized plants operating before 1995 (0.04 kg HCFC-23/kg HCFC-22 produced).

The five plants that have operated since 1994 measure (or, for the plants that have since closed, measured) concentrations of HFC-23 as well as mass flow rates of process streams to estimate their generation of HFC-23. Plants using thermal oxidation to abate their HFC-23 emissions monitor the performance of their oxidizers to verify that the HFC-23 is almost completely destroyed. One plant that releases a small fraction of its byproduct HFC-23 periodically measures HFC-23 concentrations at process vents using gas chromatography. This information is combined with information on quantities of products (e.g., HCFC-22) to estimate HFC-23 emissions.

To estimate 1990 through 2009 emissions, reports from an industry association were used that aggregated HCFC-22 production and HFC-23 emissions from all U.S. HCFC-22 producers and reported them to EPA (ARAP 1997, 1999, 2000, 2001, 2002, 2003, 2004, 2005, 2006, 2007, 2008, 2009, and 2010). To estimate 2010 through 2022 emissions, facility-level data (including both HCFC-22 production and HFC-23 emissions) reported through EPA's GHGRP were analyzed. In 1997 and 2008, comprehensive reviews of plant-level estimates of HFC-23 emissions and HCFC-22 production were performed (RTI 1997; RTI 2008). The 1997 and 2008 reviews enabled U.S. totals to be reviewed, updated, and where necessary, corrected. The reviews also allowed plant-level uncertainty analyses (Monte-Carlo simulations) to be performed for 1990, 1995, 2000, 2005, and 2006. Estimates of annual U.S. HCFC-22 production are presented in Table 4-61.

Table 4-61: HCFC-22 Production (kt)

Year	1990	2005	2012	2018	2019	2020	2021	2022
Production	139	156	96	C	C	C	C	C

C (CBI)

Note: HCFC-22 production in 2013 through 2022 is considered confidential business information (CBI) as there were only two producers of HCFC-22 in those years.

Uncertainty

The uncertainty analysis presented in this section was based on a plant-level Monte Carlo stochastic simulation for 2006. The Monte Carlo analysis used estimates of the uncertainties in the individual variables in each plant's estimating procedure. This analysis was based on the generation of 10,000 random samples of model inputs from the probability density functions for each input. A normal probability density function was assumed for all measurements and biases except the equipment leak estimates for one plant; a log-normal probability density function was used for this plant's equipment leak estimates. The simulation for 2006 yielded a 95-percent confidence interval for U.S. emissions of 6.8 percent below to 9.6 percent above the reported total.

The relative errors yielded by the Monte Carlo stochastic simulation for 2006 were applied to the U.S. emission estimate for 2022. The resulting estimates of absolute uncertainty are likely to be reasonably accurate because (1) the methods used by the two remaining plants to estimate their emissions are not believed to have changed significantly since 2006, and (2) although the distribution of emissions among the plants has changed between 2006 and 2022 (because one plant has closed), the plant that currently accounts for most emissions had a relative uncertainty in its 2006 (as well as 2005) emissions estimate that was similar to the relative uncertainty for total U.S. emissions. Thus, the closure of one plant is not likely to have a large impact on the uncertainty of the national emission estimate.

The results of the Approach 2 quantitative uncertainty analysis are summarized in Table 4-62. HFC-23 emissions from HCFC-22 production were estimated to be between 1.7 and 2.0 MMT CO_2 Eq. at the 95 percent confidence level. This indicates a range of approximately 7 percent below and 10 percent above the emission estimate of 1.8 MMT CO_2 Eq.

Table 4-62: Approach 2 Quantitative Uncertainty Estimates for HFC-23 Emissions from HCFC-22 Production (MMT CO_2 Eq. and Percent)

Source	Gas	2022 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
HCFC-22 Production	HFC-23	1.8	1.7	2.0	-7%	+10%

[a] Range of emissions reflects a 95 percent confidence interval.

QA/QC and Verification

General quality assurance/quality control (QA/QC) procedures were applied consistent with the U.S. Inventory QA/QC plan, which is in accordance with Volume 1, Chapter 6 of *2006 IPCC Guidelines* as described in the introduction of the IPPU chapter (see Annex 8 for more details). Under the GHGRP, EPA verifies annual facility-level reports through a multi-step process (e.g., including a combination of pre-and post-submittal electronic checks and manual reviews by staff) to identify potential errors and ensure that data submitted to EPA are accurate, complete, and consistent (EPA 2015).[51] Based on the results of the verification process, EPA follows up with facilities to resolve mistakes that may have occurred. The post-submittals checks are consistent with a number of general and category-specific QC procedures, including: range checks, statistical checks, algorithm checks, and year-to-year checks of reported data and emissions.

The GHGRP also requires source-specific quality control measures for the HCFC-22 Production category. Under EPA's GHGRP, HCFC-22 producers are required to (1) measure concentrations of HFC-23 and HCFC-22 in the product stream at least weekly using equipment and methods (e.g., gas chromatography) with an accuracy and precision of 5 percent or better at the concentrations of the process samples, (2) measure mass flows of HFC-23 and HCFC-22 at least weekly using measurement devices (e.g., flowmeters) with an accuracy and precision of 1 percent of full scale or better, (3) calibrate mass measurement devices at the frequency recommended by the manufacturer using traceable standards and suitable methods published by a consensus standards organization, (4) calibrate gas chromatographs at least monthly through analysis of certified standards, and (5) document these calibrations.

Recalculations Discussion

The 2019 emissions estimate increased by 0.05 kg of HFC-23 to reflect newly reported emissions from a facility that destroys HFC-23. This increased the 2019 emissions estimate by two ten thousandths of a percent.

Planned Improvements

At this time, there are no specific planned improvements for estimating HFC-23 emissions from HCFC-22 production.

4.15 Production of Fluorochemicals Other Than HCFC-22 (CRT Source Category 2B9b)

This reporting category, fluorochemical production (2B9b), facilities in the United States produced or transformed approximately 200 fluorinated gases other than HCFC-22 in 2022, including saturated and unsaturated hydrofluorocarbons (HFCs), saturated and unsaturated perfluorocarbons (PFCs), sulfur hexafluoride (SF_6), nitrogen trifluoride (NF_3), hydrofluoroethers (HFEs), perfluoroalkylamines, and dozens of others. Emissions from fluorochemical production may include emissions of the intentionally manufactured chemical as well as reactant and by-product emissions. The compounds emitted depend upon the production or transformation process, but may include, e.g., HFCs, PFCs, SF_6, nitrous oxide (N_2O), NF_3, and many others. Potential sources of fluorinated GHG emissions at fluorochemical production facilities include process vents, equipment leaks, and evacuating returned

[51] EPA (2015). Greenhouse Gas Reporting Program Report Verification. Available online at: https://www.epa.gov/sites/production/files/2015-07/documents/ghgrp_verification_factsheet.pdf.

containers[52] Production-related emissions of fluorinated GHGs occur from both process vents and equipment leaks. Process vent emissions occur from manufacturing equipment such as reactors, distillation columns, and packaging equipment. Equipment leak emissions, or fugitive emissions, occur from valves, flanges, pump seals, compressor seals, pressure relief valves, connectors, open-ended lines, and sampling connections. In addition, users of fluorinated GHGs may return empty containers (e.g., cylinders) to the production facility for reuse; prior to reuse, the residual fluorinated GHGs (often termed "heels") may be evacuated from the container and are a potential emission source. In many cases, these "heels" are recovered or exhausted to a treatment device for destruction. In other cases, however, they are released into the atmosphere.[53]

Emissions of all HFCs, PFCs, NF_3, and SF_6 from production of fluorochemicals other than hydrochlorofluorocarbon (HCFC)-22 are presented in Table 4-63 below for the years 1990, 2005, and the period 2018 to 2022. Per the IPCC methodological guidance, emissions from energy use are currently accounted for as part of fossil fuel combustion in the industrial end-use sector reported under the Energy chapter.

The fluorinated GHG emissions reported under the Greenhouse Gas Reporting Program (GHGRP) include emissions of HFCs, PFCs, SF_6, NF_3, and numerous "other" fluorinated GHGs, such as octafluorotetrahydrofuran (C_4F_8O), trifluoromethyl sulfur pentafluoride (SF_5CF_3), and hexafluoropropylene oxide. Because they are not included among the seven UNFCCC-reportable gases or gas groups, the "other" fluorinated GHGs are not included in *Inventory* totals. However, their emissions are presented below because they often have high GWPs and large GWP-weighted emissions.

Total emissions of HFCs, PFCs, SF_6, and NF_3 from fluorochemical production are estimated to have increased from 32 MMT CO_2 Eq. (3,400 MT) in 1990 to a peak of 45 MMT CO_2 Eq. (5,700 MT) in 1999, declining to 3.9 MMT CO_2 Eq. (860 MT) in 2016[54] and rising again to 6.0 MMT CO_2 Eq. (1,200 MT) in 2022. These trends reflect estimated changes in fluorinated gas production and increasing use of control devices. Prior to 2000, only 2 facilities are known to have operated control devices to destroy fluorinated GHG emissions. After 2000, additional production facilities began to install and use control devices to destroy fluorinated GHG emissions,[55] and fluorinated GHG emissions declined sharply from 45 MMT CO_2 Eq. (5,700 MT) in 1999 to 13 MMT CO_2 Eq. (2,300 MT) in 2005. Emissions continued to fall more slowly through 2016, reflecting the installation of controls at an additional 4 facilities in 2011, 2012, 2015, and 2016. Total fluorinated GHG emissions rose from 2017 to 2022 as production increased at some facilities.

Emissions from the production of fluorochemicals other than HCFC-22 are reported under fluorochemical production (CRT category 2B9) in conjunction with emissions from HCFC-22 production described in Section 4.14 of this chapter.

HFC Emissions

Estimated emissions of HFCs increased from 8.7 MMT CO_2 Eq. in 1990 to a peak of 14 MMT CO_2 Eq. in 1999 (1,200 to 2,600 MT), declining with some fluctuation to 2.5 MMT CO_2 Eq. in 2022. Emissions in 1990 were primarily from facilities producing compounds other than saturated HFCs. The subsequent trends in emissions were driven by the growth in production of saturated HFCs and the imposition of controls. Production of saturated HFCs is estimated to have increased from around 0.3 MMT CO_2 Eq. (2,000 MT) in 1990 to over 300 MMT CO_2 Eq. (100,000 MT) by

[52] The totals presented below also include emissions from destruction of previously produced fluorinated GHGs that are shipped to production facilities for destruction, e.g., because they are found to be irretrievably contaminated.

[53] IPCC (2019) *2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories*, Calvo Buendia, E., Tanabe, K., Kranjc, A., Baasansuren, J., Fukuda, M., Ngarize S., Osako, A., Pyrozhenko, Y., Shermanau, P. and Federici, S. (eds). Published: IPCC, Switzerland.

[54] Emissions in MMT CO_2 Eq. were similar in 2017, but the 2017 emissions in MT were considerably higher (4,500 MT) due to anomalously high emissions of one low-GWP, unsaturated HFC at one facility.

[55] One facility is assumed to have installed controls in 2000, another installed controls in 2003, and three facilities are assumed to have installed controls in 2005.

2010 as HFCs replaced ozone-depleting substances, which were being phased out under the Montreal Protocol and Clean Air Act (EPA 2023a; EPA 2023b). This increase in HFC production drove HFC emissions to their 1999 peak. However, estimated emissions declined significantly from 1999 to 2005 due to the assumed addition of controls in 2000 and subsequent years. Estimated emissions of HFCs resumed their increase from 2005 to 2010, reaching 7.2 MMT CO_2 Eq. (2,300 MT), but again declined sharply in 2011 to 4.6 MMT CO_2 Eq. (1,200 MT) based on addition of controls. Since 2012, HFC emissions have continued to trend downward with some fluctuations, hitting a minimum of 1.7 MMT CO_2 Eq. in 2021. With the phase-out of production of saturated HFCs (Kigali Amendment, and U.S. AIM program), the downward trend of HFC emissions is expected to continue, but the share of HFC emissions that are not associated with saturated HFC production (approximately 0.7 MMT CO_2 Eq. in 2022) is likely to persist in the absence of additional controls.

PFC Emissions

Emissions of PFCs increased gradually from 18 MMT CO_2 Eq. (2,000 MT) in 1990 to 24 MMT CO_2 Eq. (2,800 MT) in 1999 but dropped to 4.0 MMT CO_2 Eq. (490 MT) by 2005, reflecting the addition of controls at high-emitting facilities and apparent changes to the mix of products produced at another facility.[56] Overall PFC emissions from 2005 to 2022 have remained relatively steady, oscillating around 2.5 MMT CO_2 Eq. The upward trend between 1990 and 1999 was largely driven by the three facilities that reported their historical emissions to the EPA. In the absence of historical emissions data for other facilities, the quantities of fluorinated GHGs produced or transformed at other facilities emitting PFCs are estimated to have remained generally steady between 1990 and 2009 and therefore do not contribute to the emissions trend before 2010. For most of the fluorinated GHGs produced at these facilities, there was no available industry information to inform activity estimates or trends for 1990 to 2009. Therefore, as discussed in the Methodology section below, 2010 production values from EPA's GHGRP were assumed to have held constant for these compounds from 1990 to 2010.

SF_6 Emissions

Emissions of SF_6 are estimated to have risen gradually from 5.8 MMT CO_2 Eq. (250 MT) in 1990 to a peak of 7.5 MMT CO_2 Eq. (320 MT) in 1995, to have declined slowly to 7.0 MMT CO_2 Eq. in 2000, and then to have declined more rapidly to a minimum of 0.0004 MMT CO_2 Eq. (0.01 MT) in 2017, after which emissions rose and fluctuated between 0.056 MMT CO_2 Eq. (in 2020) and 0.0024 MMT CO_2 Eq. (in 2022). The rapid emissions decline after 2000 was driven first by the imposition of controls at one facility and then by the cessation of production in 2010 at a major U.S. SF_6-producing facility.

NF_3 Emissions

Since 1990, estimated emissions of NF_3 have fluctuated between 0.11 MMT CO_2 Eq. and 0.72 MMT CO_2 Eq., with peaks occurring in 2000 (0.71 MMT CO_2 Eq.), 2010 (0.70 MMT CO_2 Eq.), and 2020 (0.72 MMT CO_2 Eq.), and lows occurring in 1990 (0.29 MMT CO_2 Eq.), 2003 (0.33 MMT CO_2 Eq.), and 2018 (0.11 MMT CO_2 Eq.). NF_3 may be emitted both from the production of NF_3 and from the production of other fluorochemicals. The dominant source since 2010 has been production of NF_3. Trends after 2010 were driven by changes both in NF_3 production and in

[56] In a summary of 1990 through 2010 emissions submitted to EPA (described more below), 3M, which owns several facilities that historically emitted PFCs, noted that the mix of products produced at its various facilities had changed over time, leading to changes in the magnitude and contents of emissions. This change in magnitude and contents was particularly pronounced at 3M's Decatur facility (referred to elsewhere in this document as "3M Company"), where emissions declined from 15.8 MMT CO_2 Eq. in 2000 to 0.53 MMT CO_2 Eq. in 2002, and where the contents of emissions changed from HFCs, PFCs, SF_6 and other fluorinated GHGs in 2000 to PFCs and other fluorinated GHGs in 2003. (Emissions in 2002 were not differentiated by group). Emissions were also reduced after the installation of a control device at the Cordova facility. 3M noted that Initial start-up of the thermal oxidizer occurred in 2003, but that it took time to optimize the operation of the thermal oxidizer and treatment of the various gas streams, leading to a decrease in emissions over several years.

the emission rate (kg NF_3 emitted/kg NF_3 produced) for NF_3 production, with both contributing to increased emissions since 2018. For 1990 through 2009, the NF_3 that is emitted from the production of NF_3 is assumed to be influenced by the trajectory of NF_3 production, which is generally assumed to follow production trends in the semiconductor industry except where NF_3 facility capacity limits production further. Semiconductor production increased steadily from 1995 to 2007 but is estimated to have declined from 2007 through 2010. As described in the Methodology section under "Estimated Emissions for 3M facilities," the NF_3 that is emitted from production of other fluorochemicals is assumed to have been emitted as a constant fraction of the "other" fluorinated GHGs whose 1990 through 2010 emissions were reported by 3M facilities. This fraction was estimated based on the fraction of "other" fluorinated GHG emissions accounted for by NF_3 between 2011 and 2015 and is highly uncertain. Nevertheless, because the highest-emitting 3M facilities reported decreasing emissions of all other fluorinated GHG groups between 2000 and 2005 (due to the installation of a control device at one facility and apparent production changes at another), NF_3 emissions also appear likely to have decreased during this period.

Other Fluorinated GHG Emissions

Other fluorinated GHGs, i.e., those not included in the UNFCCC-reportable gases or gas groups, are also emitted in significant quantities from fluorinated gas production and transformation processes. Estimated emissions of these other fluorinated GHGs are provided in Table 4-64 for the years 1990, 2005, and the period 2018 to 2022. The other fluorinated GHGs with the highest estimated emissions in 2022 are presented separately, and the remaining other fluorinated GHGs are aggregated.

Total emissions of other fluorinated GHGs increased from 4.7 MMT CO_2 Eq. (450 MT) in 1990 to a peak of 10.1 MMT CO_2 (870 MT) in 2000, declining rapidly to 0.90 MMT CO_2 Eq. in 2009 and then declining more slowly to 0.13 MMT CO_2 Eq. (40 MT) in 2021 and 2022. Between 1990 and 2009, estimated emissions of other fluorinated GHGs were primarily driven by the emissions reported by 3M facilities, which showed significant declines between 2000 and 2005, reflecting apparent production changes at one facility and the installation of a control device at another. The decline in emissions from 2019 to 2020 was due to a decrease in the emission rate at one facility.

Table 4-63: Emissions of HFCs, PFCs, SF_6, and NF_3 from Production of Fluorochemicals Other Than HCFC-22 (MMT CO_2 Eq.)

Gas	1990	2005	2018	2019	2020	2021	2022
HFC-23	6.7	1.7	1.3	1.1	0.9	0.7	1.0
HFC-125	0.1	1.9	0.4	0.4	0.4	0.4	0.3
HFC-143a	0.1	0.8	0.7	0.6	0.3	0.2	0.3
HFC-134a	+	0.4	0.3	0.3	0.2	0.2	0.3
1H,4H-Perfluorobutane	0.0	0.0	0.0	+	+	+	0.2
1H,6H-Perfluorohexane	0.0	0.0	0.0	+	+	+	0.2
Other HFCs	1.6	0.5	0.2	0.2	0.2	0.2	0.3
Perfluorocyclobutane	11.2	0.7	1.3	1.4	1.1	1.3	1.3
PFC-14 (Perfluoromethane)	2.4	1.4	1.0	0.9	0.9	0.9	1.0
Other PFCs	3.9	1.9	0.7	0.7	0.4	0.4	0.6
Nitrogen trifluoride	0.3	0.6	0.1	0.6	0.7	0.5	0.5
Sulfur hexafluoride	5.8	3.3	+	+	+	+	+
Total	**32.3**	**13.2**	**5.9**	**6.2**	**5.2**	**4.9**	**5.9**

+ Does not exceed 0.05 MMT CO_2 Eq.

Note: Table does not sum due to independent rounding.

Table 4-64: Emissions of HFCs, PFCs, SF_6, and NF_3 from Production of Fluorochemicals Other Than HCFC-22 (Metric Tons)

Gas	1990	2005	2018	2019	2020	2021	2022
HFC-23	540	140	100	89	71	56	77
HFC-125	43	600	130	130	120	110	105
HFC-143a	30	160	160	120	63	49	57
HFC-134a	37	340	200	220	180	180	190
1H,4H-Perfluorobutane	0	0	0	1.2	0.60	1.2	53
1H,6H-Perfluorohexane	0	0	0	0.92	0.47	0.90	41
Other HFCs	500	400	270	260	230	250	270
Perfluorocyclobutane	1,200	70	130	150	120	130	140
PFC-14 (Perfluoromethane)	360	210	150	130	140	140	160
Other PFCs	420	210	71	77	41	49	59
Nitrogen trifluoride	18	37	6.7	35	45	31	31
Sulfur hexafluoride	250	140	0.15	0.17	0.24	0.21	0.10
Total HFCs, PFCs, SF_6, and NF_3	**3,400**	**2,300**	**1,200**	**1,200**	**1,000**	**1,000**	**1,200**

+ Does not exceed 0.5 MT.

Note: Table does not sum due to independent rounding.

Table 4-65: Emissions of Other Fluorinated GHGs from Production of Fluorochemicals Other Than HCFC-22 (MMT CO_2 Eq.)

Gas	1990	2005	2018	2019	2020	2021	2022
Octafluorotetrahydrofuran	2.4	1.9	+	0.1	+	+	+
1,1,1,2,2,3,3-Heptafluoro-3-(1,2,2,2-tetrafluoroethoxy)-propane	+	+	+	+	+	+	+
Trifluoromethyl sulphur pentafluoride	1.2	0.9	+	0.1	+	+	+
Hexafluoropropylene oxide	0.3	0.3	0.3	0.3	+	+	+
FC-3283/FC-8270 (Perfluorotripropylamine)	+	+	+	+	+	+	+
Others	0.8	0.5	0.1	0.1	0.1	+	+
Total Other Fluorinated GHGs	**4.7**	**3.7**	**0.6**	**0.6**	**0.1**	**0.1**	**0.1**

+ Does not exceed 0.5 MT.

Note: Table does not sum due to independent rounding.

Table 4-66: Emissions of Other Fluorinated GHGs from Production of Fluorochemicals Other Than HCFC-22 (Metric Tons)

Gas	1990	2005	2018	2019	2020	2021	2022
Octafluorotetrahydrofuran	170	140	4	4	2	1	2
1,1,1,2,2,3,3-Heptafluoro-3-(1,2,2,2-tetrafluoroethoxy)-propane	6	4	5	6	3	6	3
Trifluoromethyl sulphur pentafluoride	66	53	3	4	1	1	1
Hexafluoropropylene oxide	34	34	32	32	2	2	2

FC-3283/FC-8270 (Perfluorotripropylamine)	+	+	+	+	1	1	1
Others	170	120	76	84	35	33	35
Total Other Fluorinated GHGs	450	350	120	130	43	43	45

+ Does not exceed 0.5 MT.

Note: Table does not sum due to independent rounding.

Table 4-67: Production and Transformation of Fluorinated GHGs (kt)[a]

Set of Facilities	1990	2005	2018	2019	2020	2021	2022
Facilities reporting their F-GHG emissions, production, and transformation to GHGRP after 2010[b]	86	271	376	371	352	348	370
Facilities reporting only their F-GHG production and transformation to GHGRP after 2010	3.3	3.3	11.2	9.7	8.2	7.5	11.2
Total Production and Transformation	89	274	387	381	360	356	381

[a] Totals are presented across species to protect confidential business information.

[b] Includes 1 facility that reported production, but not emissions, of SF_6 through 2010.

Note: Tables may not sum due to independent rounding.

Methodology

The *2006 IPCC Guidelines* as elaborated by the 2019 Refinement include Tier 1, Tier 2, and Tier 3 methods for estimating fluorinated GHG emissions from production of fluorinated compounds. The Tier 1 method calculates emissions by multiplying a default emission factor by total production. Specific default emission factors exist for production of SF_6 and NF_3; a more general default emission factor covers production of all other fluorinated GHGs. (The more general default emission factor was developed based on data from U.S. facilities collected under the GHGRP between 2011 and 2016.) The Tier 2 method calculates emissions using a mass-balance approach. The Tier 3 method is based on the collection of plant-specific data on the types and quantities of fluorinated GHGs emitted from process vents, leaks, container venting, and other sources, considering any abatement technology. The Tier 3 method is often implemented by developing and applying facility-specific emission factors indexed to production.

Based on available data on emissions and activity, EPA used a form of the IPCC Tier 3 method to estimate fluorinated GHG emissions from most U.S. production of fluorinated compounds. Emissions from U.S. production for which there are fewer data are based on the Tier 1 method.

Overview of GHGRP Data for this Source Category

As discussed further below, much of the data used to develop the estimates presented here come from the GHGRP. The data were collected under two sections of the GHGRP regulation—Subpart L, Fluorinated Gas Production; and Subpart OO, Suppliers of Industrial Greenhouse Gases. Under Subpart L, certain fluorinated gas production facilities must report their emissions from a range of processes and sources, detailed further below. Data collected under Subpart L include emissions data for calendar years 2011 through 2022. Under Subpart OO, fluorinated GHG suppliers (including fluorinated GHG producers) must report the quantities of each fluorinated GHG that they produce, transform, destroy, import, or export. Data collected under Subpart OO include production and transformation data for calendar years 2010 through 2022. Facilities' production and transformation data are not shown here because they are considered confidential business information under the GHGRP.

Emissions Reported Under Subpart L of the GHGRP

Under Subpart L, facilities that produce a fluorinated gas must report their greenhouse gas emissions if the facility emits 25,000 MT CO_2 Eq. or more per year in combined emissions from fluorinated gas production, stationary fuel combustion units, miscellaneous uses of carbonate, and all other applicable source categories listed in the rule. (For purposes of calculating emissions from fluorinated gas production for inclusion in the total that is compared to the threshold, emissions are assumed to be uncontrolled.) Facilities must report their fluorinated GHG emissions from the production and transformation of fluorinated gases, from venting of residual fluorinated GHGs from containers, and from destruction of previously produced fluorinated GHGs. The emissions reported from production and transformation include both emissions from process vents and emissions from equipment leaks.

Under the GHGRP, "fluorinated GHGs," whose emissions must be reported, include SF_6, NF_3, and any fluorocarbon except for substances with vapor pressures below 1 Torr at 25 degrees C and substances that are regulated as "controlled substances" under EPA's ozone-protection regulations at 40 CFR Part 82, Subpart A (e.g., chlorofluorocarbons [CFCs], hydrochlorofluorocarbons [HCFCs], and halons). In addition to SF_6 and NF_3, this definition includes hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), hydrofluoroethers (HFEs), fully fluorinated tertiary amines, perfluoropolyethers (including PFPMIE), and hydrofluoropolyethers, and others. "Fluorinated gases," from whose production or transformation emissions must be reported, include the fluorinated GHGs detailed above as well as CFCs and HCFCs.[57]

Facilities calculate emissions from process vents using one of two methods. For vents that emit 10,000 MT CO_2 Eq. or more (considering controls) of fluorinated GHGs from continuous processes, facilities must use emissions testing to establish an emission factor at least every ten years, or sooner if the process changes in a way that will significantly affect emissions from the vent. For other process vents, facilities may use measurements, engineering calculations, or engineering assessments to establish the emission factor. Facilities then calculate their annual emissions based on the measured or calculated emission factor and related activity data, considering the extent to which the process is controlled and any destruction device or process malfunctions.

To calculate emissions from equipment leaks, facilities that report under Subpart L are required to collect information on the number and type of pieces of equipment; service of each piece of equipment; concentration of each fluorinated GHG in the stream; and the time period each piece of equipment was in service. Facilities use one or more of the following methods to calculate emissions from equipment leaks (EPA 1995):

- Average Emission Factor Approach in EPA Protocol for Equipment Leak Estimates.
- Other Approaches in EPA Protocol for Equipment Leak Estimates in conjunction with EPA Method 21.
- Other Approaches in EPA Protocol for Equipment Leak Estimates in conjunction with site-specific leak detection methods.
- Site-specific leak detection methods.

Most emissions are reported by chemical; the exceptions are (1) fluorinated GHGs that are emitted in quantities of 1,000 MT CO_2 Eq. or less across all production and transformation processes at a facility and (2) fluorinated GHGs that are emitted from facilities that produce only one fluorinated GHG, where the emitted fluorinated GHG is not the fluorinated gas produced. In these cases, the emissions are reported in CO_2 Eq. by fluorinated GHG group. There are 12 fluorinated GHG groups, each of which encompasses a set of GHGs with roughly similar atmospheric behavior, including similar GWPs and atmospheric lifetimes. These include, e.g., fully fluorinated GHGs such as PFCs and SF_6, saturated HFCs with two or fewer hydrogen-carbon bonds, saturated HFCs with more than two carbon-hydrogen bonds, unsaturated HFCs and PFCs, and others (see Table 4-68 for a full list).

[57] HCFC-22 is considered a fluorinated gas under the GHGRP, but emissions from HCFC-22 production are reported separately from emissions from production of other fluorinated gases.

Table 4-68: Fluorinated GHG Groups Under Which Certain Emissions Are Reported Under Subpart L of the GHGRP and Associated GWPs

Fluorinated GHG Group	GHGRP Default Global Warming Potential (100-yr.)
Fully fluorinated GHGs	10,000
Saturated hydrofluorocarbons (HFCs) with 2 or fewer carbon-hydrogen bonds	3,700
Saturated HFCs with 3 or more carbon-hydrogen bonds	930
Saturated hydrofluoroethers (HFEs) and hydrochlorofluoroethers (HCFEs) with 1 carbon-hydrogen bond	5,700
Saturated HFEs and HCFEs with 2 carbon-hydrogen bonds	2,600
Saturated HFEs and HCFEs with 3 or more carbon-hydrogen bonds	270
Fluorinated formates	350
Fluorinated acetates, carbonofluoridates, and fluorinated alcohols other than fluorotelomer alcohols	30
Unsaturated PFCs, unsaturated HFCs, unsaturated HCFCs, unsaturated halogenated ethers, unsaturated halogenated esters, fluorinated aldehydes, and fluorinated ketones	1
Fluorotelomer alcohols	1
Fluorinated GHGs with carbon-iodine bond(s)	1
Other fluorinated GHGs	2,000

Two other datasets reported under Subpart L are relevant to estimating uncontrolled emission factors. (As discussed further below, such uncontrolled emission factors are applied to years before Subpart L reporting began (for CY 2011) and before emission controls were put into place.) First, in addition to reporting emissions by chemical at the facility level, facilities report emissions from each production and transformation process at the facility in tons of CO_2 Eq. by fluorinated GHG group. To calculate CO_2 Eq. emissions, facilities use a chemical-specific 100-year GWP where one is available for the compound of interest. If no chemical-specific 100-year GWP is available for the compound of interest, facilities use the GHGRP default GWP for the fluorinated GHG group of which the compound is a member. These default GWPs are shown in Table 4-63.

Second, for each process, facilities also report the extent to which emissions are abated (the effective destruction efficiency or EDE) as a range. The EDE is calculated as follows:

$$EDE = 1 - \frac{CE_{PV}}{UE_{PV}}$$

where:

EDE = Effective destruction efficiency of the process

CE_{PV} = Actual GWP-weighted controlled emissions from all vents for the process, MT CO_2 Eq.

UE_{PV} = Hypothetical GWP-weighted uncontrolled emissions from all vents for the process, MT CO_2 Eq. (CE_{PV} will equal UE_{PV} if the process is not controlled, resulting in a calculated EDE of 0).

Note that the EDE is based on the extent to which emissions from process vents are controlled. Emissions from equipment leaks are not included in the EDE calculation. Table 4-69 provides the EDE ranges available for facilities to report and the arithmetic means of each range. The use of these datasets to calculate uncontrolled emission factors is discussed in more detail in the "1990-2010 Emissions Estimates" section below.

Verification of GHGRP Reports

Data reported under the GHGRP, including emissions and production, are electronically verified using range checks, internal consistency checks, and time-series consistency checks. Where the data fail a preliminary check, EPA contacts the facility to see whether there is an explanation for the issue or whether the data are indeed erroneous. In the latter case, facilities are required to correct the data. Where one or more of the anomalous data elements is not explained or corrected, the report for that facility for that year is considered unverified.

1990-2010 Emissions Estimates

For 14 of the 17 fluorinated gas production facilities that have reported their emissions under the GHGRP, 1990 through 2010 emissions are estimated using (1) facility- and chemical-specific emission factors based on the emissions data discussed under "2011-2022 Emissions" below, (2) reported or estimated production and transformation of fluorinated GHGs at each facility in each year, i.e., activity data, and (3) reported and estimated levels of emissions control at each facility in each year. (For the other 3 fluorinated ga production facilities that have reported their emissions under the GHGRP, 1990 through 2010 emissions were estimated using data submitted by the company, as explained further below.)

Facility- and Chemical-Specific Emission Factors Reflecting Emissions Controls

Facility- and chemical-specific emission factors were developed based on the 2011 to 2015 emissions reported under the GHGRP (discussed above) and the 2011 to 2015 production and transformation of fluorinated GHGs reported under the GHGRP. (Production and transformation of CFCs and HCFCs are not reported under the GHGRP.) For each emitted fluorinated GHG at each facility, emissions of the fluorinated GHG were summed over the five-year period. This sum was then divided by the sum of the quantities of all fluorinated GHGs produced or transformed at the facility over the five-year period.[58] As discussed further below in the Uncertainty section, emissions of any particular fluorinated GHG are likely to occur only from a subset of the production or transformation processes at each facility, but in the absence of information on chemical-specific emissions at the process level, it was assumed that all fluorinated GHG production and transformation processes at the facility emit all fluorinated GHGs at the facility. This yielded the emission factors for each fluorinated GHG at each facility. Both emissions and activity (production + transformation) totals were summed over the five-year period to account for the intermittent and variable nature of some emissions and production/transformation processes. Compounds that were not emitted or produced/transformed between 2011 and 2015 but that were emitted or produced/transformed later were assumed not to have been emitted or produced/transformed (as applicable) before 2011.

Facility- and Chemical-Specific Emission Factors Reflecting No Emissions Controls

The 2011 to 2015 emissions reported under the GHGRP reflect emissions controls to the extent those are implemented at each facility. Because facilities have not always controlled their fluorinated GHG emissions since 1990, uncontrolled emission factors were developed for each facility to apply to years when the facility's emissions were not believed to be controlled. To estimate uncontrolled emissions, GHGRP data were first used to assess the 2011 to 2015 levels of control for each production or transformation process at each facility.

To calculate uncontrolled emissions from each process and fluorinated GHG group, a point estimate of the effective destruction efficiency (EDE, described above) was required and was estimated using the arithmetic mean

[58] Permit data for two facilities indicated that they began controlling emissions at some point between 2011 and 2015. However, the actual emissions reported by these facilities did not change substantially after the date when the permit indicated that controls were imposed. For this reason, the reported 2011 to 2015 emissions and emission factors are believed to be representative of emissions for these facilities before 2011.

of the lower and upper bounds of the EDE range reported for the process.[59] This was consistent with the approach taken in the *2019 Refinement* to develop the Tier 1 factor for fluorinated gas production facilities. The reported vented emissions for each process and fluorinated GHG group were divided by (1 - arithmetic mean EDE) to obtain the estimated uncontrolled emissions from process vents for that process and fluorinated GHG group. For each fluorinated GHG group, the controlled emissions across processes (including emissions from both vents and leaks) and the uncontrolled emissions across processes (including emissions from both vents and leaks) were then summed, and the first was divided by the second. This yielded an average level of control for each fluorinated GHG group at each facility. All fluorinated GHGs within each fluorinated GHG group at each facility were assumed to be controlled to the same level. To estimate the uncontrolled emissions of each fluorinated GHG within each group at each facility, the emissions of each fluorinated GHG were divided by the level of control estimated for its fluorinated GHG group at the facility. The same procedure was used to estimate uncontrolled emission factors as had been used to estimate controlled emission factors: the estimated uncontrolled 2011 to 2015 emissions of each fluorinated GHG were summed, and this sum was divided by the sum of the quantities of all fluorinated GHGs produced or transformed at the facility from 2011 to 2015.

Table 4-69: Destruction Efficiency Range Values Used to Estimate Pre-Abatement Emissions for Production and Transformation Processes

DE ranges	Lower Bound	Upper Bound	Arithmetic Mean of Bounds
>=0% to <75%	0.0	0.75	0.375
>=75% to <95%	0.75	0.95	0.85
>=95% to <99%	0.95	0.99	0.97
>=99%	0.99	0.9999	0.995

Estimated Levels of Emissions Controls

As discussed above, both uncontrolled emission factors and controlled emission factors were developed for each facility and fluorinated GHG; these emission factors were developed for estimating emissions from production and transformation processes for years 1990 to 2010. The following information and assumptions were used to determine whether and when emissions from facilities were likely to have been controlled from 1990 to 2010. For the estimated status of emissions controls at each facility reporting under Subpart L, and, where relevant, the starting year for those controls, see Table 4-70.

- Facilities with publicly available information on the presence and use of control devices were assumed to control their emissions starting in the year specified in the publicly available information. Publicly available information included operating permits, news articles on facility modifications, company press releases, etc. Where the publicly available information documents that a control device was in place beginning in a certain year, the facility was assumed to control process emissions beginning in that year, and the controlled emission factor was used in estimating emissions for that year and the following years. The uncontrolled emission factor was used to estimate emissions in earlier years.
- In the absence of other control information, facilities that never reported DRE ranges other than ">=0% to <75%" for their production and transformation processes during reporting years 2011 and 2012 were assumed to have no control devices in place during the time period 1990 to 2012.
- Facilities that reported DRE ranges other than ">=0% to <75%" for at least one production or transformation process for 2011 or 2012 but for which other control information was not available were assumed to have begun controlling their emissions in 2005.

[59] Note that facilities would report a range of 0% to 75% even if they do not abate emissions at all; thus, the assumption that emissions are 37.5 percent controlled may overestimate the hypothetical uncontrolled emissions of some facilities, e.g., those that do not abate any emissions.

Table 4-70: Estimated Starting Years for Emission Controls at Each Fluorinated Gas Production Facility Reporting under Subpart L of the GHGRP

Facility Name	Estimated Start Year	Basis of Estimation
3M COMPANY	No controls	Never reported a DRE range other than ">=0% to <75%"
3M CORDOVA	2003	Climate News Article[60]
3M Cottage Grove Center - Site	2016	Reported a DRE range other than ">=0% to <75%" for the first time in 2016
Airgas Therapeutics LLC - Scott Medical Products	No controls	Never reported a DRE range other than ">=0% to <75%"
ANDERSON DEVELOPMENT COMPANY	No controls	Never reported a DRE range other than ">=0% to <75%"
ARKEMA, INC.	2005	Reported a DRE range other than ">=0% to <75%" in 2011
Chemours - Corpus Christi Plant	No controls	Never reported a DRE range other than ">=0% to <75%"
CHEMOURS CHAMBERS WORKS	2005	Reported a DRE range other than ">=0% to <75%" in 2011
CHEMOURS COMPANY - FAYETTEVILLE WORKS	2015	Reported a DRE range other than ">=0% to <75%" for the first time in 2015
CHEMOURS EL DORADO	2005	Reported a DRE range other than ">=0% to <75%" in 2011
CHEMOURS LOUISVILLE WORKS	No controls	Never reported a DRE range other than ">=0% to <75%"
CHEMOURS WASHINGTON WORKS	2005	Reported a DRE range other than ">=0% to <75%" in 2011
DAIKIN AMERICA INC.	1993	Title V operating permit[61]
HONEYWELL INTERNATIONAL INC - BATON ROUGE PLANT	2012	Title V operating permit[62]
HONEYWELL INTERNATIONAL INC - GEISMAR COMPLEX	2011	Title V operating permit[63]
Honeywell Metropolis	No controls	Never reported a DRE range other than ">=0% to <75%" (did not report under Subpart L)
MEXICHEM FLUOR INC.	1993	Title V operating permit[64]
Versum Materials US, LLC	No controls	Never reported a DRE range other than ">=0% to <75%"

Activity Data

The activity data for production and transformation of fluorinated compounds for 1990 to 2010 are based on production and transformation data reported to EPA by certain facilities for certain years, on production capacity data, and on fluorinated GHG production and consumption trends estimated for the various fluorinated GHG-consuming industries.

Production and Production Capacity Data

Production data are available from reporting to the U.S. GHGRP under Subpart OO, Suppliers of Industrial Greenhouse Gases, and from an industry survey conducted by U.S. EPA in 2008 and 2009. Production and transformation data were reported under Subpart OO for 2010 and later years. The responses to the industry survey included production data for certain fluorinated gases at certain facilities for the years 2004, 2005, and

[60] See https://insideclimatenews.org/news/29122022/3m-cordova-illinois-pfas-cf4-pollution/.

[61] Daikin (2013) http://lf.adem.alabama.gov/WebLink/DocView.aspx?id=29951882&dbid=0.

[62] Honeywell (2011) https://edms.deq.louisiana.gov/app/doc/view?doc=8579001.

[63] Honeywell (2012) https://edms.deq.louisiana.gov/app/doc/view?doc=7812895.

[64] See https://edms.deq.louisiana.gov/app/doc/view?doc=1309650.

2006. 2004 to 2006 production data are available for 15 fluorinated compounds. Year 2006 production at an SF_6-producing facility was estimated based on production capacity data as described below (Rand 2007). Production of certain compounds at one other facility was estimated based on 2003 production capacity estimates from SRI 2004.

Estimated Production

Estimated production for facilities and fluorinated GHGs for which production or production capacity data were available for some years before 2010.

For facilities and fluorinated GHGs for which production or production capacity data were available for 2006 or 2003, production between 2006 or 2003 (as applicable) and 2010 (or 2011) was estimated by interpolating between the 2006 production or 2003 production capacity value and the 2010 (or 2011) production value reported under Subpart OO.

For the years before the earliest year with production or production capacity data (e.g., years 1990 to 2002 or 2003), production was estimated based on growth or consumption trends for the major industries using each fluorinated GHG.

- For fluorinated compounds that are commonly emitted in the semiconductor industry, estimates of U.S. layer-weighted semiconductor production (Total Manufactured Layer Area, or TMLA) were used to inform the fluorinated compound production estimates (EPA 2023c). Fluorinated compound production values were assumed to vary with TMLA from 1990 to 2002 or 2003. For example, 1998 production of PFC-14 at a particular facility was estimated by multiplying the 2003 production of PFC-14 at that facility by the ratio between the TMLA estimated for 1998 and the TMLA estimated for 2003. Fluorinated compounds for which TMLA was used to estimate production include PFC-14, PFC-116, PFC-218, perfluorocyclobutane (c-C_4F_8), and NF_3. (Note that the TMLA data were also extrapolated from year 1995 to 1990 based on the average change per year from 1995 to 2009.)

- SF_6 is commonly used in electric power systems, magnesium production, and electronics manufacturing. SF_6 consumption estimates across these three industries for 1990 to 2003 were used to inform the SF_6 production data (EPA 2023d); SF_6 production was assumed to vary with consumption totals from 1990 to 2003.

- For HFCs commonly used as replacements for ozone-depleting substances (ODS), such as HFCs used as substitutes for CFCs and HCFCs in air-conditioning and refrigeration equipment, HFC production data for certain fluorinated compounds from the Vintaging Model (VM) were used to inform the HFC production estimates (EPA 2023b). HFC production values were assumed to vary with the VM estimates of production. The industry trend data were applied to the list of HFCs in Table 4-71.

Table 4-71: List of Saturated HFCs, Unsaturated HFCs (Hydrofluoroolefins or HFOs), and Unsaturated HCFCs (Hydrochlorofluoroolefins or HCFOs) whose 1990-2009 Production Was Estimated Using Vintaging Model, Virgin Manufacturing by Chemical

Fluorinated Gas
HFC-23
HFC-32
HFC-125
HFC-134a
HFC-143a
HFC-152a
HFC-236fa
HFC-245fa
HFC-365mfc
HCFO-1233zd(E)
HFO-1234yf
HFO-1234ze
HFO-1336mzz(Z)
HFC-4310mee

Estimated production for facilities and fluorinated GHGs for which production data before 2010 were not available.

In the absence of production data for the period 1990 to 2009, the production data reported to the GHGRP under Subpart OO were extrapolated backward based on the industry trends discussed above. For compounds for which industry trend data were unavailable, production was assumed to have remained constant over the time series.

In both cases, 2009 production was estimated by conducting a trend analysis on the Subpart OO production data for years 2010 to 2015. In instances where there did not appear to be a trend, the average of the production values for years 2010 to 2015 was used as the estimated production for year 2009. In instances where there was a trend, the year 2010 (or 2011) production value was used as the estimated production for year 2009.

If the industry trend information discussed above was applicable to a fluorinated compound, it was assumed that production varied with the industry trend from 1990 to 2009. If no industry trend information was available, it was assumed that production from 1990 to 2008 remained constant at the 2009 value.

For facilities and fluorinated compounds where information was available on annual production capacity, the estimated activity data was reviewed and compared to the known production capacity. For instances where the estimated activity data exceeded known production capacity for a certain year, the production estimate was set equal to the capacity value. In addition, where information was available on the starting year for production of a fluorinated GHG at a facility, production was only estimated beginning in the process startup year through 2009.

Estimated Emissions for 3M Facilities

3M provided 1990, 1995, 2000, and 2002 through 2010 emissions data for three facilities: 3M Cordova, 3M Company, and 3M Cottage Grove Center - Site.[65] Therefore, speciated 1990-2010 emissions at these facilities were estimated using a different methodology than that described above.[66]

[65] For 1990, 1995, and 2000, 3M provided emissions data for a Pilot Development Center in addition to the other three facilities. Emissions by group from the Pilot Development Center were added to and are represented by the emissions by group for 3M Cottage Grove Center – Site.

[66] 3M's methods for estimating its emissions are described in detail in "3M Global EHS Laboratory Response to EPA Data Request on Fluorochemical Emissions," February 2024 (3M, 2024). In brief, 3M estimated emissions from its processes using

3M emissions data were provided by facility and by fluorinated GHG group in metric tons of CO_2 Eq., weighted by 100-year GWPs from various IPCC Assessment Reports. The fluorinated GHG groups included HFCs, PFCs, SF_6, HFEs, and other fluorinated GHGs. (3M noted that the "other fluorinated GHG" category included NF_3.) GWPs from the IPCC *Third Assessment Report* (TAR) were used to report totals for 1990, 1995, 2000, and 2003 to 2006. GWPs from the IPCC *Fifth Assessment Report* (AR5) was used to report totals for 2002, and GWPs from the IPCC *Fourth Assessment Report* (AR4) were used to report totals for 2007 to 2010. The emissions were also categorized as emissions from electrochemical fluorination (ECF) processes and downstream (DS) emissions. The DS emissions for 1990, 1995, and 2000 were reported as a total for each facility rather than by fluorinated GHG group.

To present emissions estimates by compound, EPA needed to disaggregate the data provided by 3M. The first step was to disaggregate the 1990, 1995, and 2000 DS emissions into fluorinated GHG groups. Since the 2003 to 2006 data were calculated using the same set of GWPs as the 1990, 1995, and 2000 data, the DS emissions of each group at each facility for 2003 to 2006 were divided by the total DS 2003 to 2006 emissions at that facility to obtain a set of fractions. These fractions were then multiplied by the 1990, 1995, and 2000 DS totals to sort those emissions into groups.

For 2002, ECF and DS emissions were only reported under the PFC group. (3M noted that chemical classifications were not preserved when 2002 emissions were recalculated using GWP values from AR5.) Since data for every other year showed emissions reported from multiple fluorinated GHG groups, and since 2004 was the closest year with emissions well sorted into fluorinated GHG groups, the ECF and DS emissions for 2002 were separated into multiple fluorinated GHG groups using the 2004 ECF and DS groups shares for each facility.

The next step was to disaggregate the emissions of each fluorinated GHG group into emissions of the relevant compounds in that group. To accomplish this, EPA assumed that emissions of each fluorinated GHG group before 2011 consisted of the same fluorinated GHGs, in the same proportions, as from 2011 through 2015. However, each compound's share of the GWP-weighted emissions of the group in a given year depends on the GWPs used for that compound and for the other compounds in the group in that year. To account for this, EPA multiplied the reported 2011 to 2015 emissions of each compound in metric tons by the corresponding GWPs for that compound from the TAR, AR4, and AR5 to generate three sets of emissions by compound in metric tons of CO_2 Eq. For each set, the sum of emissions across 2011 to 2015 for each compound were divided by the total emissions for the corresponding fluorinated GHG group for those five years to calculate shares for each group.

The 3M emissions data by group for 1990, 1995, 2000, and 2002 to 2010 were then speciated by compound using the appropriate set of share values for each year. Since 3M Company only reported emissions of one compound in 2011 to 2015 but had emissions from multiple fluorinated GHG groups in 1990, 1995, 2000, and 2002 to 2010, the share values for 3M Cordova were used to speciate the 1990, 1995, 2000, and 2002-2010 emissions by group for 3M COMPANY. The speciated emissions in metric tons of CO_2 Eq. by compound for each facility were then divided by the appropriate TAR, AR4, or AR5 GWP for each compound to obtain the estimated emissions in metric tons of each compound for 1990, 1995, 2000, and 2002 to 2010.

Linear interpolation was then used to estimate emissions for 1991 to 1994, 1996 to 1999, and 2001 for each compound for these three facilities.

Estimated Emissions for Facilities that Produce Fluorinated GHGs but Do Not Report Under Subpart L

There is a subset of facilities that report production and transformation of fluorinated gases under Subpart OO and that also have emission levels less than the threshold value for reporting under Subpart L (i.e., uncontrolled emissions below the 25,000-MT CO_2 Eq. threshold). For these facilities, EPA developed emission estimates based on aggregated production estimates and the Tier 1 default emission factor in the 2019 Refinement. Because the

emission factors that were developed using methods similar to those used for developing emission factors under the GHGRP. As under the GHGRP, emission factors were multiplied by different types of activity data (e.g., production) to estimate emissions for each facility and year. In 2003 and later years, 3M also accounted for emission reductions attributable to operation of the thermal oxidizer at the Cordova plant.

specific fluorinated GHGs emitted are not known, the emissions were assumed to consist of the fluorinated GHGs shown in Table 3.28b of chapter 3.10.2 of Volume 3 IPPU (IPCC 2019), in the proportions shown in that table. Emissions are assumed to have been flat at the 2010 value in the years before 2010.

Estimated Emissions for SF_6 Production Facility

For an SF_6 production facility that ceased production in 2010, the year before emissions from fluorinated gas production were required to be reported under the GHGRP, SF_6 emissions were estimated using historical production capacity, the global growth rate of SF_6 sales reported in RAND 2007, and the Tier 1 default emission factor for production of SF_6 in the 2019 Refinement. For this plant, a 1982 SF_6 production capacity of 1,200 short tons (Perkins 1982) was multiplied by the ratio between the RAND survey SF_6 sales totals for 2006 and 1982, 1.52 (RAND 2007), resulting in estimated production of 1,652 metric tons in 2006. This production was assumed to have declined linearly to zero in 2011.

2011-2022 Emissions Estimates

For the 17 fluorinated gas production facilities that have reported their emissions under the GHGRP, 2011 to 2022 emissions are estimated using the fluorinated GHG emissions reported under Subpart L of the GHGRP.

As discussed above, most emissions reported under Subpart L are reported by chemical, but some emissions are reported only by fluorinated GHG group in MT CO_2 Eq. Between 2011 and 2022, the share of total CO_2 Eq. emissions reported only by fluorinated GHG group has ranged between 1 and 2 percent. In this analysis, to ensure that all emissions are reported by species, emissions that are reported only by fluorinated GHG group are assumed to consist of the fluorinated GHGs in that group that are reported by chemical at the facility. As discussed further in the Uncertainty section, this is likely to result in incorrect speciation of some emissions, but the impact of this incorrect speciation is expected to be small.

Estimated Emissions for Facilities that Produce Fluorinated GHGs but Do Not Report Under Subpart L

As discussed above, for facilities that produce fluorinated GHGs but that do not report their emissions under subpart L, EPA developed emission estimates based on aggregated production estimates and the Tier 1 default emission factor in the 2019 Refinement. Because the specific fluorinated GHGs emitted are not known, the emissions were assumed to consist of the fluorinated GHGs shown in Table 3.28b of chapter 3.10.2 of Volume 3 IPPU (IPCC 2019), in the proportions shown in that table.

Uncertainty

The estimates in this memo are subject to a number of uncertainties. These uncertainties are generally greater for years before 2011, when reporting of fluorinated GHG emissions from fluorinated gas production began under the GHGRP, than for 2011 and following years. However, the emissions estimated from 2011 to 2022 are also subject to various uncertainties. The uncertainties for both the 1990 to 2010 and 2011 to 2022 periods are discussed in more detail below.

1990-2010 Uncertainty

The uncertainty of emissions estimated for 1990 through 2010 is considerably greater than that for emissions for 2011 through 2022 because emissions were not reported under the GHGRP. EPA has estimated emissions using estimated emission rates, fluorochemical production and transformation activity, and levels of control, and each set of estimates is subject to uncertainty.

Uncertainty regarding activity data

Identity of emitting processes

In reality, emissions of particular fluorinated GHGs are linked to production and/or transformation of particular fluorinated gases at facilities. However, GHGRP information/data does not link emissions of specific fluorinated GHGs to production or transformation of specific fluorinated gases. For the estimates presented here, therefore, all emissions are indexed to total production across all fluorinated gases. This may not capture trends in emissions that are driven by trends in production or transformation of subsets of the fluorinated gases produced at a facility.

Produced and emitted gases change over time

The set of gases produced at a facility, and therefore the set of fluorinated GHGs that are emitted by that facility, may change over time. It is likely that certain production and transformation processes that existed from 2011 to 2015 (the basis of the emission factors used to back-cast emissions in this analysis) did not exist throughout the entire previous time series (1990 to 2010). In such cases, emissions of the fluorinated GHGs emitted from the new processes will be overestimated by this analysis for certain years before 2011. On the other hand, it is also likely that some production and transformation processes, and their associated fluorinated GHG emissions, occurred only during the 1990 to 2010 period and not later, meaning that their emissions are not represented in the emission factors developed based on the 2011 to 2015 emissions and production data collected under the GHGRP. Such emissions will therefore not be captured by this analysis. The most prominent example of the second situation is probably production of CFCs and HCFCs other than HCFC-22 between 1990 and 2009, which has declined steadily since 1990 as the production of CFCs and HCFCs for emissive uses has been phased out under the Montreal Protocol and Clean Air Act. Production of CFCs and HCFCs can sometimes result in emissions of HFCs or PFCs.

Quantity of produced gases

Where production or production capacity data were available for certain fluorinated gases, facilities, and years before 2010, those data were incorporated into this analysis. However, even for facilities and compounds for which data were available in certain years, there were several years for which data were not available. For multiple produced compounds, data were available only in 2010. To estimate trends in production of compounds for years before production or production capacity data were available, production of certain compounds was indexed to known national production or consumption trends for those compounds. This is the case for most HFCs, several PFCs, SF_6, and NF_3. National production estimates are available for HFCs, increasing confidence in country-level production estimates, but the distribution of production among the various HFC-producing facilities is uncertain. Where estimated production was indexed to consumption (for several PFCs, SF_6, and NF_3), the uncertainty is larger than for HFCs because changes in net imports/exports (which are not known) may also affect the production trend.

For certain fluorinated gases, trend information was not available; therefore, production was back-cast by assuming that it had remained constant at the 2010 level from 1990 through 2009. This is a highly uncertain assumption.

Some production and transformation activity is not reported under Subpart OO or modeled in back-casting

Under Subpart OO, quantities of fluorinated GHGs that are produced and transformed at the same facility are not reported to us, although any emissions from such processes are reported under Subpart L. Such unreported production and transformation are therefore not captured in the 1990 to 2010 activity estimates used to estimate 1990 through 2010 emissions. To the extent that such unreported production and transformation drive emissions and change over time, the trends will not be captured by this analysis.

Facilities that no longer produce fluorinated gases or that started producing them after 1990

Some facilities may have produced fluorinated gases at some point between 1990 and 2010 that no longer produced those compounds after 2010. One SF_6 producer is known to fall into this category and its 1990 to 2010 emissions were estimated, but there may be other facilities that are not included in this analysis. On the other hand, some facilities for which 1990 to 2010 emissions were estimated may not have produced them over the

entire time series, in which case emissions of the compounds those facilities are assumed to have emitted could be overestimated.

Uncertainty regarding emission factors

Emission rates change over time

The emission factors used to estimate 1990 to 2010 emissions are based on the emissions and production reported from 2011 to 2015, reflecting emission rates during that period. For processes that have been used throughout the timeseries, emission rates may have changed over time as the process was optimized to increase efficiency, decreasing by-product emissions, or alternatively, as the process was optimized to maximize production, which sometimes increases by-product emissions. Emission rates also depend on the extent to which emissions are controlled at the facility, the uncertainties for which are discussed further below.

Emissions from container venting and destruction may not scale with production

In this analysis, emissions from container venting and destruction of previously produced fluorinated GHGs were included in the emission factors used to estimate 1990 to 2010 emissions. This implicitly assumes that such emissions scale with production and transformation. While this seems likely to be broadly true, there may be exceptions. However, since emissions from container venting and destruction are generally a small share of facility emissions (2 percent, on average), the impact of such exceptions is expected to be small.

Uncertainty regarding levels of control

In this analysis, the arithmetic mean of the DRE range reported by each facility for each process was used to estimate the DRE for that process and the uncontrolled emissions for that process. Since the emissions implied by the bounds of each DRE range span at least a factor of four,[67] this is an uncertain assumption. The uncertainty is mitigated somewhat by the fact that there are generally several processes at each facility, meaning that departures from the assumed mean average out to some extent. There is also uncertainty in the assumptions that (1) all fluorinated GHGS within a particular fluorinated GHG group are abated to the same extent and (2) facilities for which control device start dates are unavailable began to control emissions in 2005.

Quantitative uncertainty estimate for uncontrolled emission factors from *2019 Refinement*

As noted above, 2011 to 2016 data from the GHGRP was used to develop the Tier 1 default uncontrolled emission factor for the *2019 Refinement*, using methods similar to those described here. A Monte Carlo analysis performed to assess the uncertainty of the Tier 1 default factor indicated that the uncertainty for each facility's uncontrolled emission factor was less than 50 percent. This uncertainty estimate considered the uncertainty regarding the levels of control, but not the uncertainty of applying factors from one time period at the facility to much earlier time period (although the variability of each facility's emission factor over the 6-year span of the *2019 Refinement* analysis was found to be relatively low).

Uncertainty regarding the identity of 3M emitted compounds

For the three 3M facilities that submitted their 1990 through 2010 emissions by fluorinated GHG group, it is assumed that the emissions of each group consist of the compounds in that group that were reported by species by the facility from 2011 through 2014. However, 3M indicated that the mix of products made at its facilities had changed over time, which would have affected the identities of the fluorinated GHGs emitted. For example, at one facility, only one compound was reported to be emitted for 2011-2015 but 3M's historical emissions data showed multiple fluorinated GHG groups for that facility for 1990 to 2010. For that facility, it is assumed that emissions consisted of the compounds in each gas type that were reported by species by the 3M facility that was determined to be the most similar. Additionally, there were a few years of data for these three facilities where some emissions were reported as a total rather than separated by group. For these years, the group shares were assumed to be

[67] For example, the DRE range 0 to 75% implies emissions of (1-0) x uncontrolled emissions to (1-75%) x uncontrolled emissions, or, rearranging and calculating, 0.25 x uncontrolled emissions to 1 x uncontrolled emissions, a factor of four.

the same as in nearby years. There is uncertainty involved with each of the assumptions made while speciating emissions for these three facilities, though the uncertainty is minimal regarding total emissions in metric tons of CO_2 Eq. In at least one case, the speciation method appears to have resulted in an overestimate for an individual compound. In this analysis, 3M's emissions of C_4F_8O are estimated to have peaked at around 410 MT in 2000, but at least one study has inferred considerably lower global emissions (around 120 MT) for that year based on atmospheric measurements of C_4F_8O (Vollmer et al. 2019).

2011-2022 Uncertainty

Emissions from 2011 to 2022 reflect reporting by fluorinated gas production facilities under the GHGRP. As discussed above, emissions reported under the GHGRP are based on facility- and process-specific measurements or calculations and are therefore expected to be reasonably accurate for the reporting facilities. (Emissions from the largest sources, process vents emitting 10,000 MT CO_2 Eq. or more annually, are estimated using Tier 3 methods.)

Unverified reports

Ninety-five percent (171/180) of the Subpart L reports submitted by fluorinated gas production facilities from 2011 to 2022 are considered to be fully verified; five percent (9/180) of the reports include one or more data elements that are not verified. One facility accounts for two thirds (6/9) of the unverified reports. Many of the issues in the unverified reports for this facility relate to time-series inconsistencies that have arisen as the facility updates reports for recent years, but not previous years, to reflect refinements to estimated emission rates. This facility has accounted for between 6 percent (in 2011) and 29 percent (in 2022) of the GWP-weighted emissions reported for this source category. The uncertainties for this facility therefore have an appreciable impact on the uncertainty of the estimates for the source category as a whole, particularly in years before 2022.

Facilities that do not produce fluorinated gases but may emit fluorinated GHGs from other fluorochemical production processes

Under the GHGRP, EPA collects information from facilities that produce fluorinated gases. While this likely includes most, and possibly all, U.S. facilities that produce fluorochemicals of any kind, it is possible that some fluorochemical producers do not report either their production of fluorochemicals or their emissions of fluorinated GHGs to EPA under the GHGRP. In this case, emissions estimates based only on GHGRP reporting would underestimate actual emissions.

At fluorinated gas production facilities that currently report their emissions under the GHGRP, it is possible that some processes that emit fluorinated GHGs neither produce nor transform a fluorinated gas, in which case their emissions would not be reported under the GHGRP. In that case, emissions estimates based only on GHGRP reporting would underestimate actual emissions.

Exclusion of nitrous oxide

The GHGRP does not currently require facilities to report emissions of nitrous oxide (N_2O) from fluorinated gas production or transformation, but the IPCC *2019 Refinement* includes a default emission factor for N_2O from production of NF_3, implying such emissions may occur. The GHGRP data (and this analysis) may therefore underestimate emissions of N_2O from fluorinated gas production. Because the GWP of N_2O is considerably lower than that of saturated HFCs, PFCs, and other fluorinated GHGs, any underestimate is expected to be relatively small.

Identity of emitted compounds

In this analysis, it is assumed that emissions that are reported only in MT CO_2 Eq. by fluorinated GHG group consist of the compounds in that group that are reported by species by the facility. However, if that were actually the case, emissions of those compounds would have been included in the speciated emissions rather than reported separately in MT CO_2 Eq. This analysis therefore incorrectly speciates some emissions. As noted in the Methodology section, the share of total CO_2 Eq. emissions reported only by fluorinated GHG group is small, ranging

between 1 and 2 percent. Moreover, while the emissions are not assigned to the exact species emitted, they are assigned to a species that is closely related and likely to have similar atmospheric impacts (e.g., another saturated HFC with two or fewer carbon-hydrogen bonds). The impact of this uncertainty is therefore limited.

Quantities of Reactants Consumed or Fluorinated Gases Produced

The emissions reported under Subpart L are required to be calculated using process activity data, such as the quantity of reactants consumed or the quantity of the fluorinated gas product produced. In general, the uncertainties in process activity levels are expected to be small. The *2019 Refinement* places such uncertainties "in the region of 1 percent."

Because the uncertainties enumerated above are either small or difficult to quantify, EPA did not attempt to include them in the 2022 quantitative uncertainty estimate for this source category. The 2022 quantitative uncertainty estimate includes the following uncertainties:

Process Vent Emission Factors

Process vent emission factors that were developed based on stack testing (for continuous process vents emitting 10,000 MT CO_2 Eq. or more) were estimated to have an uncertainty (95-percent confidence interval) of ±35 percent based on Subpart L requirements.[68] Process vent emission factors that were developed based on calculations (for batch process vents and for continuous process vents emitting less than 10,000 MT CO_2 Eq.) were estimated to have a larger uncertainty of ±50 percent. Continuous processes were assumed to have two vents per process; batch processes were assumed to have five vents per process.[69]

Equipment Leak Estimates

The estimated equipment leaks reported by each facility for each process were estimated to have an uncertainty of ± 90 percent. The uncertainty of leak estimates depends on the method used to estimate leaks; there are multiple methods. For simplicity, this analysis uses a conservatively high uncertainty estimate that is appropriate for the Average EF Approach.

Venting of Residual Gas in Containers

The reported emissions of fluorinated GHGs from venting of residual gas in returned containers were estimated to have an uncertainty of ± 30 percent for each facility. This estimate is based on the Subpart L requirement to either measure the contents of each container or to measure the contents of at least 30 representative containers for each compound and container size and type.

Facilities that produce fluorinated gases but do not report their emissions to the GHGRP

EPA estimated emissions for fluorinated gas production facilities that do not report their emissions under Subpart L of the GHGRP. The estimates presented here for 2011 to 2022 are based on aggregated production estimates, the Tier 1 default emission factor in the *2019 Refinement*, and the default fluorinated GHG speciation from Table 3.28b (chapter 3.10.2 of *2019 Refinement*). There is considerable uncertainty in both the magnitude of the emissions and the identity of the emitted compounds. The *2019 Refinement* estimates the uncertainty of the Tier 1 emission factor as -98 percent to +470 percent. (In the quantitative uncertainty estimate below, which is based on error propagation, values of ±98 percent were used because error propagation requires the assumption of symmetric uncertainty bounds.) In 2022, estimated emissions from the six non-reporting facilities accounted for 44 percent of total estimated U.S. emissions from fluorinated gas production and transformation. In contrast,

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[68] *Technical Support Document for Emissions from Production of Fluorinated Gases*, Office of Air and Radiation, U.S. Environmental Protection Agency, November 5, 2010. Available online at: https://www.epa.gov/sites/default/files/2015-02/documents/subpart-l_techsuppdoc.pdf.

[69] *Economic Impact Analysis for the Mandatory Reporting of Greenhouse Gas Emissions F-Gases: Subparts I, L, DD, QQ, SS*, U.S. Environmental Protection Agency, November 2010. Available online at: https://www.regulations.gov/document/EPA-HQ-OAR-2009-0927-0179.

production and transformation by these facilities accounted for just three percent of total fluorinated GHG production and transformation across all facilities. Because the emissions estimated for several of the six facilities exceeded the 25,000 MT CO_2 Eq. reporting threshold under Subpart L, but these facilities have not reported their emissions under Subpart L, it appears likely that emissions from at least some facilities are overestimated.

The four uncertainties listed immediately above were convolved using error propagation to arrive at an overall uncertainty estimate for 2022. The results of the Approach 1 quantitative uncertainty analysis are summarized in Table 4-72. Emissions of HFCs, PFCs, SF_6, and NF_3 from production of fluorochemicals other than HCFC-22 were estimated to fall between 4.83 and 7.08 MMT CO_2 Eq. at the 95 percent confidence level. This indicates a range of approximately 19 percent below and 19 percent above the emission estimate of 5.95 MMT CO_2 Eq.

Table 4-72: Approach 1 Quantitative Uncertainty Estimates for HFC, PFC, SF_6, and NF_3 from Production of Fluorochemicals other than HCFC-22 (MMT CO_2 Eq. and Percent)

Source	Gas	2022 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate (MMT CO_2 Eq.)		Uncertainty Range Relative to Emission Estimate (%)	
			Lower Bound[a]	Upper Bound[a]	Lower Bound	Upper Bound
Production of Fluorochemicals other than HCFC-22	HFCs, PFCs, SF_6, and NF_3	5.95	4.83	7.08	-19%	+19%

[a] Absolute lower and upper bounds were calculated using the corresponding lower and upper bounds in percentages.

QA/QC and Verification

General quality assurance/quality control (QA/QC) procedures were applied consistent with the U.S. Inventory QA/QC plan, which is in accordance with Volume 1, Chapter 6 of *2006 IPCC Guidelines* as described in the introduction of the IPPU chapter (see Annex 8 for more details). Under the GHGRP, EPA verifies annual facility-level reports through a multi-step process (e.g., including a combination of pre-and post-submittal electronic checks and manual reviews by staff) to identify potential errors and ensure that data submitted to EPA are accurate, complete, and consistent (EPA 2015).[70] Based on the results of the verification process, EPA follows up with facilities to resolve mistakes that may have occurred. The post-submittals checks are consistent with a number of general and category-specific QC procedures, including: range checks, statistical checks, algorithm checks, and year-to-year checks of reported data and emissions.

The GHGRP also requires source-specific quality control measures for the Fluorinated Gas Production category. Under the GHGRP, fluorinated gas producers are required to (1) develop and periodically update process vent-specific emission factors using either measurements or engineering calculations, depending on the nature of the process (continuous vs. batch) and the magnitude of emissions from the vent, (2) take more measurements of vent emissions where variability is high, (3) use methods for sampling, measuring volumetric flow rates, non-fluorinated-GHG gas analysis, and measuring stack gas moisture that have been validated using a scientifically sound validation protocol, (4) use a quality-assured analytical measurement technology capable of detecting the analyte of interest at the concentration of interest and use a sampling and analytical procedure validated with the analyte of interest at the concentration of interest, (5) periodically test the performance of destruction devices used to control emissions, (6) account for any malfunctions in the process or destruction device, (6) account for emissions from equipment leaks, (7) measure the quantities of residual gas that are vented from returned containers (or develop an emission factor based on at least 30 measurements per gas and container size and type), (8) calibrate mass measurement devices at the frequency recommended by the manufacturer using traceable

[70] EPA (2015). Greenhouse Gas Reporting Program Report Verification. Available online at: https://www.epa.gov/sites/production/files/2015-07/documents/ghgrp_verification_factsheet.pdf.

standards and suitable methods published by a consensus standards organization, (9) calibrate analytical equipment used to determine the concentration of fluorinated GHGs, and (10) document all measurements and calibrations.

The 1990, 1995, 2000, and 2002 through 2010 emissions data reported by 3M for three facilities was compared to the 1990 through 2010 emissions previously calculated for those facilities using the same calculation method used for other facilities that have reported their emissions under the GHGRP since 2011. The overall trajectory of the 3M-reported emissions, as well as the minima and maxima of those emissions, were similar to those previously calculated, but the increases and decreases in the 3M-reported emissions were more gradual. 3M explained that the gradual changes were due to changes in the compounds and quantities produced and to the gradual deployment and optimization of the destruction device at the 3M Cordova facility.

Recalculations

This is a new category included for the current (i.e., 1990 to 2022) *Inventory*, thus, no recalculations were performed.

Planned Improvements

EPA is planning to refine its estimates of emissions from non-reporting facilities after confirming with the facilities that their actual per-facility uncontrolled emissions fall below 25,000 MT CO_2 Eq.. EPA is also planning to refine its estimates of emissions for other facilities between 1990 and 2009, e.g., by comparing these against emissions inferred from atmospheric measurements. Moreover, EPA is continuing to seek datasets that can be used to improve and/or QA/QC emissions estimates, particularly for the years 1990 to 2009. These datasets may include, for example, real-time facility-specific estimates or additional global "top-down," atmosphere-based emissions estimates that could be used to establish an upper limit on emissions of certain compounds.

4.16 Carbon Dioxide Consumption (CRT Source Category 2B10)

Carbon dioxide (CO_2) is used for a variety of commercial applications, including food processing, chemical production, carbonated beverage production, and refrigeration, and is also used in petroleum production for enhanced oil recovery (EOR). CO_2 used for EOR is injected underground to enable additional petroleum to be produced. For the purposes of this analysis, CO_2 used in food and beverage applications is assumed to be emitted to the atmosphere. This reporting category (2B10) includes emissions from IPCC assessment reports that do not fall within any other CRT source category, which includes emissions from CO_2 consumption. A further discussion of CO_2 used in EOR is described in the Energy chapter in Box 3-6 titled "Carbon Dioxide Transport, Injection, and Geological Storage" and is not included in this section.

Carbon dioxide is produced from naturally-occurring CO_2 reservoirs, as a byproduct from the energy and industrial production processes (e.g., ammonia production, fossil fuel combustion, ethanol production), and as a byproduct from the production of crude oil and natural gas, which contain naturally occurring CO_2 as a component.

In 2022, the amount of CO_2 produced and captured for commercial applications and subsequently emitted to the atmosphere was 5.0 MMT CO_2 Eq. (5,000 kt) (see Table 4-73 and Table 4-74). This is less than a 1 percent increase (10 kt) from 2021 levels and is an increase of approximately 240 percent (3,528 kt) since 1990.

Table 4-73: CO_2 Emissions from CO_2 Consumption (MMT CO_2 Eq.)

Year	1990	2005	2018	2019	2020	2021	2022
CO_2 Consumption	1.5	1.4	4.1	4.9	5.0	5.0	5.0

Table 4-74: CO_2 Emissions from CO_2 Consumption (kt CO_2)

Year	1990	2005	2018	2019	2020	2021	2022
CO_2 Consumption	1,472	1,375	4,130	4,870	4,970	4,990	5,000

Methodology and Time-Series Consistency

Carbon dioxide emission estimates for 1990 through 2022 utilize a country-specific method and were based on the quantity of CO_2 extracted and transferred for industrial applications (i.e., non-EOR end-uses). Some of the CO_2 produced by these facilities is used for EOR, and some is used in other commercial applications (e.g., chemical manufacturing, food and beverage). The IPCC does not have specific methodological guidelines for CO_2 consumption, but the country-specific methodology used is consistent with a Tier 3 approach since it relies on facility-specific information.

2010 through 2022

For 2010 through 2022, data from EPA's GHGRP (Subpart PP) were aggregated from facility-level reports to develop a national-level estimate for use in the *Inventory* (EPA 2023). Facilities report CO_2 extracted or produced from natural reservoirs and industrial sites, and CO_2 captured from energy and industrial processes and transferred to various end-use applications to EPA's GHGRP. This analysis includes only reported CO_2 transferred to food and beverage end-uses. EPA is continuing to analyze and assess integration of CO_2 transferred to other end-uses to enhance the completeness of estimates under this source category. Other end-uses include industrial applications, such as metal fabrication. EPA is analyzing the information reported to ensure that other end-use data excludes non-emissive applications and publication will not reveal CBI. Additionally, a small amount of CO_2 is used as a refrigerant; use and emissions from this application are reported under Section 4.25 Substitution of Ozone Depleting Substances (CRT Source Category 2F). Reporters subject to EPA's GHGRP Subpart PP are also required to report the quantity of CO_2 that is imported and/or exported. Currently, these data are not publicly available through the GHGRP due to data confidentiality reasons and hence are excluded from this analysis.

Facilities subject to Subpart PP of EPA's GHGRP are required to measure CO_2 extracted or produced. More details on the calculation and monitoring methods applicable to extraction and production facilities can be found under Subpart PP: Suppliers of Carbon Dioxide of the regulation, Part 98[71] The number of facilities that reported data to EPA's GHGRP Subpart PP (Suppliers of Carbon Dioxide) for 2010 through 2022 is much higher (ranging from 44 to 53) than the number of facilities included in the *Inventory* for the 1990 to 2009 time period prior to the availability of GHGRP data (4 facilities). The difference is largely due to the fact the 1990 to 2009 data includes only CO_2 transferred to end-use applications from naturally occurring CO_2 reservoirs and excludes industrial sites.

1990 through 2009

For 1990 through 2009, data from EPA's GHGRP are not available. For this time period, CO_2 production data from four naturally-occurring CO_2 reservoirs were used to estimate annual CO_2 emissions. These facilities were Jackson Dome in Mississippi, Bravo and West Bravo Domes in New Mexico, and McCallum Dome in Colorado. The facilities in Mississippi and New Mexico produced CO_2 for use in both EOR and in other commercial applications (e.g.,

[71] See http://www.ecfr.gov/cgi-bin/text-idx?tpl=/ecfrbrowse/Title40/40cfr98_main_02.tpl.

chemical manufacturing, food production). The fourth facility in Colorado (McCallum Dome) produced CO_2 for commercial applications only (New Mexico Bureau of Geology and Mineral Resources 2006).

Carbon dioxide production data and the percentage of production that was used for non-EOR applications for the Jackson Dome, Mississippi facility were obtained from Advanced Resources International (ARI 2006, 2007) for 1990 to 2000, and from the Annual Reports of Denbury Resources (Denbury Resources 2002 through 2010) for 2001 to 2009 (see Table 4-75). Denbury Resources reported the average CO_2 production in units of MMCF CO_2 per day for 2001 through 2009 and reported the percentage of the total average annual production that was used for EOR. Production from 1990 to 1999 was set equal to 2000 production, due to lack of publicly available production data for 1990 through 1999. Carbon dioxide production data for the Bravo Dome and West Bravo Dome were obtained from ARI for 1990 through 2009 (ARI 1990 to 2010). Data for the West Bravo Dome facility were only available for 2009. The percentage of total production that was used for non-EOR applications for the Bravo Dome and West Bravo Dome facilities for 1990 through 2009 were obtained from New Mexico Bureau of Geology and Mineral Resources (Broadhead 2003; New Mexico Bureau of Geology and Mineral Resources 2006). Production data for the McCallum Dome (Jackson County), Colorado facility were obtained from the Colorado Oil and Gas Conservation Commission (COGCC) for 1999 through 2009 (COGCC 2014). Production data for 1990 to 1998 and percentage of production used for EOR were assumed to be the same as for 1999, due to lack of publicly available data.

Table 4-75: CO_2 Production (kt CO_2) and the Percent Used for Non-EOR Applications

Year	Jackson Dome, MS CO_2 Production (kt) (% Non-EOR)	Bravo Dome, NM CO_2 Production (kt) (% Non-EOR)	West Bravo Dome, NM CO_2 Production (kt) (% Non-EOR)	McCallum Dome, CO CO_2 Production (kt) (% Non-EOR)	Total CO_2 Production from Extraction and Capture Facilities (kt)	% Non-EOR[a]
1990	1,344 (100%)	63 (1%)	+	65 (100%)	NE	NE
2005	1,254 (27%)	58 (1%)	+	63 (100%)	NE	NE
2018	IE	IE	IE	IE	58,400[b]	7%
2019	IE	IE	IE	IE	61,300[b]	8%
2020	IE	IE	IE	IE	44,700[b]	11%
2021	IE	IE	IE	IE	43,980[b]	11%
2022	IE	IE	IE	IE	46,800[b]	11%

+ Does not exceed 0.5 percent.
NE (Not Estimated)
IE (Included Elsewhere)
[a] Includes only food and beverage applications.
[b] For 2010 through 2022, the publicly available GHGRP data were aggregated at the national level based on GHGRP CBI criteria. The Dome-specific CO_2 production values are accounted for (i.e., included elsewhere) in the Total CO_2 Production from Extraction and Capture Facilities values starting in 2010 and are not able to be disaggregated.

Methodological approaches were applied to the entire time series to ensure consistency in emissions from 1990 through 2022. The methodology for CO_2 consumption spliced activity data from two different sources: Industry data for 1990 through 2009 and GHGRP data starting in 2010. Consistent with the *2006 IPCC Guidelines*, the overlap technique was applied to compare the two data sets for years where there was overlap (IPCC 2006). The data sets were determined to be inconsistent; the GHGRP data include CO_2 from industrial sources while the industry data do not. No adjustments were made to the activity data for 1990 through 2009 because the *2006 IPCC Guidelines* indicate that it is not good practice to use the overlap technique when the data sets are inconsistent.

Uncertainty

There is uncertainty associated with the data reported through EPA's GHGRP. Specifically, there is uncertainty associated with the amount of CO_2 consumed for food and beverage applications, given the GHGRP does have provisions that Subpart PP reporters are not required to report to the GHGRP if their emissions fall below certain

thresholds, in addition to the exclusion of the amount of CO_2 transferred to all other end-use categories. This latter category might include CO_2 quantities that are being used for non-EOR industrial applications such as firefighting. Second, uncertainty is associated with the exclusion of imports/exports data for CO_2 suppliers. Currently these data are not publicly available through EPA's GHGRP and hence are excluded from this analysis. EPA verifies annual facility-level reports through a multi-step process (e.g., combination of electronic checks and manual reviews by staff) to identify potential errors and ensure that data submitted to EPA are accurate, complete, and consistent. Based on the results of the verification process, EPA follows up with facilities to resolve mistakes that may have occurred.[72] Given the lack of specific uncertainty ranges available on the data used, EPA assigned an uncertainty range of ±5 percent and a normal probability density function for CO_2 consumed for food and beverage applications. The uncertainty range is derived from the default range for solvent use in Section 5.5 of Chapter 3 of the *2006 IPCC Guidelines*. These values are representative of CO_2 used in food and beverage based on expert judgment (RTI 2023).

The results of the Approach 2 quantitative uncertainty analysis are summarized in Table 4-76. Carbon dioxide consumption CO_2 emissions for 2022 were estimated to be between 4.8 and 5.2 MMT CO_2 Eq. at the 95 percent confidence level. This indicates a range of approximately 5 percent below to 5 percent above the emission estimate of 5.0 MMT CO_2 Eq.

Table 4-76: Approach 2 Quantitative Uncertainty Estimates for CO_2 Emissions from CO_2 Consumption (MMT CO_2 Eq. and Percent)

Source	Gas	2022 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
CO_2 Consumption	CO_2	5.0	4.8	5.2	-5%	+5%

[a] Range of emission estimates predicted by Monte Carlo stochastic simulation for a 95 percent confidence interval.

QA/QC and Verification

General quality assurance/quality control (QA/QC) procedures were applied consistent with the U.S. Inventory QA/QC plan, which is in accordance with Volume 1, Chapter 6 of *2006 IPCC Guidelines* as described in the introduction of the IPPU chapter (see Annex 8 for more details). More details on the greenhouse gas calculation, monitoring and QA/QC methods applicable to CO_2 Consumption can be found under Subpart PP (Suppliers of Carbon Dioxide) of the regulation (40 CFR Part 98).[73] EPA verifies annual facility-level GHGRP reports through a multi-step process (e.g., combination of electronic checks and manual reviews) to identify potential errors and ensure that data submitted to EPA are accurate, complete, and consistent (EPA 2015).[74] Based on the results of the verification process, EPA follows up with facilities to resolve mistakes that may have occurred. The post-submittals checks are consistent with a number of general and category-specific QC procedures, including range checks, statistical checks, algorithm checks, and year-to-year checks of reported data and emissions.

Recalculations Discussion

No recalculations were performed for the 1990 through 2021 portion of the time series.

[72] See https://www.epa.gov/sites/production/files/2015-07/documents/ghgrp_verification_factsheet.pdf.

[73] See http://www.ecfr.gov/cgi-bin/text-idx?tpl=/ecfrbrowse/Title40/40cfr98_main_02.tpl.

[74] See https://www.epa.gov/sites/production/files/2015-07/documents/ghgrp_verification_factsheet.pdf.

Planned Improvements

EPA will continue to evaluate the potential to include additional GHGRP data on other emissive end-uses to improve the accuracy and completeness of estimates for this source category. Particular attention will be made to ensuring time-series consistency of the emissions estimates presented in future *Inventory* reports, consistent with IPCC and UNFCCC guidelines. This is required as the facility-level reporting data from EPA's GHGRP, with the program's initial requirements for reporting of emissions in calendar year 2010, are not available for all inventory years (i.e., 1990 through 2009) as required for this *Inventory*. In implementing improvements and integration of data from EPA's GHGRP, EPA will rely on the latest guidance from the IPCC on the use of facility-level data in national inventories.[75]

These improvements are still in process and will be incorporated into future *Inventory* reports. These are near-to medium-term improvements.

4.17 Phosphoric Acid Production (CRT Source Category 2B10)

Phosphoric acid (H_3PO_4) is a basic raw material used in the production of phosphate-based fertilizers. Phosphoric acid production from natural phosphate rock is a source of carbon dioxide (CO_2) emissions, due to the chemical reaction of the inorganic carbon (calcium carbonate) component of the phosphate rock. This reporting category (2B10) includes emissions that do not fall within any other CRT source category, which includes production of phosphoric acid. Emissions from fuels consumed for energy purposes during the production of phosphoric acid are accounted for as part of fossil fuel combustion in the industrial end-use sector reported under the Energy chapter.

Phosphate rock is mined in Florida and North Carolina, which account for more than 75 percent of total domestic output, and in Idaho and Utah (USGS 2023). It is used primarily as a raw material for wet-process phosphoric acid production. The composition of natural phosphate rock varies, depending on the location where it is mined. Natural phosphate rock mined in the United States generally contains inorganic carbon in the form of calcium carbonate (limestone) and may also contain organic carbon.

The phosphoric acid production process involves chemical reaction of the calcium phosphate ($Ca_3(PO_4)_2$) component of the phosphate rock with sulfuric acid (H_2SO_4) and recirculated phosphoric acid (H_3PO_4) (EFMA 2000). Phosphate rock also contains naturally occurring limestone ($CaCO_3$), ranging from 0.2 to 4.5 percent (as CO_2), with domestic phosphate rock from Florida containing 3.1 percent limestone (as CO_2) (EFMA 2000). The generation of CO_2 from limestone in the phosphate rock is from the associated limestone-sulfuric acid reaction, as shown below:

$$CaCO_3 + H_2SO_4 + H_2O \rightarrow CaSO_4 \cdot 2H_2O + CO_2$$

Total U.S. phosphate rock production in 2022 was an estimated 21 million metric tons (USGS 2023). Between 1990 and 2022, domestic phosphate rock production decreased by approximately 58 percent. Total imports of phosphate rock to the United States in 2022 were 2.4 million metric tons (USGS 2023). Between 2018 and 2021, most of the imported phosphate rock (95 percent) came from Peru, with 5 percent from Morocco (USGS 2023). All phosphate rock mining companies in the United States are vertically integrated with fertilizer plants that produce phosphoric acid located near the mines.

Total CO_2 emissions from phosphoric acid production were 0.8 MMT CO_2 Eq. (840 kt CO_2) in 2022 (see Table 4-77 and Table 4-78). Domestic consumption of phosphate rock in 2022 was estimated to have decreased 3.9 percent

[75] See http://www.ipcc-nggip.iges.or.jp/public/tb/TFI_Technical_Bulletin_1.pdf.

relative to 2021 levels. The COVID-19 pandemic did not impact the domestic phosphate rock market as both the fertilizer industry and related agricultural businesses were considered essential industries and were unaffected by pandemic "stay-at-home" orders issued in March 2020 (USGS 2021a).

Table 4-77: CO_2 Emissions from Phosphoric Acid Production (MMT CO_2 Eq.)

Year	1990	2005	2018	2019	2020	2021	2022
Phosphoric Acid Production	1.5	1.3	0.9	0.9	0.9	0.9	0.8

Table 4-78: CO_2 Emissions from Phosphoric Acid Production (kt CO_2)

Year	1990	2005	2018	2019	2020	2021	2022
Phosphoric Acid Production	1,529	1,342	937	909	901	874	840

Methodology and Time-Series Consistency

The United States uses a country-specific methodology consistent with and comparable to an IPCC Tier 1 approach to calculate emissions from production of phosphoric acid from phosphate rock based on the stoichiometry of the process reaction shown above. The *2006 IPCC Guidelines* do not provide a method for estimating process emissions (CO_2) from phosphoric acid production. Carbon dioxide emissions from production of phosphoric acid from phosphate rock are estimated by multiplying the average amount of inorganic carbon (expressed as CO_2) contained in the natural phosphate rock as calcium carbonate by the amount of phosphate rock that is used annually to produce phosphoric acid, accounting for domestic production and net imports for consumption. The estimation methodology is as follows:

Equation 4-10: CO_2 Emissions from Phosphoric Acid Production

$$E_{pa} = C_{pr} \times Q_{pr}$$

where,

E_{pa} = CO_2 emissions from phosphoric acid production, metric tons

C_{pr} = Average amount of carbon (expressed as CO_2) in natural phosphate rock, metric ton CO_2/ metric ton phosphate rock

Q_{pr} = Quantity of phosphate rock used to produce phosphoric acid

The CO_2 emissions calculation methodology assumes that all of the inorganic carbon (calcium carbonate) content of the phosphate rock reacts to produce CO_2 in the phosphoric acid production process and is emitted with the stack gas. The methodology also assumes that none of the organic carbon content of the phosphate rock is converted to CO_2 and that all of the organic carbon content remains in the phosphoric acid product.

From 1993 to 2004, the U.S. Geological Survey (USGS) *Mineral Yearbook: Phosphate Rock* disaggregated phosphate rock mined annually in Florida and North Carolina from phosphate rock mined annually in Idaho and Utah, and reported the annual amounts of phosphate rock exported and imported for consumption (see Table 4-79). For the years 1990 through 1992, and 2005 through 2022, only nationally aggregated mining data was reported by USGS. For the years 1990, 1991, and 1992, the breakdown of phosphate rock mined in Florida and North Carolina and the amount mined in Idaho and Utah are approximated using data reported by USGS for the average share of U.S. production in those states from 1993 to 2004. For the years 2005 through 2022, the same approximation method is used, but the share of U.S. production was assumed to be consistent with the ratio of production capacity in those states, which were obtained from the USGS commodity specialist for phosphate rock (USGS 2012; USGS 2021b). For 1990 through 2022, data on U.S. domestic consumption of phosphate rock, consisting of domestic reported sales and use of phosphate rock, exports of phosphate rock (primarily from Florida and North Carolina), and imports of phosphate rock for consumption, were obtained from USGS *Minerals Yearbook: Phosphate Rock*

(USGS 1994 through 2015b) and from USGS *Minerals Commodity Summaries: Phosphate Rock* (USGS 2016 through 2021a, 2022). From 2004 through 2022, the USGS reported no exports of phosphate rock from U.S. producers (USGS 2022).

The carbonate content of phosphate rock varies depending upon where the material is mined. Composition data for domestically mined and imported phosphate rock were provided by the Florida Institute of Phosphate Research, now known as the Florida Industrial and Phosphate Research Institute (FIPR 2003a). Phosphate rock mined in Florida contains approximately 1 percent inorganic C, and phosphate rock imported from Morocco contains approximately 1.46 percent inorganic C. Calcined phosphate rock mined in North Carolina and Idaho contains approximately 0.41 percent and 0.27 percent inorganic C, respectively (see Table 4-79). Similar to the phosphate rock mined in Morocco, phosphate rock mined in Peru contains approximately 5 percent CO_2 (Golder Associates and M3 Engineering 2016).

Carbonate content data for phosphate rock mined in Florida are used to calculate the CO_2 emissions from consumption of phosphate rock mined in Florida and North Carolina (more than 75 percent of domestic production), and carbonate content data for phosphate rock mined in Morocco and Peru are used to calculate CO_2 emissions from consumption of imported phosphate rock. The CO_2 emissions calculation assumes that all of the domestic production of phosphate rock is used in uncalcined form. As of 2006, the USGS noted that one phosphate rock producer in Idaho produces calcined phosphate rock; however, no production data were available for this single producer (USGS 2006). The USGS confirmed that no significant quantity of domestic production of phosphate rock is in the calcined form (USGS 2012).

Table 4-79: Phosphate Rock Domestic Consumption, Exports, and Imports (kt)

Location/Year	1990	2005	2018	2019	2020	2021	2022
U.S. Domestic Consumption[a]	49,800	35,200	23,300	23,400	22,600	21,900	21,000
FL and NC	*42,494*	*28,160*	*18,170*	*18,250*	*17,630*	*17,080*	*16,380*
ID and UT	*7,306*	*7,040*	*5,130*	*5,150*	*4,970*	*4,820*	*4,620*
Exports—FL and NC	6,240	0	0	0	0	0	0
Imports	451	2,630	2,770	2,140	2,520	2,460	2,400
Total U.S. Consumption	**44,011**	**37,830**	**26,070**	**25,540**	**25,120**	**24,360**	**23,400**

[a] U.S. domestic consumption values are based on reported phosphate rock sold or used by producers.
Note: Totals may not sum due to independent rounding.

Table 4-80: Chemical Composition of Phosphate Rock (Percent by Weight)

Composition	Central Florida	North Florida	North Carolina (calcined)	Idaho (calcined)	Morocco	Peru
Total Carbon (as C)	1.60	1.76	0.76	0.60	1.56	NA
Inorganic Carbon (as C)	1.00	0.93	0.41	0.27	1.46	NA
Organic Carbon (as C)	0.60	0.83	0.35	0.00	0.10	NA
Inorganic Carbon (as CO_2)	3.67	3.43	1.50	1.00	5.00	5.00

NA (Not Available)
Sources: FIPR (2003a), Golder Associates and M3 Engineering (2016)

Methodological approaches were applied to the entire time series to ensure consistency in emissions estimates from 1990 through 2022.

Uncertainty

Phosphate rock production data used in the emission calculations were developed by the USGS through monthly and semiannual voluntary surveys of the active phosphate rock mines during 2021. Prior to 2006, USGS provided the data disaggregated regionally; however, beginning in 2006, only total U.S. phosphate rock production was

reported. Regional production for 2021 was estimated based on regional production data from 2017 to 2020 and multiplied by regionally-specific emission factors. There is uncertainty associated with the degree to which the estimated 2021 regional production data represents actual production in those regions. Total U.S. phosphate rock production data are not considered to be a significant source of uncertainty because all the domestic phosphate rock producers report their annual production to the USGS. Data for exports of phosphate rock used in the emission calculations are reported to the USGS by phosphate rock producers and are not considered to be a significant source of uncertainty. Data for imports for consumption are based on international trade data collected by the U.S. Census Bureau. These U.S. government economic data are not considered to be a significant source of uncertainty. Based on expert judgement of the USGS, EPA assigned an uncertainty range of ±5 percent to the percentage of phosphate rock produced from Florida and North Carolina, and ±5 percent to phosphoric acid production and imports (USGS 2012). Per this expert judgment, a normal probability density function was assigned for all activity data.

An additional source of uncertainty in the calculation of CO_2 emissions from phosphoric acid production is the carbonate composition of phosphate rock, as the composition of phosphate rock varies depending upon where the material is mined and may also vary over time. The *Inventory* relies on one study (FIPR 2003a) of chemical composition of the phosphate rock; limited data are available beyond this study. Another source of uncertainty is the disposition of the organic carbon content of the phosphate rock. A representative of FIPR indicated that in the phosphoric acid production process, the organic carbon content of the mined phosphate rock generally remains in the phosphoric acid product, which is what produces the color of the phosphoric acid product (FIPR 2003b). Organic carbon is therefore not included in the calculation of CO_2 emissions from phosphoric acid production.

A third source of uncertainty is the assumption that all domestically-produced phosphate rock is used in phosphoric acid production and used without first being calcined. Calcination of the phosphate rock would result in conversion of some of the organic carbon in the phosphate rock into CO_2; however, according to air permit information available to the public, at least one facility has calcining units permitted for operation (NCDENR 2013).

Finally, USGS indicated that in 2021 less than 5 percent of domestically-produced phosphate rock was used to manufacture elemental phosphorus and other phosphorus-based chemicals, rather than phosphoric acid (USGS 2022). According to USGS, there is only one domestic producer of elemental phosphorus, in Idaho, and no data were available concerning the annual production of this single producer. Elemental phosphorus is produced by reducing phosphate rock with coal coke, and it is therefore assumed that 100 percent of the carbonate content of the phosphate rock will be converted to CO_2 in the elemental phosphorus production process. The calculation for CO_2 emissions assumes that phosphate rock consumption, for purposes other than phosphoric acid production, results in CO_2 emissions from 100 percent of the inorganic carbon content in phosphate rock, but none from the organic carbon content.

The results of the Approach 2 quantitative uncertainty analysis are summarized in Table 4-81. 2022 phosphoric acid production CO_2 emissions were estimated to be between 0.7 and 1.1 MMT CO_2 Eq. at the 95 percent confidence level. This indicates a range of approximately 18 percent below and 20 percent above the emission estimate of 0.8 MMT CO_2 Eq.

Table 4-81: Approach 2 Quantitative Uncertainty Estimates for CO_2 Emissions from Phosphoric Acid Production (MMT CO_2 Eq. and Percent)

Source	Gas	2022 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (MMT CO_2 Eq.)		Uncertainty Range Relative to Emission Estimate[a] (%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Phosphoric Acid Production	CO_2	0.8	0.7	1.1	-18%	+20%

[a] Range of emission estimates predicted by Monte Carlo stochastic simulation for a 95 percent confidence interval.

QA/QC and Verification

For more information on the general QA/QC process applied to this source category, consistent with the U.S. Inventory QA/QC plan, which is in accordance with Volume 1, Chapter 6 of *2006 IPCC Guidelines* as described in the introduction of the IPPU chapter (see Annex 8 for more details).

Recalculations Discussion

Recalculations were performed for 2021 to reflect updated USGS data on the total U.S. production of phosphate rock. This update resulted in a decrease of 35 kt CO_2 in 2021.

Planned Improvements

EPA continues to evaluate potential improvements to the *Inventory* estimates for this source category, which include direct integration of EPA's GHGRP data for 2010 through 2022 along with assessing applicability of reported GHGRP data to update the inorganic carbon content of phosphate rock for prior years to ensure time-series consistency. Specifically, EPA would need to assess that averaged inorganic carbon content data (by region or other approaches) meets GHGRP confidential business information (CBI) screening criteria. EPA would then need to assess the applicability of GHGRP data for the averaged inorganic carbon content (by region or other approaches) from 2010 through 2022, along with other information to inform estimates in prior years in the time series (1990 through 2009) based on the sources of phosphate rock used in production of phosphoric acid over time. In implementing improvements and integration of data from EPA's GHGRP, EPA will rely upon the latest guidance from the IPCC on the use of facility-level data in national inventories.[76] These long-term planned improvements are still in development by EPA and have not been implemented into the current *Inventory* report.

4.18 Iron and Steel Production (CRT Source Category 2C1) and Metallurgical Coke Production

Iron and steel production is a multi-step process that generates process-related emissions of carbon dioxide (CO_2) and methane (CH_4) as raw materials are refined into iron and then transformed into crude steel. This reporting category (2C1) includes emissions from the production of iron and steel. Per the IPCC methodological guidance, emissions from conventional fuels (e.g., natural gas, fuel oil) consumed for energy purposes during the production of iron and steel are accounted for as part of fossil fuel combustion in the industrial end-use sector reported under the Energy chapter.

Iron and steel production includes seven distinct production processes: metallurgical coke production, sinter production, direct reduced iron (DRI) production, pellet production, pig iron.[77] production, electric arc furnace

[76] See http://www.ipcc-nggip.iges.or.jp/public/tb/TFI_Technical_Bulletin_1.pdf and the *2019 Refinement*, Volume 1, Chapter 2, Section 2.3, *Use of Facility Data in Inventories* at https://www.ipcc-nggip.iges.or.jp/public/2019rf/pdf/1_Volume1/19R_V1_Ch02_DataCollection.pdf.

[77] Pig iron is the common industry term to describe what should technically be called crude iron. Pig iron is a subset of crude iron that has lost popularity over time as industry trends have shifted. Throughout this report, pig iron will be used

(EAF) steel production, and basic oxygen furnace (BOF) steel production. The number of production processes at a particular plant is dependent upon the specific plant configuration. Most process CO_2 generated from the iron and steel industry is a result of the production of crude iron.

In addition to the production processes mentioned above, CO_2 is also generated at iron and steel mills through the consumption of process byproducts (e.g., blast furnace gas, coke oven gas) used for various purposes including heating, annealing, and electricity generation. Process byproducts sold off-site for use as synthetic natural gas are also accounted for in these calculations. In general, CO_2 emissions are generated in these production processes through the reduction and consumption of various carbon-containing inputs (e.g., ore, scrap, flux, coke byproducts). Fugitive CH_4 emissions can also be generated from these processes, as well as from sinter, direct iron, and pellet production.

In 2022, approximately eleven integrated iron and steel steelmaking facilities utilized BOFs to refine and produce steel from iron, and raw steel was produced at 101 facilities across the United States. As of 2020, approximately 29 percent of steel production was attributed to BOFs and 71 percent to EAFs (AISI 2020). The trend in the United States for integrated facilities has been a shift towards fewer BOFs and more EAFs. EAFs use scrap steel as their main input and use significantly less energy than BOFs. There are also 14 cokemaking facilities, of which 3 facilities are co-located with integrated iron and steel facilities (ACCCI 2021). In the United States, seven states account for roughly 61 percent of total raw steel production: Indiana, Alabama, Tennessee, Kentucky, Mississippi, Arkansas, and Ohio (AISI 2023).

Total annual production of crude steel in the United States was fairly constant between 2000 and 2008 and ranged from a low of 99,320,000 tons to a high of 109,880,000 tons (2001 and 2004, respectively). Due to the decrease in demand caused by the global economic downturn (particularly from the automotive industry), crude steel production in the United States sharply decreased to 65,459,000 tons in 2009. Crude steel production was fairly constant from 2011 through 2014, and after a dip in production from 2014 to 2015, crude steel production steadily increased. Crude steel production dipped again in 2020 due to the COVID-19 pandemic and returned to pre-pandemic levels in 2021. Production declined by approximately 6 percent in 2022 (AISI 2023). This decline may be attributable to projections for decreased global end-use consumption due to multiple factors including the conflict in Ukraine, continuing coronavirus disease 2019 (COVID-19) mitigation measures in China, rising energy costs and interest rates, and global inflation (USGS 2023a). The United States was the fourth largest producer of raw steel in the world, behind China, India, and Japan, accounting for approximately 4.3 percent of world production in 2022 (AISI 2004 through 2023).

The majority of CO_2 emissions from the iron and steel production process come from the use of metallurgical coke in the production of pig iron and from the consumption of other process byproducts, with lesser amounts emitted from the use of carbon-containing flux and from the removal of carbon from pig iron used to produce steel.

According to the *2006 IPCC Guidelines*, the production of metallurgical coke from coking coal is considered to be an energy use of fossil fuel, and the use of coke in iron and steel production is considered to be an industrial process source. The *2006 IPCC Guidelines* suggest that emissions from the production of metallurgical coke should be reported separately in the Energy sector, while emissions from coke consumption in iron and steel production should be reported in the Industrial Processes and Product Use sector. The approaches and emission estimates for both metallurgical coke production and iron and steel production, however, are presented here because much of the relevant activity data is used to estimate emissions from both metallurgical coke production and iron and steel production. For example, some byproducts (e.g., coke oven gas) of the metallurgical coke production process are consumed during iron and steel production, and some byproducts of the iron and steel production process (e.g., blast furnace gas) are consumed during metallurgical coke production. Emissions associated with the consumption of these byproducts are attributed at the point of consumption. Emissions associated with the use of conventional

interchangeably with crude iron, but it should be noted that in other data sets or reports pig iron and crude iron may not be used interchangeably and may provide different values.

fuels (e.g., natural gas, fuel oil) for electricity generation, heating and annealing, or other miscellaneous purposes downstream of the iron and steelmaking furnaces are reported in the Energy chapter.

Metallurgical Coke Production

Emissions of CO_2 from metallurgical coke production in 2022 were 3.0 MMT CO_2 Eq. (2,954 kt CO_2) (see Table 4-82 and Table 4-83). Emissions decreased by 8 percent from 2021 to 2022 and have decreased by 47 percent since 1990. Coke production in 2022 was about 9 percent lower than in 2021 and 59 percent below 1990 (EIA 2023, AISI 2023).

Significant activity data for 2020 through 2022 were not available in time for publication of this report due to industry consolidation that impacts the publication of data without revealing confidential business information. Activity data for these years were estimated using 2019 values adjusted based on GHGRP emissions data, as described in the Methodology and Time-Series Consistency section below.

Table 4-82: CO_2 Emissions from Metallurgical Coke Production (MMT CO_2 Eq.)

Gas	1990	2005	2018	2019	2020	2021	2022
CO_2	5.6	3.9	1.3	3.0	2.3	3.2	3.0

Table 4-83: CO_2 Emissions from Metallurgical Coke Production (kt CO_2)

Gas	1990	2005	2018	2019	2020	2021	2022
CO_2	5,608	3,921	1,282	3,006	2,325	3,224	2,954

Iron and Steel Production

Emissions of CO_2 and CH_4 from iron and steel production in 2022 were 37.7 MMT CO_2 Eq. (37,718 kt) and 0.0077 MMT CO_2 Eq. (0.3 kt CH_4), respectively (see Table 4-84 through Table 4-87). Emissions from iron and steel production decreased by 2 percent from 2021 to 2022 and have decreased by 62 percent since 1990, due to restructuring of the industry, technological improvements, and increased scrap steel utilization. Carbon dioxide emission estimates include emissions from the consumption of carbonaceous materials in the blast furnace, EAF, and BOF, as well as blast furnace gas and coke oven gas consumption for other activities at the steel mill.

Significant activity data for 2020 through 2022 were not available in time for publication of this report due to industry consolidation that impacts the publication of data without revealing confidential business information. Activity data for these years were estimated using 2019 values adjusted based on GHGRP emissions data, as described in the Methodology and Time-Series Consistency section below.

In 2022, domestic production of pig iron decreased by 11 percent from 2021 levels. Overall, domestic pig iron production has declined since the 1990s; pig iron production in 2022 was 59 percent lower than in 2000 and 60 percent below 1990. Carbon dioxide emissions from iron production have decreased by 81 percent (37.0 MMT CO_2 Eq.) since 1990. Carbon dioxide emissions from steel production have decreased by 16 percent (1.3 MMT CO_2 Eq.) since 1990, while overall CO_2 emissions from iron and steel production have declined by 62 percent (61.4 MMT CO_2 Eq.) from 1990 to 2022.

Table 4-84: CO_2 Emissions from Iron and Steel Production (MMT CO_2 Eq.)

Source/Activity Data	1990	2005	2018	2019	2020	2021	2022
Sinter Production	2.4	1.7	0.9	0.9	0.7	0.8	0.8
Iron Production	45.7	17.7	9.6	9.4	8.4	9.0	8.7
Pellet Production	1.8	1.5	0.9	0.9	0.8	0.8	0.8
Steel Production	8.0	9.4	6.0	5.8	5.7	5.8	6.7
Other Activities[a]	41.2	35.9	24.1	23.2	19.8	22.1	20.8
Total	**99.1**	**66.2**	**41.6**	**40.1**	**35.4**	**38.6**	**37.7**

[a] Includes emissions from blast furnace gas and coke oven gas combustion for activities at the steel mill other than consumption in blast furnace, EAFs, or BOFs.
Note: Totals may not sum due to independent rounding.

Table 4-85: CO_2 Emissions from Iron and Steel Production (kt CO_2)

Source/Activity Data	1990	2005	2018	2019	2020	2021	2022
Sinter Production	2,448	1,663	937	876	749	836	787
Iron Production	45,709	17,666	9,589	9,365	8,420	9,038	8,673
Pellet Production	1,817	1,503	924	878	751	838	789
Steel Production	7,964	9,395	5,982	5,812	5,657	5,816	6,655
Other Activities [a]	41,194	35,934	24,149	23,158	19,820	22,119	20,814
Total	**99,132**	**66,161**	**41,581**	**40,089**	**35,398**	**38,648**	**37,718**

[a] Includes emissions from blast furnace gas and coke oven gas combustion for activities at the steel mill other than consumption in blast furnace, EAFs, or BOFs.
Note: Totals may not sum due to independent rounding.

Table 4-86: CH_4 Emissions from Iron and Steel Production (MMT CO_2 Eq.)

Source/Activity Data	1990	2005	2018	2019	2020	2021	2022
Sinter Production	+	+	+	+	+	+	+

+ Does not exceed 0.05 MMT CO_2 Eq.

Table 4-87: CH_4 Emissions from Iron and Steel Production (kt CH_4)

Source/Activity Data	1990	2005	2018	2019	2020	2021	2022
Sinter Production	0.9	0.6	+	+	+	+	+

+ Does not exceed 0.5 kt.

Methodology and Time-Series Consistency

Emission estimates for metallurgical coke, EAF steel production, and BOF steel production presented in this chapter utilize a country-specific approach based on Tier 2 methodologies provided by the *2006 IPCC Guidelines*, in accordance with the IPCC methodological decision tree and available data. These Tier 2 methodologies call for a mass balance accounting of the carbonaceous inputs and outputs during the iron and steel production process and the metallurgical coke production process. Estimates for pig iron production apply Tier 2 methods consistent with the *2006 IPCC Guidelines*, in accordance with the IPCC methodological decision tree and available data. Tier 1 methods are used for certain iron and steel production processes (i.e., sinter production, pellet production and DRI production) for which available data are insufficient to apply a Tier 2 method (e.g., country-specific carbon contents of inputs and outputs are not known). The majority of emissions are captured with higher tier methods, as sinter production, pellet production, and DRI production only account for roughly 8 percent of total iron and steel production emissions.

The Tier 2 methodology equation is as follows:

Equation 4-11: CO_2 Emissions from Coke, Pig Iron, EAF Steel, and BOF Steel Production, based on *2006 IPCC Guidelines* Tier 2 Methodologies

$$E_{CO_2} = \left[\sum_a (Q_a \times C_a) - \sum_b (Q_b \times C_b)\right] \times \frac{44}{12}$$

where,

E_{CO2} = Emissions from coke, pig iron, EAF steel, or BOF steel production, metric tons

a = Input material *a*

b = Output material *b*

Q_a = Quantity of input material *a*, metric tons

C_a = Carbon content of input material *a*, metric tons C/metric ton material

Q_b = Quantity of output material *b*, metric tons

C_b = Carbon content of output material *b*, metric tons C/metric ton material

44/12 = Stoichiometric ratio of CO_2 to C

The Tier 1 methodology equations are as follows:

Equation 4-12: *2006 IPCC Guidelines* Tier 1: Emissions from Sinter, Direct Reduced Iron, and Pellet Production (Equations 4.6, 4.7, and 4.8)

$$E_{s,p} = Q_s \times EF_{s,p}$$

$$E_{d,CO2} = Q_d \times EF_{d,CO2}$$

$$E_{p,CO2} = Q_p \times EF_{p,CO2}$$

where,

$E_{s,p}$ = Emissions from sinter production process for pollutant *p* (CO_2 or CH_4), metric ton

Q_s = Quantity of sinter produced, metric tons

$EF_{s,p}$ = Emission factor for pollutant *p* (CO_2 or CH_4), metric ton *p*/metric ton sinter

$E_{d,CO2}$ = Emissions from DRI production process for CO_2, metric ton

Q_d = Quantity of DRI produced, metric tons

$EF_{d,CO2}$ = Emission factor for CO_2, metric ton CO_2/metric ton DRI

$E_{p,CO2}$ = Emissions from pellet production process for CO_2, metric ton

Q_p = Quantity of pellets produced, metric tons

$EF_{p,CO2}$ = Emission factor for CO_2, metric ton CO_2/metric ton pellets produced

A significant number of activity data that serve as inputs to emissions calculations were unavailable for 2020 through 2022 at the time of publication and were estimated using 2019 values. To estimate annual emissions for these years, the EPA used process emissions data from the EPA's Greenhouse Gas Reporting Program (GHGRP) subpart Q for the iron and steel sector to adjust the estimated values for 2020 through 2022. GHGRP process emissions data decreased by approximately 14 percent from 2019 to 2020, increased by approximately 12 percent from 2020 to 2021, and decreased by approximately 6 percent from 2021 to 2022 (EPA 2023). These percentage changes were applied to 2019 activity data values to produce estimates for 2020 through 2022.

Metallurgical Coke Production

Coking coal is used to manufacture metallurgical coke which is used primarily as a reducing agent in the production of iron and steel but is also used in the production of other metals including zinc and lead (see Zinc Production and Lead Production sections of this chapter). Emissions associated with producing metallurgical coke from coking coal are estimated and reported separately from emissions that result from the iron and steel production process. To estimate emissions from metallurgical coke production, a Tier 2 method provided by the *2006 IPCC Guidelines* was

utilized. The amount of carbon contained in materials produced during the metallurgical coke production process (i.e., coke, coke breeze and coke oven gas) is deducted from the amount of carbon contained in materials consumed during the metallurgical coke production process (i.e., natural gas, blast furnace gas, and coking coal). For calculations, activity data for these inputs, including natural gas, blast furnace gas, and coking coke consumed for metallurgical coke production, are in units consistent with the carbon content values. Light oil, which is produced during the metallurgical coke production process, is excluded from the deductions due to data limitations. The amount of carbon contained in these materials is calculated by multiplying the material-specific carbon content by the amount of material consumed or produced (see Table 4-88). The amount of coal tar produced was approximated using a production factor of 0.03 tons of coal tar per ton of coking coal consumed. The amount of coke breeze produced was approximated using a production factor of 0.075 tons of coke breeze per ton of coking coal consumed (Steiner 2008; DOE 2000). Data on the consumption of carbonaceous materials (other than coking coal) as well as coke oven gas production were available for integrated steel mills only (i.e., steel mills with co-located coke plants); therefore, carbonaceous material (other than coking coal) consumption and coke oven gas production were excluded from emission estimates for merchant coke plants. Carbon contained in coke oven gas used for coke-oven underfiring was not included in the deductions to avoid double-counting.

Table 4-88: Material Carbon Contents for Metallurgical Coke Production

Material	kg C/kg
Coal Tar[a]	0.62
Coke[a]	0.83
Coke Breeze[a]	0.83
Coking Coal[b]	0.75
Material	**kg C/GJ**
Coke Oven Gas[c]	12.1
Blast Furnace Gas[c]	70.8

[a] Source: IPCC (2006), Vol. 3 Chapter 4, Table 4.3
[b] Source: EIA (2017b)
[c] Source: IPCC (2006), Vol. 2 Chapter 1, Table 1.3

Although the *2006 IPCC Guidelines* provide a Tier 1 CH_4 emission factor for metallurgical coke production (i.e., 0.1 g CH_4 per metric ton of coke production), it is not appropriate to use because CO_2 emissions were estimated using the Tier 2 mass balance methodology. The mass balance methodology makes a basic assumption that all carbon that enters the metallurgical coke production process either exits the process as part of a carbon-containing output or as CO_2 emissions. This is consistent with a preliminary assessment of aggregated facility-level greenhouse gas CH_4 emissions reported by coke production facilities under EPA's GHGRP. The assessment indicates that CH_4 emissions from coke production are insignificant and below 500 kt or 0.05 percent of total national emissions. Pending resources and significance, EPA continues to assess the possibility of including these emissions in future Inventories to enhance completeness but has not incorporated these emissions into this report.

Data relating to the mass of coking coal consumed at metallurgical coke plants and the mass of metallurgical coke produced at coke plants were taken from the Energy Information Administration (EIA) *Quarterly Coal Report: October through December* (EIA 1998 through 2019) and EIA *Quarterly Coal Report: January through March* (EIA 2021 through 2023) (see Table 4-89). Data on the volume of natural gas consumption, blast furnace gas consumption, and coke oven gas production for metallurgical coke production at integrated steel mills were obtained from the American Iron and Steel Institute (AISI) *Annual Statistical* Report (AISI 2004 through 2023) and through personal communications with AISI (Steiner 2008) (see Table 4-90). These data from the AISI *Annual Statistical Report* were withheld for 2020 through 2022, so the 2019 values were used as estimated data for the missing 2020 through 2022 values and adjusted using GHGRP emissions data, as described earlier in this Methodology and Time-Series Consistency section.

The factor for the quantity of coal tar produced per ton of coking coal consumed was provided by AISI (Steiner 2008). The factor for the quantity of coke breeze produced per ton of coking coal consumed was obtained through Table 2-1 of the report *Energy and Environmental Profile of the U.S. Iron and Steel Industry* (DOE 2000). Data on

natural gas consumption and coke oven gas production at merchant coke plants were not available and were excluded from the emission estimate. Carbon contents for metallurgical coke, coal tar, coke oven gas, and blast furnace gas were provided by the *2006 IPCC Guidelines*. The carbon content for coke breeze was assumed to equal the carbon content of coke. Carbon contents for coking coal was from EIA.

Table 4-89: Production and Consumption Data for the Calculation of CO_2 Emissions from Metallurgical Coke Production (Thousand Metric Tons)

Source/Activity Data	1990	2005	2018	2019	2020	2021	2022
Metallurgical Coke Production							
Coking Coal Consumption at Coke Plants	35,269	21,259	16,635	16,261	13,076	15,957	14,523
Coke Production at Coke Plants	25,054	15,167	12,525	11,676	9,392	11,381	10,337
Coke Breeze Production	2,645	1,594	1,248	1,220	981	1,197	1,089
Coal Tar Production	1,058	638	499	488	392	479	436

Table 4-90: Production and Consumption Data for the Calculation of CO_2 Emissions from Metallurgical Coke Production (Million ft^3)

Source/Activity Data	1990	2005	2018	2019	2020	2021	2022
Metallurgical Coke Production							
Coke Oven Gas Production	250,767	114,213	80,750	77,692	66,492	74,206	69,829
Natural Gas Consumption	599	2,996	2,275	2,189	1,873	2,091	1,967
Blast Furnace Gas Consumption	24,602	4,460	4,022	3,914	3,350	3,738	3,518

Iron and Steel Production

To estimate emissions from pig iron production in the blast furnace, the amount of carbon contained in the produced pig iron and blast furnace gas were deducted from the amount of carbon contained in inputs (i.e., metallurgical coke, sinter, natural ore, pellets, natural gas, fuel oil, coke oven gas, carbonate fluxes or slagging materials, and direct coal injection). For calculations, activity data for these inputs, including coke consumed for pig iron production, are in units consistent with the carbon content values. The carbon contained in the pig iron, blast furnace gas, and blast furnace inputs was estimated by multiplying the material-specific carbon content by each material type (see Table 4-91). In the absence of a default carbon content value from the *2006 IPCC Guidelines* for pellet, sinter, or natural ore consumed for pig iron production, a country-specific approach based on Tier 2 methodology is used. Pellet, sinter, and natural ore used as an input for pig iron production is assumed to have the same carbon content as direct reduced iron (2 percent), based on expert judgment (RTI 2024). Carbon in blast furnace gas used to pre-heat the blast furnace air is combusted to form CO_2 during this process. Carbon contained in blast furnace gas used as a blast furnace input was not included in the deductions to avoid double-counting.

Emissions from steel production in EAFs were estimated by deducting the carbon contained in the steel produced from the carbon contained in the EAF anode, charge carbon, and scrap steel added to the EAF. Small amounts of carbon from DRI and pig iron to the EAFs were also included in the EAF calculation. For BOFs, estimates of carbon contained in BOF steel were deducted from carbon contained in inputs such as natural gas, coke oven gas, fluxes (i.e., limestone and dolomite), and pig iron. In each case, the carbon was calculated by multiplying material-specific carbon contents by each material type (see Table 4-91). For EAFs, the amount of EAF anode consumed was approximated by multiplying total EAF steel production by the amount of EAF anode consumed per metric ton of steel produced (0.002 metric tons EAF anode per metric ton steel produced [Steiner 2008]). The amount of carbon-containing flux (i.e., limestone and dolomite) used in EAF and BOF steel production was deducted from the "Other Process Uses of Carbonates" source category (CRT Source Category 2A4) to avoid double-counting.

Carbon dioxide emissions from the consumption of blast furnace gas and coke oven gas for other activities occurring at the steel mill were estimated by multiplying the amount of these materials consumed for these purposes by the material-specific carbon content (see Table 4-91).

Table 4-91: Material Carbon Contents for Iron and Steel Production

Material	kg C/kg
Coke	0.83
Direct Reduced Iron	0.02
Dolomite	0.13
EAF Carbon Electrodes	0.82
EAF Charge Carbon	0.83
Limestone	0.12
Pig Iron	0.04
Steel	0.01
Material	**kg C/GJ**
Coke Oven Gas	12.1
Blast Furnace Gas	70.8

Source: IPCC (2006), Table 4.3. Coke Oven Gas and Blast Furnace Gas, Table 1.3.

Carbon dioxide emissions associated with sinter production, direct reduced iron production, pellet production, pig iron production, steel production, and other steel mill activities were summed to calculate the total CO_2 emissions from iron and steel production (see Table 4-84 and Table 4-85).

The sinter production process results in fugitive emissions of CH_4, which are emitted via leaks in the production equipment, rather than through the emission stacks or vents of the production plants. The fugitive emissions were calculated by applying Tier 1 emission factors taken from the *2006 IPCC Guidelines* for sinter production (see Table 4-92). Although the *2006 IPCC Guidelines* also provide a Tier 1 methodology for CH_4 emissions from pig iron production, it is not appropriate to use because CO_2 emissions for pig iron production are estimated using the Tier 2 mass balance methodology. The mass balance methodology makes a basic assumption that all carbon that enters the pig iron production process either exits the process as part of a carbon-containing output or as CO_2 emissions; the estimation of CH_4 emissions is precluded. Annual analysis of facility-level emissions reported during iron production further supports this assumption and indicates that CH_4 emissions are below 500 kt CO_2 Eq. and well below 0.05 percent of total national emissions. The production of direct reduced iron could also result in emissions of CH_4 through the consumption of fossil fuels (e.g., natural gas, etc.); however, these emission estimates are excluded due to data limitations. Pending further analysis and resources, EPA may include these emissions in future reports to enhance completeness. EPA is still assessing the possibility of including these emissions in future reports and have not included this data in the current report.

Table 4-92: CH_4 Emission Factors for Sinter and Pig Iron Production

Material Produced	Factor	Unit
Sinter	0.07	kg CH_4/metric ton

Source: IPCC (2006), Table 4.2.

Emissions of CO_2 from sinter production, direct reduced iron production, and pellet production were estimated by multiplying total national sinter production, total national direct reduced iron production, and total national pellet production by Tier 1 CO_2 emission factors (see Table 4-93). Because estimates of sinter production, direct reduced iron production, and pellet production were not available, production was assumed to equal consumption.

Table 4-93: CO_2 Emission Factors for Sinter Production, Direct Reduced Iron Production, and Pellet Production

Material Produced	Metric Ton CO_2/Metric Ton
Sinter	0.2
Direct Reduced Iron	0.7
Pellet Production	0.03

Source: IPCC (2006), Table 4.1.

The consumption of coking coal, natural gas, distillate fuel, and coal used in iron and steel production are adjusted for within the Energy chapter to avoid double-counting of emissions reported within the IPPU chapter as these fuels were consumed during non-energy related activities. More information on this methodology and examples of adjustments made between the IPPU and Energy chapters are described in Annex 2.1, Methodology for Estimating Emissions of CO_2 from Fossil Fuel Combustion.

Sinter consumption and pellet consumption data for 1990 through 2020 were obtained from AISI's *Annual Statistical Report* (AISI 2004 through 2022) and through personal communications with AISI (Steiner 2008) (see Table 4-94). These data from the AISI *Annual Statistical Report* were withheld for 2020 through 2022, so the 2019 values were used as estimated data for the missing 2020 through 2022 values and adjusted using GHGRP emissions data, as described earlier in this Methodology and Time-Series Consistency section.

In general, direct reduced iron (DRI) consumption data were obtained from the U.S. Geological Survey (USGS) *Minerals Yearbook – Iron and Steel Scrap* (USGS 1991 through 2022; USGS 2023b) and personal communication with the USGS Iron and Steel Commodity Specialist (Tuck 2023a). Data for DRI consumed in EAFs were not available for the years 1990 and 1991. EAF DRI consumption in 1990 and 1991 was calculated by multiplying the total DRI consumption for all furnaces by the EAF share of total DRI consumption in 1992. Data for DRI consumed in BOFs were not available for the years 1990 through 1993. BOF DRI consumption in 1990 through 1993 was calculated by multiplying the total DRI consumption for all furnaces (excluding EAFs and cupola) by the BOF share of total DRI consumption (excluding EAFs and cupola) in 1994.

The Tier 1 CO_2 emission factors for sinter production, direct reduced iron production and pellet production were obtained through the *2006 IPCC Guidelines* (IPCC 2006). Time-series data for pig iron production, coke, natural gas, fuel oil, sinter, and pellets consumed in the blast furnace; pig iron production; and blast furnace gas produced at the iron and steel mill and used in the metallurgical coke ovens and other steel mill activities were obtained from AISI's *Annual Statistical Report* (AISI 2004 through 2021) and through personal communications with AISI (Steiner 2008) (see Table 4-94 and Table 4-95). Data including blast furnace gas, coke oven gas, natural gas, limestone, sinter, and natural ore consumption for blast furnaces, coke production, and steelmaking furnaces (EAFs and BOFs) from the AISI *Annual Statistical Report* were withheld for 2020 through 2022, so the 2019 values were used as estimated data for the missing 2020 through 2022 values and adjusted using GHGRP emissions data, as described earlier in this Methodology and Time-Series Consistency section. Similarly, the percent of total steel production for EAF and BOF steelmaking processes were withheld for 2021 and 2022, so the 2020 values were used as estimated data for the missing 2021 values and adjusted using GHGRP emissions data, as described earlier in this Methodology and Time-Series Consistency section.

Data for EAF steel production, carbon-containing flux, EAF charge carbon, and natural gas consumption were obtained from AISI's *Annual Statistical Report* (AISI 2004 through 2022) and through personal communications with AISI (AISI 2006 through 2016, Steiner 2008). The factor for the quantity of EAF anode consumed per ton of EAF steel produced was provided by AISI (Steiner 2008). Data for BOF steel production, carbon-containing flux, natural gas, natural ore, pellet, sinter consumption as well as BOF steel production were obtained from AISI's *Annual Statistical Report* (AISI 2004 through 2023) and through personal communications with AISI (Steiner 2008). Data for EAF consumption of natural gas and BOF consumption of coke oven gas, limestone, and natural ore from the AISI *Annual Statistical Report* were not available for 2021 and 2022, so 2020 values were used as estimated data for the missing 2021 and 2022 values and adjusted using GHGRP emissions data, as described earlier in this

Methodology and Time-Series Consistency section. Data for EAF and BOF scrap steel, pig iron, and DRI consumption were obtained from the USGS *Minerals Yearbook – Iron and Steel Scrap* (USGS 1991 through 2022; USGS 2023b) and personal communication with the USGS Iron and Steel Commodity Specialist (Tuck 2023a). Data on coke oven gas and blast furnace gas consumed at the iron and steel mill (other than in the EAF, BOF, or blast furnace) were obtained from AISI's *Annual Statistical Report* (AISI 2004 through 2021) and through personal communications with AISI (Steiner 2008). These data were not available for 2021 and 2022, so 2020 values were used as estimated data for the missing 2021 and 2022 values and adjusted using GHGRP emissions data, as described earlier in this Methodology and Time-Series Consistency section. Some data from the *AISI Annual Statistical Report* on natural gas consumption were withheld for 2020 through 2022, so the 2019 values were used as estimated data for the missing 2020 through 2022 values and adjusted using GHGRP emissions data, as described earlier in this Methodology and Time-Series Consistency section.

Data on blast furnace gas and coke oven gas sold for use as synthetic natural gas were obtained from EIA's *Natural Gas Annual 2019* (EIA 2020). Carbon contents for direct reduced iron, EAF carbon electrodes, EAF charge carbon, limestone, dolomite, pig iron, and steel were provided by the *2006 IPCC Guidelines*. The carbon contents for natural gas, fuel oil, and direct injection coal were obtained from EIA (EIA 2017b) and EPA (EPA 2010). Heat contents for fuel oil and direct injection coal were obtained from EIA (EIA 1992, 2011); natural gas heat content was obtained from Table 37 of AISI's *Annual Statistical Report* (AISI 2004 through 2021). Heat contents for coke oven gas and blast furnace gas were provided in Table 37 of AISI's *Annual Statistical Report* (AISI 2004 through 2021) and confirmed by AISI staff (Carroll 2016).

Table 4-94: Production and Consumption Data for the Calculation of CO_2 and CH_4 Emissions from Iron and Steel Production (Thousand Metric Tons)

Source/Activity Data	1990	2005	2018	2019	2020	2021	2022
Sinter Production	12,239	8,315	4,687	4,378	3,747	4,182	3,935
Direct Reduced Iron Production	517	1,303	C	C	C	C	C
Pellet Production	60,563	50,096	30,793	29,262	25,044	27,949	26,300
Pig Iron Production							
Coke Consumption	24,946	13,832	7,618	7,291	6,240	6,964	6,553
Pig Iron Production	49,669	37,222	24,058	22,302	18,320	22,246	19,791
Direct Injection Coal Consumption	1,485	2,573	2,569	2,465	2,110	2,354	2,216
EAF Steel Production							
EAF Anode and Charge Carbon Consumption	67	1,127	1,133	1,137	1,118	1,129	1,123
Scrap Steel Consumption	42,691	46,600	C	C	C	C	C
Flux Consumption	319	695	998	998	998	998	998
EAF Steel Production	33,511	52,194	58,904	61,172	51,349	57,307	53,926
BOF Steel Production							
Pig Iron Consumption	47,307	34,400	C	C	C	C	C
Scrap Steel Consumption	14,713	11,400	C	C	C	C	C
Flux Consumption	576	582	408	363	311	347	326
BOF Steel Production	43,973	42,705	27,704	26,591	21,384	23,865	22,457

C (Confidential)

Table 4-95: Production and Consumption Data for the Calculation of CO_2 Emissions from Iron and Steel Production (Million ft^3 unless otherwise specified)

Source/Activity Data	1990	2005	2018	2019	2020	2021	2022
Pig Iron Production							
Natural Gas Consumption	56,273	59,844	40,204	37,934	32,465	36,232	34,095
Fuel Oil Consumption (thousand gallons)	163,397	16,170	3,365	2,321	1,986	2,217	2,086

Coke Oven Gas Consumption	22,033	16,557	13,337	12,926	11,063	12,346	11,618
Blast Furnace Gas Production	1,439,380	1,299,980	871,860	836,033	715,509	798,522	751,418
EAF Steel Production							
Natural Gas Consumption	15,905	19,985	8,556	9,115	7,801	8,706	8,192
BOF Steel Production							
Coke Oven Gas Consumption	3,851	524	405	389	333	372	350
Other Activities							
Coke Oven Gas Consumption	224,883	97,132	67,008	64,377	55,096	61,489	57,861
Blast Furnace Gas Consumption	1,414,778	1,295,520	867,838	832,119	712,159	794,783	747,900

Methodological approaches were applied to the entire time series to ensure consistency in emissions from 1990 through 2022.

Uncertainty

The estimates of CO_2 emissions from metallurgical coke production are based on assessing uncertainties in material production and consumption data and average carbon contents. Uncertainty is associated with the total U.S. coking coal consumption, total U.S. coke production, and materials consumed during this process. Data for coking coal consumption and metallurgical coke production are from different data sources (EIA) than data for other carbonaceous materials consumed at coke plants (AISI), which does not include data for merchant coke plants. There is uncertainty associated with the fact that coal tar and coke breeze production were estimated based on coke production because coal tar and coke breeze production data were not available. Since merchant coke plant data is not included in the estimate of other carbonaceous materials consumed at coke plants, the mass balance equation for CO_2 from metallurgical coke production cannot be reasonably completed; therefore, for the purpose of this analysis, uncertainty parameters are applied to primary data inputs to the calculation (i.e., coking coal consumption and metallurgical coke production) only.

The estimates of CO_2 emissions from iron and steel production are based on material production and consumption data and average carbon contents. There is uncertainty associated with the assumption that pellet production, direct reduced iron and sinter consumption are equal to production. There is uncertainty with the representativeness of the associated IPCC default emission factors. There is uncertainty associated with the assumption that all coal used for purposes other than coking coal is for direct injection coal. There is also uncertainty associated with the carbon contents for pellets, sinter, and natural ore, which are assumed to equal the carbon contents of direct reduced iron, when consumed in the blast furnace. There is uncertainty associated with the consumption of natural ore under current industry practices. For EAF steel production, there is uncertainty associated with the amount of EAF anode and charge carbon consumed due to inconsistent data throughout the time series. Also for EAF steel production, there is uncertainty associated with the assumption that 100 percent of the natural gas attributed to "steelmaking furnaces" by AISI is process-related and nothing is combusted for energy purposes. Uncertainty is also associated with the use of process gases such as blast furnace gas and coke oven gas. Data are not available to differentiate between the use of these gases for processes at the steel mill versus for energy generation (i.e., electricity and steam generation); therefore, all consumption is attributed to iron and steel production. These data and carbon contents produce a relatively accurate estimate of CO_2 emissions; however, there are uncertainties associated with each.

For calculating the emissions estimates from iron and steel and metallurgical coke production, EPA utilizes a number of data points taken from the AISI *Annual Statistical Report* (ASR). This report serves as a benchmark for information on steel companies in United States, regardless if they are a member of AISI, which represents integrated producers (i.e., blast furnace and EAF). During the compilation of the 1990 through 2016 *Inventory* report EPA initiated conversation with AISI to better understand and update the qualitative and quantitative uncertainty metrics associated with AISI data elements. AISI estimates their data collection response rate to range from 75 to 90 percent, with certain sectors of the iron and steel industry not being covered by the ASR; therefore, there is some inherent uncertainty in the values provided in the AISI ASR, including material production and consumption data. There is also some uncertainty to which materials produced are exported to Canada. As

indicated in the introduction to this section, the trend for integrated facilities has moved to more use of EAFs and fewer BOFs. This trend may not be completely captured in the current data which also increases uncertainty. EPA assigned an uncertainty range of ±10 percent for the primary data inputs (i.e., consumption and production values for each production process, heat and carbon content values), a normal probability density function for consumption and production values for each production process, and a triangular probability density function for heat and carbon content values to calculate overall uncertainty from iron and steel production, and using this suggested uncertainty provided in Table 4.4 of the *2006 IPCC Guidelines* is appropriate based on expert judgment (RTI 2023). During EPA's discussion with AISI, AISI noted that an uncertainty range of ±5 percent would be a more appropriate approximation to reflect their coverage of integrated steel producers in the United States. EPA will continue to assess the best range of uncertainty for these values. EPA assigned an uncertainty range of ±25 percent and a triangular probability density function for the Tier 1 CO_2 emission factors for the sinter, direct reduced iron, and pellet production processes, and using this suggested uncertainty provided in Table 4.4 of the *2006 IPCC Guidelines* is appropriate based on expert judgment (RTI 2023).

The results of the Approach 2 quantitative uncertainty analysis are summarized in Table 4-96 for metallurgical coke production and iron and steel production. Total CO_2 emissions from metallurgical coke production and iron and steel production for 2022 were estimated to be between 34.3 and 47.1 MMT CO_2 Eq. at the 95 percent confidence level. This indicates a range of approximately 16 percent below and 16 percent above the emission estimate of 40.7 MMT CO_2 Eq. Total CH_4 emissions from metallurgical coke production and iron and steel production for 2022 were estimated to be between 0.007 and 0.008 MMT CO_2 Eq. at the 95 percent confidence level. This indicates a range of approximately 7 percent below and 7 percent above the emission estimate of 0.0077 MMT CO_2 Eq.

Table 4-96: Approach 2 Quantitative Uncertainty Estimates for CO_2 and CH_4 Emissions from Iron and Steel Production and Metallurgical Coke Production (MMT CO_2 Eq. and Percent)

Source	Gas	2022 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Metallurgical Coke & Iron and Steel Production	CO_2	40.7	34.3	47.1	-16%	+16%
Metallurgical Coke & Iron and Steel Production	CH_4	+	+	+	-7%	+7%

+ Does not exceed 0.05 MMT CO_2 Eq.

[a] Range of emission estimates predicted by Monte Carlo stochastic simulation for a 95 percent confidence interval.

QA/QC and Verification

General quality assurance/quality control (QA/QC) procedures were applied consistent with the U.S. Inventory QA/QC plan, which is in accordance with Volume 1, Chapter 6 of *2006 IPCC Guidelines* as described in the introduction of the IPPU chapter (see Annex 8 for more details). As part of a multiyear improvement effort, EPA is reviewing the iron and steel methodology and available data, conducting additional category specific QC checks and will report on findings when that review is complete (i.e., projected to be complete at earliest for the 2025 report). More information is provided under Planned Improvements below.

Recalculations Discussion

Recalculations were performed for the year 2021 with updated USGS values for DRI, pig iron, and scrap steel consumption for both BOF and EAF steel production. Additionally, revisions to GHGRP data for 2020 and 2021 resulted in minor changes to activity data that were adjusted using GHGRP data, as described in the Methodology and Time-Series Consistency section. Compared to the previous *Inventory*, CO_2 emissions from steel production increased by less than 1 percent (7 kt CO_2) in 2020 and by less than 1 percent (211 kt CO_2) in 2021.

Planned Improvements

Significant activity data for 2020 through 2022 were not available for this report and were estimated using 2019 values and adjusted using GHGRP emissions data. EPA will continue to explore sources of 2020 through 2022 data and other estimation approaches. EPA will evaluate and analyze data reported under EPA's GHGRP to improve the emission estimates for Iron and Steel Production process categories. Particular attention will be made to ensure time-series consistency of the emissions estimates presented in future *Inventory* reports, consistent with IPCC and UNFCCC guidelines. This is required as the facility-level reporting data from EPA's GHGRP, with the program's initial requirements for reporting of emissions in calendar year 2010, are not available for all inventory years (i.e., 1990 through 2009) as required for this *Inventory*. In implementing improvements and integration of data from EPA's GHGRP, EPA will rely on the latest guidance from the IPCC on the use of facility-level data in national inventories.[78] This is a near to medium-term improvement, and per preliminary work, EPA estimates that the earliest this improvement could be incorporated is the next (i.e., 2025) *Inventory* submission.

Additional improvements include accounting for emission estimates for the production of metallurgical coke in the Energy chapter as well as identifying the amount of carbonaceous materials, other than coking coal, consumed at merchant coke plants. Other potential improvements include identifying the amount of coal used for direct injection and the amount of coke breeze, coal tar, and light oil produced during coke production. Efforts will also be made to identify information to better characterize emissions from the use of process gases and fuels within the Energy and IPPU chapters. Additional efforts will be made to improve the reporting and transparency in accounting for fuels between the IPPU and Energy chapters, particularly the inclusion of a quantitative summary of the carbon balance in the United States. This planned improvement is a long-term improvement and is still in development. It is not included in this current *Inventory* report. EPA estimates that the earliest this improvement could be incorporated is the next (i.e., 2025) *Inventory* submission.

4.19 Ferroalloy Production (CRT Source Category 2C2)

Ferroalloys are composites of iron (Fe) and other elements such as silicon (Si), manganese (Mn), and chromium (Cr). This reporting category (2C2) includes emissions of carbon dioxide (CO_2) and methane (CH_4) from the production of several ferroalloys. Per the IPCC methodological guidance, emissions from fuels consumed for energy purposes during the production of ferroalloys are accounted for as part of fossil fuel combustion in the industrial end-use sector reported under the Energy chapter. Emissions from the production of two types of ferrosilicon (25 to 55 percent and 56 to 95 percent silicon), silicon metal (96 to 99 percent silicon), and miscellaneous alloys (32 to 65 percent silicon) have been calculated.

Emissions from the production of ferrochromium and ferromanganese are not included because of the small number of manufacturers of these materials in the United States. Government information disclosure rules prevent the publication of production data for these production facilities. Additionally, production of ferrochromium in the United States ceased in 2009 (USGS 2013a).

Similar to emissions from the production of iron and steel, CO_2 is emitted when metallurgical coke is oxidized during a high-temperature reaction with iron and the selected alloying element. Due to the strong reducing

[78] See http://www.ipcc-nggip.iges.or.jp/public/tb/TFI_Technical_Bulletin_1.pdf and the *2019 Refinement*, Volume 1, Chapter 2, Section 2.3, *Use of Facility Data in Inventories* at https://www.ipcc-nggip.iges.or.jp/public/2019rf/pdf/1_Volume1/19R_V1_Ch02_DataCollection.pdf.

environment, CO is initially produced and eventually oxidized to CO_2. A representative reaction equation for the production of 50 percent ferrosilicon (FeSi) is given below:

$$Fe_2O_3 + 2SiO_2 + 7C \rightarrow 2FeSi + 7CO$$

While most of the carbon contained in the process materials is released to the atmosphere as CO_2, a percentage is also released as CH_4 and other volatiles. The amount of CH_4 that is released is dependent on furnace efficiency, operation technique, and control technology.

Ferroalloys are used to alter the material properties of the steel. Ferroalloys are produced in conjunction with the iron and steel industry, often at co-located facilities, and production trends closely follow that of the iron and steel industry. As of 2020, 11 facilities in the United States produce ferroalloys (USGS 2022b).

Emissions of CO_2 from ferroalloy production in 2022 were 1.3 MMT CO_2 Eq. (1,327 kt CO_2) (see Table 4-97 and Table 4-98), which is a 15 percent reduction since 2021 and a 38 percent reduction since 1990. Emissions of CH_4 from ferroalloy production in 2022 were 0.01 MMT CO_2 Eq. (0.4 kt CH_4), which is a 15 percent decrease since 2021 and a 45 percent decrease since 1990. Variability in emissions over the past five years is attributable to facility shutdowns in 2018 and 2020 (USGUS 2020; USGS 2021). The latter facility reopened its ferrosilicon production facility in 2021, owing to increased demand for ferrosilicon products and improved domestic pricing (USGS 2022c).

Table 4-97: CO_2 and CH_4 Emissions from Ferroalloy Production (MMT CO_2 Eq.)

Gas	1990	2005	2018	2019	2020	2021	2022
CO_2	2.2	1.4	2.1	1.6	1.4	1.6	1.3
CH_4	+	+	+	+	+	+	+
Total	**2.2**	**1.4**	**2.1**	**1.6**	**1.4**	**1.6**	**1.3**

+ Does not exceed 0.05 MMT CO_2 Eq.

Note: Totals may not sum due to independent rounding.

Table 4-98: CO_2 and CH_4 Emissions from Ferroalloy Production (kt)

Gas	1990	2005	2018	2019	2020	2021	2022
CO_2	2,152	1,392	2,063	1,598	1,377	1,567	1,327
CH_4	1	+	1	+	+	+	+

+ Does not exceed 0.5 kt

Methodology and Time-Series Consistency

Emissions of CO_2 and CH_4 from ferroalloy production are calculated[79] using a Tier 1 method from the *2006 IPCC Guidelines*, in accordance with the IPCC methodological decision tree and available data. Annual ferroalloy production is multiplied by material-specific emission factors provided by IPCC (IPCC 2006). The Tier 1 equations for CO_2 and CH_4 emissions are as follows:

Equation 4-13: *2006 IPCC Guidelines* Tier 1: CO_2 Emissions for Ferroalloy Production (Equation 4.15)

$$E_{CO_2} = \sum_i (MP_i \times EF_i)$$

[79] EPA has not integrated aggregated facility-level GHGRP information to inform these estimates. The aggregated information (e.g., activity data and emissions) associated with production of ferroalloys did not meet criteria to shield underlying confidential business information (CBI) from public disclosure.

where,

E_{CO2} = CO_2 emissions, metric tons

MP_i = Production of ferroalloy type *i*, metric tons

EF_i = Generic emission factor for ferroalloy type *i*, metric tons CO_2/metric ton specific ferroalloy product

Equation 4-14: *2006 IPCC Guidelines* Tier 1: CH_4 Emissions for Ferroalloy Production (Equation 4.18)

$$E_{CH_4} = \sum_i (MP_i \times EF_i)$$

where,

E_{CH4} = CH_4 emissions, kg

MP_i = Production of ferroalloy type *i*, metric tons

EF_i = Generic emission factor for ferroalloy type *i*, kg CH_4/metric ton specific ferroalloy product

Default emission factors were used because country-specific emission factors are not currently available. The following emission factors were used to develop annual CO_2 and CH_4 estimates:

- Ferrosilicon, 25 to 55 percent Si and Miscellaneous Alloys, 32 to 65 percent Si: 2.5 metric tons CO_2/metric ton of alloy produced, 1.0 kg CH_4/metric ton of alloy produced.
- Ferrosilicon, 56 to 95 percent Si: 4.0 metric tons CO_2/metric ton alloy produced, 1.0 kg CH_4/metric ton of alloy produced.
- Silicon Metal: 5.0 metric tons CO_2/metric ton metal produced, 1.2 kg CH_4/metric ton metal produced.

It was assumed that 100 percent of the ferroalloy production was produced using petroleum coke in an electric arc furnace process (IPCC 2006), although some ferroalloys may have been produced with coking coal, wood, other biomass, or graphite carbon inputs. The amount of petroleum coke consumed in ferroalloy production was calculated assuming that the petroleum coke used is 90 percent carbon (C) and 10 percent inert material (Onder and Bagdoyan 1993).

The use of petroleum coke for ferroalloy production is adjusted for within the Energy chapter as this fuel was consumed during non-energy related activities. Additional information on the adjustments made within the Energy sector for non-energy use of fuels is described in both the Methodology section of CO_2 from Fossil Fuel Combustion (3.1 Fossil Fuel Combustion [CRT Source Category 1A]) and Annex 2.1, Methodology for Estimating Emissions of CO_2 from Fossil Fuel Combustion.

Ferroalloy production data for 1990 through 2022 (see Table 4-99) were obtained from the U.S. Geological Survey (USGS) through the *Minerals Yearbook: Silicon* (USGS 1996 through 2022) and the *Minerals Industry Survey: Silicon* (USGS 2023a). The following data were available from the USGS publications for the time series:

- Ferrosilicon, 25 to 55 percent Si: Annual production data were available from 1990 through 2010.
- Ferrosilicon, 56 to 95 percent Si: Annual production data were available from 1990 through 2010.
- Silicon Metal: Annual production data were available from 1990 through 2005. Production data for 2005 were used as estimates for 2006 through 2010 because data for these years were not available due to government information disclosure rules.
- Miscellaneous Alloys, 32 to 65 percent Si: Annual production data were available from 1990 through 1998. Starting 1999, USGS reported miscellaneous alloys and ferrosilicon containing 25 to 55 percent silicon as a single category.

Starting with the 2011 publication, USGS ceased publication of production quantity by ferroalloy product and began reporting all the ferroalloy production data as a single category (i.e., Total Silicon Materials Production). This is due to the small number of ferroalloy manufacturers in the United States and government information disclosure rules. Ferroalloy product shares developed from the 2010 production data (i.e., ferroalloy product production divided by total ferroalloy production) were used with the total silicon materials production quantity to estimate the production quantity by ferroalloy product type for 2011 through 2022 (USGS 2017 through 2022).

Table 4-99: Production of Ferroalloys (Metric Tons)

Year	1990	2005	2018	2019	2020	2021	2022
Ferrosilicon 25%-55%	321,385	123,000	189,846	147,034	126,681	144,227	122,119
Ferrosilicon 56%-95%	109,566	86,100	167,511	129,736	111,778	127,259	107,752
Silicon Metal	145,744	148,000	183,642	142,229	122,541	139,514	118,128
Misc. Alloys 32-65%	72,442	NA	NA	NA	NA	NA	NA

NA (Not Available) for product type, aggregated with ferrosilicon (25-55% Si)

Methodological approaches were applied to the entire time series to ensure consistency in emissions from 1990 through 2022.

Uncertainty

Annual ferroalloy production was reported by the USGS in three broad categories until the 2010 publication: ferroalloys containing 25 to 55 percent silicon (including miscellaneous alloys), ferroalloys containing 56 to 95 percent silicon, and silicon metal (through 2005 only, 2005 value used as an estimate for 2006 through 2010). Starting with the *2011 Minerals Yearbook: Silicon*, USGS started reporting all the ferroalloy production under a single category: total silicon materials production. The total silicon materials quantity was allocated across the three categories, based on the 2010 production shares for the three categories. Refer to the Methodology section for further details. Additionally, production data for silvery pig iron (alloys containing less than 25 percent silicon) are not reported by the USGS to avoid disclosing proprietary company data. Emissions from this production category, therefore, were not estimated.

Some ferroalloys may be produced using wood or other biomass as a primary or secondary carbon source (carbonaceous reductants); however, information and data regarding these practices were not available. Emissions from ferroalloys produced with wood or other biomass would not be counted under this source because wood-based carbon is of biogenic origin.[80] Even though emissions from ferroalloys produced with coking coal or graphite inputs would be counted in national trends, they may be generated with varying amounts of CO_2 per unit of ferroalloy produced. The most accurate method for these estimates would be to base calculations on the amount of reducing agent used in the process, rather than the amount of ferroalloys produced. These data, however, were not available, and are also often considered confidential business information.

Emissions of CH_4 from ferroalloy production will vary depending on furnace specifics, such as type, operation technique, and control technology. Higher heating temperatures and techniques such as sprinkle charging would reduce CH_4 emissions; however, specific furnace information was not available or included in the CH_4 emission estimates.

EPA assigned a uncertainty range of ±25 percent for the primary emission factors (i.e., ferrosilicon 25-55% Si, ferrosilicon 56-95% Si, and silicon metal), and an uncertainty range of ±5 percent for the 2010 production values for ferrosilicon 25-55% Si, ferrosilicon 56-95% Si, and silicon metal production and the 2021 total silicon materials production value used to calculate emissions from overall ferroalloy production. Using these suggested uncertainties provided in in Table 4.9 of Section 4.3.3.2 of the *2006 IPCC Guidelines* is appropriate based on expert

[80] Emissions and sinks of biogenic carbon are accounted for in the Land Use, Land-Use Change, and Forestry chapter.

judgment (RTI 2023). Per this expert judgment, a normal probability density function was assumed for all activity data, and a triangular probability density function was assumed for emission factors.

The results of the Approach 2 quantitative uncertainty analysis are summarized in Table 4-100. Ferroalloy production CO_2 emissions from 2022 were estimated to be between 1.2 and 1.5 MMT CO_2 Eq. at the 95 percent confidence level. This indicates a range of approximately 13 percent below and 13 percent above the emission estimate of 1.3 MMT CO_2 Eq. Ferroalloy production CH_4 emissions were estimated to be between a range of approximately 12 percent below and 13 percent above the emission estimate of 0.01 MMT CO_2 Eq.

Table 4-100: Approach 2 Quantitative Uncertainty Estimates for CO_2 Emissions from Ferroalloy Production (MMT CO_2 Eq. and Percent)

Source	Gas	2022 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Ferroalloy Production	CO_2	1.3	1.2	1.5	-13%	+13%
Ferroalloy Production	CH_4	+	+	+	-12%	+13%

+ Does not exceed 0.05 MMT CO_2 Eq.

[a] Range of emission estimates predicted by Monte Carlo stochastic simulation for a 95 percent confidence interval.

QA/QC and Verification

General quality assurance/quality control (QA/QC) procedures were applied consistent with the U.S. Inventory QA/QC plan, which is in accordance with Volume 1, Chapter 6 of *2006 IPCC Guidelines* as described in the introduction of the IPPU chapter (see Annex 8 for more details).

Recalculations Discussion

No recalculations were performed for the 1990 to 2021 portion of the time series.

Planned Improvements

Pending available resources and prioritization of improvements for more significant sources, EPA will continue to evaluate and analyze data reported under EPA's GHGRP that would be useful to improve the emission estimates and category-specific QC procedures for the Ferroalloy Production source category. Given the small number of facilities and reporting thresholds, particular attention will be made to ensure completeness and time-series consistency of the emissions estimates presented in future *Inventory* reports, consistent with IPCC and UNFCCC guidelines. This is required as the facility-level reporting data from EPA's GHGRP, with the program's initial requirements for reporting of emissions in calendar year 2010, are not available for all inventory years (i.e., 1990 through 2009) as required for this *Inventory*. In implementing improvements and integration of data from EPA's GHGRP, the latest guidance from the IPCC on the use of facility-level data in national inventories will be relied upon.[81] This is a long-term planned improvement, and EPA is still assessing the possibility of incorporating this improvement into the *Inventory*. This improvement has not been included in the current *Inventory* report.

[81] See http://www.ipcc-nggip.iges.or.jp/public/tb/TFI_Technical_Bulletin_1.pdf and the *2019 Refinement*, Volume 1, Chapter 2, Section 2.3, *Use of Facility Data in Inventories* at https://www.ipcc-nggip.iges.or.jp/public/2019rf/pdf/1_Volume1/19R_V1_Ch02_DataCollection.pdf.

4.20 Aluminum Production (CRT Source Category 2C3)

Aluminum is a lightweight, malleable, and corrosion-resistant metal that is used in many manufactured products, including aircraft, automobiles, bicycles, and kitchen utensils. As of recent reporting, the United States was the ninth[82] largest producer of primary aluminum with an estimated aluminum production of 860 thousand metric tons, with approximately 1.2 percent of the world total production (USGS 2022). The United States was also a major importer of primary aluminum. This reporting category (2C3) includes emissions from the production of primary aluminum—in addition to consuming large quantities of electricity—results in process-related emissions of carbon dioxide (CO_2) and two perfluorocarbons (PFCs): perfluoromethane (CF_4) and perfluoroethane (C_2F_6).

Carbon dioxide is emitted during the aluminum smelting process when alumina (aluminum oxide, Al_2O_3) is reduced to aluminum using the Hall-Héroult reduction process. The reduction of the alumina occurs through electrolysis in a molten bath of natural or synthetic cryolite (Na_3AlF_6). The reduction cells contain a carbon (C) lining that serves as the cathode. Carbon is also contained in the anode, which can be a carbon mass of paste, coke briquettes, or prebaked carbon blocks from petroleum coke. During reduction, most of this carbon is oxidized and released to the atmosphere as CO_2.

Process emissions of CO_2 from aluminum production were estimated to be 1.4 MMT CO_2 Eq. (1,446 kt) in 2022 (see Table 4-101 and Table 4-102). The carbon anodes consumed during aluminum production consist of petroleum coke and, to a minor extent, coal tar pitch. The petroleum coke portion of the total CO_2 process emissions from aluminum production is considered to be a non-energy use of petroleum coke and is accounted for here and not under the CO_2 from fossil fuel combustion source category of the Energy sector. Similarly, the coal tar pitch portion of these CO_2 process emissions is accounted for here.

Table 4-101: CO_2 Emissions from Aluminum Production (MMT CO_2 Eq.)

Year	1990	2005	2018	2019	2020	2021	2022
Aluminum Production	6.8	4.1	1.5	1.9	1.7	1.5	1.4

Table 4-102: CO_2 Emissions from Aluminum Production (kt CO_2)

Year	1990	2005	2018	2019	2020	2021	2022
Aluminum Production	6,831	4,142	1,455	1,880	1,748	1,541	1,446

In addition to CO_2 emissions, the aluminum production industry is also a source of PFC emissions. During the smelting process, when the alumina ore content of the electrolytic bath falls below critical levels required for electrolysis, rapid voltage increases occur, which are termed High Voltage Anode Effects (HVAEs). HVAEs cause carbon from the anode and fluorine from the dissociated molten cryolite bath to combine, thereby producing fugitive emissions of CF_4 and C_2F_6. In general, the magnitude of emissions for a given smelter and level of production depends on the frequency and duration of these anode effects. As the frequency and duration of the anode effects increase, emissions increase. Another type of anode effect, Low Voltage Anode Effects (LVAEs), became a concern in the early 2010s as the aluminum industry increasingly began to use cell technologies with higher amperage and additional anodes (IPCC 2019). LVAEs emit CF_4 and are included in PFC emission totals from 2006 forward.

Since 1990, emissions of CF_4 and C_2F_6 have both declined by 96 and 97 percent respectively, to 0.62 MMT CO_2 Eq.

[82] Based on the U.S. USGS (2022) Aluminum factsheet, assuming all countries grouped under the "other countries" categories all have lower production than the U.S. Available at: https://pubs.usgs.gov/periodicals/mcs2023/mcs2023-aluminum.pdf.

of CF_4 (0.1 kt) and 0.08 MMT CO_2 Eq. of C_2F_6 (0.01 kt) in 2022, respectively, as shown in Table 4-103 and Table 4-104. This decline is due both to reductions in domestic aluminum production and to actions taken by aluminum smelting companies to reduce the frequency and duration of anode effects. These actions include technology and operational changes such as employee training, use of computer monitoring, and changes in alumina feeding techniques. Since 1990, aluminum production has declined by 78 percent, while the combined CF_4 and C_2F_6 emission rate (per metric ton of aluminum produced) has been reduced by 78 percent. PFC emissions decreased by approximately 18 percent between 2021 and 2022. Aluminum production also decreased in 2022, down 3 percent from 2021.

Table 4-103: PFC Emissions from Aluminum Production (MMT CO_2 Eq.)

Gas	1990	2005	2018	2019	2020	2021	2022
CF_4	16.1	2.6	1.0	1.1	1.2	0.8	0.7
C_2F_6	3.2	0.5	0.4	0.3	0.2	0.1	0.1
Total	**19.3**	**3.1**	**1.4**	**1.4**	**1.4**	**0.9**	**0.8**

Note: Totals may not sum due to independent rounding.

Table 4-104: PFC Emissions from Aluminum Production (kt)

Gas	1990	2005	2018	2019	2020	2021	2022
CF_4	2.4	0.4	0.2	0.2	0.2	0.1	0.1
C_2F_6	0.29	0.05	0.03	0.03	0.02	0.01	0.01

In 2022, U.S. primary aluminum production totaled approximately 0.86 million metric tons, a 3 percent decrease from 2021 production levels (USGS 2023). In 2022, three companies managed production at six operational primary aluminum smelters in five states. Two smelters operated at full capacity during 2022.The other four smelters operated at reduced capacity and one of these four smelters began a temporary shutdown in June (USGS 2023). Domestic smelters were operating at about 52 percent of capacity of 1.64 million tons per year at year end 2022 (USGS 2023).

Methodology and Time-Series Consistency

Process CO_2 and PFC (i.e., CF_4 and C_2F_6) emission estimates from primary aluminum production for 2010 through 2022 are available from EPA's GHGRP Subpart F (Aluminum Production) (EPA 2023). Under EPA's GHGRP, facilities began reporting primary aluminum production process emissions (for 2010) in 2011; as a result, GHGRP data (for 2010 through 2022) are available to be incorporated into the *Inventory*. EPA's GHGRP mandates that all facilities that contain an aluminum production process must report: CF_4 and C_2F_6 emissions from anode effects in all prebake and Søderberg electrolysis cells, CO_2 emissions from anode consumption during electrolysis in all prebake and Søderberg cells, and all CO_2 emissions from onsite anode baking. To estimate the process emissions, EPA's GHGRP uses the process-specific equations detailed in Subpart F (aluminum production).[83] These equations are based on the Tier 2/Tier 3 IPCC (2006) methods for primary aluminum production, and Tier 1 methods when estimating missing data elements. It should be noted that the same methods (i.e., *2006 IPCC Guidelines*) were used for estimating the emissions prior to the availability of the reported GHGRP data in the *Inventory*. Prior to 2010, aluminum production data were provided through EPA's Voluntary Aluminum Industrial Partnership (VAIP).

As previously noted, the use of petroleum coke for aluminum production is adjusted for within the Energy chapter to avoid double counting emissions as this fuel was consumed during non-energy related activities. Additional information on the adjustments made within the Energy sector for non-energy use of fuels is described in both the

[83] Code of Federal Regulations, Title 40: Protection of Environment, Part 98: Mandatory Greenhouse Gas Reporting, Subpart F—Aluminum Production. See https://www.ecfr.gov/cgi-bin/text-idx?SID=24a41781dfe4218b339e914de03e8727&mc=true&node=pt40.23.98&rgn=div5#sp40.23.98.f.

Methodology section of CO_2 from Fossil Fuel Combustion (3.2 Carbon Emitted from Non-Energy Uses of Fossil Fuels [CRT Source Category 1A]) and Annex 2.3, Methodology for Estimating Carbon Emitted from Non-Energy Uses of Fossil Fuels.

Process CO_2 Emissions from Anode Consumption and Anode Baking

Carbon dioxide emission estimates for the years prior to the introduction of EPA's GHGRP in 2010 were estimated using *2006 IPCC Guidelines* methods, but individual facility reported data were combined with process-specific emissions modeling. These estimates were based on information previously gathered from EPA's Voluntary Aluminum Industrial Partnership (VAIP) program, U.S. Geological Survey (USGS) Mineral Commodity reviews, and The Aluminum Association (USAA) statistics, among other sources. Since pre- and post-GHGRP estimates use the same methodology, emission estimates are comparable across the time series.

Most of the CO_2 emissions released during aluminum production occur during the electrolysis reaction of the carbon anode, as described by the following reaction:

$$2Al_2O_3 + 3C \rightarrow 4Al + 3CO_2$$

For prebake smelter technologies, CO_2 is also emitted during the anode baking process. These emissions can account for approximately 10 percent of total process CO_2 emissions from prebake smelters.

Depending on the availability of smelter-specific data, the CO_2 emitted from electrolysis at each smelter was estimated from: (1) the smelter's annual anode consumption, (2) the smelter's annual aluminum production and rate of anode consumption (per ton of aluminum produced) for previous and/or following years, or (3) the smelter's annual aluminum production and IPCC default CO_2 emission factors. The first approach tracks the consumption and carbon content of the anode, assuming that all carbon in the anode is converted to CO_2. Sulfur, ash, and other impurities in the anode are subtracted from the anode consumption to arrive at a carbon consumption figure. This approach corresponds to either the IPCC Tier 2 or Tier 3 method, depending on whether smelter-specific data on anode impurities are used. The second approach interpolates smelter-specific anode consumption rates to estimate emissions during years for which anode consumption data are not available. This approach avoids substantial errors and discontinuities that could be introduced by reverting to Tier 1 methods for those years. The last approach corresponds to the IPCC Tier 1 method (IPCC 2006) and is used in the absence of present or historic anode consumption data.

The equations used to estimate CO_2 emissions in the Tier 2 and 3 methods vary depending on smelter type (IPCC 2006). For Prebake cells, the process formula accounts for various parameters, including net anode consumption, and the sulfur, ash, and impurity content of the baked anode. For anode baking emissions, the formula accounts for packing coke consumption, the sulfur and ash content of the packing coke, as well as the pitch content and weight of baked anodes produced. For Søderberg cells, the process formula accounts for the weight of paste consumed per metric ton of aluminum produced, and pitch properties, including sulfur, hydrogen, and ash content.

Through the VAIP, anode consumption (and some anode impurity) data have been reported for 1990, 2000, 2003, 2004, 2005, 2006, 2007, 2008, and 2009. Where available, smelter-specific process data reported under the VAIP were used; however, if the data were incomplete or unavailable, information was supplemented using industry average values recommended by IPCC (2006). Smelter-specific CO_2 process data were provided by 18 of the 23 operating smelters in 1990 and 2000, by 14 out of 16 operating smelters in 2003 and 2004, 14 out of 15 operating smelters in 2005, 13 out of 14 operating smelters in 2006, 5 out of 14 operating smelters in 2007 and 2008, and 3 out of 13 operating smelters in 2009. For years where CO_2 emissions data or CO_2 process data were not reported by these companies, estimates were developed through linear interpolation, and/or assuming representative (e.g., previously reported or industry default) values.

In the absence of any previous historical smelter-specific process data (i.e., 1 out of 13 smelters in 2009; 1 out of 14 smelters in 2006, 2007, and 2008; 1 out of 15 smelters in 2005; and 5 out of 23 smelters between 1990 and

2003), CO_2 emission estimates were estimated using Tier 1 Søderberg and/or Prebake emission factors (metric ton of CO_2 per metric ton of aluminum produced) from IPCC (2006).

Process PFC Emissions from Anode Effects

High Voltage Anode Effects

Smelter-specific PFC emissions from aluminum production for 2010 through 2022 were reported to EPA under its GHGRP. To estimate their PFC emissions from HVAEs and report them under EPA's GHGRP, smelters use an approach identical to the Tier 3 approach in the *2006 IPCC Guidelines* (IPCC 2006). Specifically, they use a smelter-specific slope coefficient as well as smelter-specific operating data to estimate an emission factor using the following equation:

$$PFC = S \times AE$$

$$AE = F \times D$$

where,

PFC = CF_4 or C_2F_6, kg/MT aluminum

S = Slope coefficient, PFC/AE

AE = Anode effect, minutes/cell-day

F = Anode effect frequency per cell-day

D = Anode effect duration, minutes

They then multiply this emission factor by aluminum production to estimate PFC emissions from HVAEs. All U.S. aluminum smelters are required to report their emissions under EPA's GHGRP.

Perfluorocarbon emissions for the years prior to 2010 were estimated using the same equation, but the slope-factor used for some smelters was technology-specific rather than smelter-specific, making the method a Tier 2 rather than a Tier 3 approach for those smelters. Emissions and background data were reported to EPA under the VAIP. For 1990 through 2009, smelter-specific slope coefficients were available and were used for smelters representing between 30 and 94 percent of U.S. primary aluminum production. The percentage changed from year to year as some smelters closed or changed hands and as the production at remaining smelters fluctuated. For smelters that did not report smelter-specific slope coefficients, IPCC technology-specific slope coefficients were applied (IPCC 2006). The slope coefficients were combined with smelter-specific anode effect data collected by aluminum companies and reported under the VAIP to estimate emission factors over time. For 1990 through 2009, smelter-specific anode effect data were available for smelters representing between 80 and 100 percent of U.S. primary aluminum production. Where smelter-specific anode effect data were not available, representative values (e.g., previously reported or industry averages) were used.

For all smelters, emission factors were multiplied by annual production to estimate annual emissions at the smelter level. For 1990 through 2009, smelter-specific production data were available for smelters representing between 30 and 100 percent of U.S. primary aluminum production. (For the years after 2000, this percentage was near the high end of the range.) Production at non-reporting smelters was estimated by calculating the difference between the production reported under VAIP and the total U.S. production supplied by USGS, and then allocating this difference to non-reporting smelters in proportion to their production capacity. Emissions were then aggregated across smelters to estimate national emissions (see Table 1-5).

Table 4-105: Summary of HVAE Emissions (MMT CO_2 Eq.)

Year	1990	2005	2018	2019	2020	2021	2022
HVAE Emissions	19.3	3.1	1.4	1.4	1.4	0.9	0.7

Low Voltage Anode Effects

LVAE emissions of CF_4 were estimated for 2006 through 2022 (see Table 1-6) based on the Tier 1 (technology-specific, production-based) method in the *2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories* (IPCC 2019). Prior to 2006, LVAE emissions are believed to have been negligible.[84] The Tier 1 method is used in the LVAE emissions calculations from aluminum production in the absence of smelter-specific data available to quantify the LVAE-specific process emissions. National aluminum production estimates (allocated to smelters as described below) and the technology used in individual smelters were the best available data to perform the emissions calculations, as smelter-specific production data is not publicly available.

The following equation was used to estimate LVAE PFC emissions:

Equation 4-15: CF_4 Emissions Resulting from Low Voltage Anode Effects

$$LVAE\ E_{CF4} = LVAE\ EF_{CF4} \times MP$$

where,

LVAE E_{CF4} = LVAE emissions of CF_4 from aluminum production, kg CF_4

LVAE EF_{CF4} = LVAE emission factor for CF_4 (default by cell technology type)

MP = Metal production by cell technology type, tons Al.

In the LVAE emissions calculations, the Metal Production (MP) factor is calculated differently for the years 2006 through 2009 than for 2010 and beyond. For years prior to GHGRP reporting (2006 through 2009), the MP factor is calculated by dividing the annual production reported by USGS with the total U.S. capacity reported for this specific year, based on the USGS yearbook and applying this national utilization factor to each facility's production capacity to obtain an estimated facility production value. For GHGRP reporting years (2010+), the methodology to calculate the MP value was changed to allocate the total annual production reported by USAA, based on the distribution of CO_2 emissions amongst the operating smelters in a specific year. The latter improves the accuracy of the LVAE emissions estimates over assuming capacity utilization is the same at all smelters. The main drawback of using this methodology to calculate the MP factor is that, in some instances, it led to production estimates that are slightly larger (less than six percent) than the production capacity reported that year. In practice, this is most likely explained by the differences in process efficiencies at each facility and to a lesser extent, differences in measurements and methods used by each facility to obtain their CO_2 estimates and the degree of uncertainty in the USGS annual production reporting.

Once LVAE emissions were estimated, they were then combined with HVAE emissions estimates to calculate total PFC emissions from aluminum production.

Table 4-106: Summary of LVAE Emissions (MMT CO_2 Eq.)

Year	2006	2018	2019	2020	2021	2022
LVAE Emissions	0.13	0.05	0.07	0.06	0.05	0.05

Production Data

Between 1990 and 2009, production data were provided under the VAIP by 21 of the 23 U.S. smelters that operated during at least part of that period. For the non-reporting smelters, production was estimated based on

[84] The *2019 Refinement* states, "Since 2006, the global aluminum industry has undergone changes in technology and operating conditions that make LVAE emissions much more prevalent[12]; these changes have occurred not only through uptake of newer technologies (e.g., $PFPB_L$ to $PFPB_M$) but also during upgrades within the same technology in order to maximize productivity and reduce energy use" (IPCC 2019). Footnote #12 uses the example of $PFPB_L$, which is prevalent in the United States, as an older technology that has been upgraded.

the difference between reporting smelters and national aluminum production levels as reported to USGS, with allocation to specific smelters based on reported production capacities (USGS 1990 through 2009).

National primary aluminum production data for 2010 through 2022 were compiled using USGS Mineral Industry Surveys, and the USGS Mineral Commodity Summaries (see Table 1-7).

Table 4-107: Production of Primary Aluminum (kt)

Year	1990	2005	2018	2019	2020	2021	2022
Production (kt)	4,048	2,481	891	1,093	1,012	889	860

Methodological approaches were applied to the entire time-series to ensure time-series consistency from 1990 through 2022.

Uncertainty

Uncertainty was estimated for the CO_2, CF_4, and C_2F_6 emission values reported by each individual facility to EPA's GHGRP, taking into consideration the uncertainties associated with aluminum production, anode effect minutes, and slope factors. The uncertainty bounds used for these parameters were established based on information collected under the VAIP and held constant through 2022. Uncertainty surrounding the reported CO_2, CF_4, and C_2F_6 emission values were determined to have a normal distribution with uncertainty ranges of approximately 6 percent below to 6 percent above, 16 percent below to 16 percent above, and 20 percent below to 20 percent above their 2022 emission estimates, respectively.

For LVAE, since emission values were not reported through EPA's GHGRP but estimated instead through a Tier 1 methodology, the uncertainty analysis examined uncertainty associated with primary capacity data as well as technology-specific emission factors. Uncertainty for each facility's primary capacity, reported in the USGS Yearbook, was estimated to have a Pert Beta distribution with an uncertainty range of 7 percent below to 7 percent above the capacity estimates based on the uncertainty of reported capacity data, the number of years since the facility reported new capacity data, and uncertainty in capacity utilization. Uncertainty was applied to LVAE emission factors according to technology using the uncertainty ranges provided in the *2019 Refinement to the 2006 IPCC Guidelines*. An uncertainty range for Horizontal Stud Søderberg (HSS) technology was not provided in the *2019 Refinement to the 2006 IPCC Guidelines* due to insufficient data, so a normal distribution and uncertainty range of ±99 percent was applied for that technology based on expert judgment. A Monte Carlo analysis was applied to estimate the overall uncertainty of the CO_2, CF_4, and C_2F_6 emission estimates for the U.S. aluminum industry as a whole, and the results are provided below.

The results of this Approach 2 quantitative uncertainty analysis are summarized in Table 4-108. Aluminum production-related CO_2 emissions were estimated to be between 1.41 and 1.48 MMT CO_2 Eq. at the 95 percent confidence level. This indicates a range of approximately 3 percent below to 3 percent above the emission estimate of 1.446 MMT CO_2 Eq. Also, production-related CF_4 emissions were estimated to be between 0.62 and 0.73 MMT CO_2 Eq. at the 95 percent confidence level. This indicates a range of approximately 8 percent below to 8 percent above the emission estimate of 0.676 MMT CO_2 Eq. Aluminum production-related C_2F_6 emissions were estimated to be between 0.075 and 0.09 MMT CO_2 Eq. at the 95 percent confidence level. This indicates a range of approximately 9 percent below to 9 percent above the emission estimate of 0.083 MMT CO_2 Eq. Finally, Aluminum production-related aggregated PFCs emissions were estimated to be between 0.71 and 0.82 MMT CO_2 Eq. at the 95 percent confidence level. This indicates a range of approximately 7 percent below to 7 percent above the emission estimate of 0.759 MMT CO_2 Eq.

Table 4-108: Approach 2 Quantitative Uncertainty Estimates for CO_2 and PFC Emissions from Aluminum Production (MMT CO_2 Eq. and Percent)

Source	Gas	2022 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Aluminum Production	CO_2	1.446	1.41	1.48	-3%	+3%
Aluminum Production	CF_4	0.676	0.62	0.73	-8%	+8%
Aluminum Production	C_2F_6	0.083	0.075	0.09	-9%	+9%
Aluminum Production	PFCs	0.759	0.71	0.82	-7%	+7%

[a] Range of emission estimates predicted by Monte Carlo stochastic simulation for a 95 percent confidence interval.

QA/QC and Verification

General quality assurance/quality control (QA/QC) procedures were applied consistent with the U.S. Inventory QA/QC plan, which is in accordance with Volume 1, Chapter 6 of *2006 IPCC Guidelines* as described in the introduction of the IPPU chapter (see Annex 8 for more details). For the GHGRP data, EPA verifies annual facility-level reports through a multi-step process (e.g., including a combination of pre-and post-submittal electronic checks and manual reviews by staff) to identify potential errors and ensure that data submitted to EPA are accurate, complete, and consistent (EPA 2015).[85] Based on the results of the verification process, EPA follows up with facilities to resolve mistakes that may have occurred. The post-submittals checks are consistent with a number of general and category-specific QC procedures, including: range checks, statistical checks, algorithm checks, and year-to-year checks of reported data and emissions.

Recalculations Discussion

No recalculations were performed for the 1990 through 2021 portion of the time series.

Planned Improvements

EPA is assessing planned improvements for future reports, but at this time has no specific planned improvements for estimating CO_2 and PFC emissions from aluminum production.

4.21 Magnesium Production and Processing (CRT Source Category 2C4)

The magnesium metal production and casting industry uses sulfur hexafluoride (SF_6) as a cover gas to prevent the rapid oxidation of molten magnesium in the presence of air. This reporting category (2C4) includes emissions from magnesium metal production and processing. Sulfur hexafluoride has been used in this application around the world for more than 30 years. A dilute gaseous mixture of SF_6 with dry air and/or carbon dioxide (CO_2) is blown over molten magnesium metal to induce and stabilize the formation of a protective crust. A small portion of the SF_6 reacts with the magnesium to form a thin molecular film of mostly magnesium oxide and magnesium fluoride.

[85] GHGRP Report Verification Factsheet. See https://www.epa.gov/sites/production/files/2015-07/documents/ghgrp_verification_factsheet.pdf.

The amount of SF_6 reacting in magnesium production and processing is considered to be negligible and thus all SF_6 used is assumed to be emitted into the atmosphere. Alternative cover gases, such as AM-cover™ (containing HFC-134a), Novec™ 612 (FK-5-1-12) and dilute sulfur dioxide (SO_2) systems can and are being used by some facilities in the United States. However, many facilities in the United States are still using traditional SF_6 cover gas systems. Carbon dioxide is also released during primary magnesium production if carbonate based raw materials, such as dolomite, are used. During the processing of these raw materials to produce magnesium, calcination occurs which results in a release of CO_2 emissions.

The magnesium industry emitted 1.1 MMT CO_2 Eq. (0.05 kt) of SF_6, 0.03 MMT CO_2 Eq. (0.02 kt) of HFC-134a, and 0.003 MMT CO_2 Eq. (2.9 kt) of CO_2 in 2022. This represents a decrease of approximately 4 percent from total 2021 emissions (see Table 4-109 and Table 4-110) and a decrease in SF_6 emissions by 3 percent. In 2022, total HFC-134a emissions decreased from 0.040 MMT CO_2 Eq. to 0.029 MMT CO_2 Eq., or a 28 percent decrease as compared to 2021 emissions. FK 5-1-12 emissions in 2022 were consistent with 2021. The emissions of the carrier gas, CO_2, increased from 2.91 kt in 2021 to 2.94 kt in 2022, or 1 percent.

Table 4-109: SF_6, HFC-134a, FK 5-1-12 and CO_2 Emissions from Magnesium Production and Processing (MMT CO_2 Eq.)

Year	1990	2005	2018	2019	2020	2021	2022
SF_6	5.6	3.0	1.1	0.9	0.9	1.2	1.1
HFC-134a	0.0	0.0	0.1	0.1	0.1	+	+
CO_2	0.1	+	+	+	+	+	+
FK 5-1-12[a]	*0.0*	*0.0*	*+*	*+*	*+*	*+*	*+*
Total	**5.7**	**3.0**	**1.1**	**1.0**	**0.9**	**1.2**	**1.2**

+ Does not exceed 0.05 MMT CO_2 Eq.

[a] Emissions of FK 5-1-12 are not included in totals.

Note: Totals may not sum due to independent rounding.

Table 4-110: SF_6, HFC-134a, FK 5-1-12 and CO_2 Emissions from Magnesium Production and Processing (kt)

Year	1990	2005	2018	2019	2020	2021	2022
SF_6	0.2	0.1	+	+	+	+	+
HFC-134a	0.0	0.0	0.1	+	+	+	+
CO_2	129.0	3.6	1.6	2.4	3.0	2.9	2.9
FK 5-1-12[a]	*0.0*	*0.0*	*+*	*+*	*+*	*+*	*+*

+ Does not exceed 0.5 kt

[a] Emissions of FK 5-1-12 are not included in totals.

Methodology and Time-Series Consistency

Emission estimates for the magnesium industry incorporate information provided by industry participants in EPA's SF_6 Emission Reduction Partnership for the Magnesium Industry as well as emissions data reported through Subpart T (Magnesium Production and Processing) of EPA's GHGRP. The Partnership started in 1999 and, in 2010, participating companies represented 100 percent of U.S. primary and secondary production and 16 percent of the casting sector production (i.e., die, sand, permanent mold, wrought, and anode casting). SF_6 emissions for 1999 through 2010 from primary production, secondary production (i.e., recycling), and die casting were generally reported by Partnership participants. Partners reported their SF_6 consumption, which is assumed to be equivalent to emissions. Along with SF_6, some Partners reported their HFC-134a and FK 5-1-12 consumed, which is also assumed to be equal to emissions. The last reporting year under the Partnership was 2010. Emissions data for 2011 through 2020 are obtained through EPA's GHGRP. Under the program, owners or operators of facilities that have a magnesium production or casting process must report emissions from use of cover or carrier gases, which include SF_6, HFC-134a, FK 5-1-12 and CO_2. Consequently, cover and carrier gas emissions from magnesium

production and processing were estimated for three time periods, depending on the source of the emissions data: 1990 through 1998 (pre-EPA Partnership), 1999 through 2010 (EPA Partnership), and 2011 through 2022 (EPA GHGRP). The methodologies described below also make use of magnesium production data published by the U.S. Geological Survey (USGS) as available.

1990 through 1998

To estimate emissions for 1990 through 1998, industry SF_6 emission factors were multiplied by the corresponding metal production and consumption (casting) statistics from USGS. For this period, it was assumed that there was no use of HFC-134a or FK 5-1-12 cover gases, and hence emissions were not estimated for these alternatives.

Sulfur hexafluoride emission factors from 1990 through 1998 were based on a number of sources and assumptions. Emission factors for primary production were available from U.S. primary producers for 1994 and 1995. The primary production emission factors were 1.2 kg SF_6 per metric ton for 1990 through 1993, and 1.1 kg SF_6 per metric ton for 1994 through 1997. The emission factor for secondary production from 1990 through 1998 was assumed to be constant at the 1999 average Partner value. An emission factor for die casting of 4.1 kg SF_6 per metric ton, which was available for the mid-1990s from an international survey (Gjestland and Magers 1996), was used for years 1990 through 1996. For 1996 through 1998, the emission factor for die casting was assumed to decline linearly to the level estimated based on Partner reports in 1999. This assumption is consistent with the trend in SF_6 sales to the magnesium sector that was reported in the RAND survey of major SF_6 manufacturers, which showed a decline of 70 percent from 1996 to 1999 (RAND 2002). Sand casting emission factors for 1990 through 2001 were assumed to be the same as the 2002 emission factor for all but one facility, which used an emission factor derived from 2011 GHGRP data and held constant to back cast emissions for 1990-1998. The emission factors for the other processes (i.e., permanent mold, wrought, and anode casting), about which less is known, were assumed to remain constant at levels defined in Table 4-110. The emission factors for the other processes (i.e., permanent mold, wrought, and anode casting) were based on discussions with industry representatives.

The quantities of CO_2 carrier gas used for each production type have been estimated using the 1999 estimated CO_2 emissions data and the annual calculated rate of change of SF_6 use in the 1990 through 1999 time period. For each year and production type, the rate of change of SF_6 use between the current year and the subsequent year was first estimated. This rate of change was then applied to the CO_2 emissions of the subsequent year to determine the CO_2 emission of the current year.

Carbon dioxide emissions from the calcination of dolomite in the primary production of magnesium were calculated based on the *2006 IPCC Guidelines* Tier 2 method by multiplying the estimated primary production of magnesium by an emissions factor of 3.62 kilogram of CO_2 per kilogram of magnesium produced.[86] For 1990 through 1998, production was estimated to be equal to the production capacity of the facility.

1999 through 2010

The 1999 through 2010 emissions from primary and secondary production were based on information provided by EPA's industry Partners. In some instances, there were years of missing Partner data, including SF_6 consumption and metal processed. For these situations, emissions were estimated through interpolation where possible, or by holding company-reported emissions (as well as production) constant from the previous year. For alternative cover gases, including HFC-134a and FK 5-1-12, mainly reported data was relied upon. That is, unless a Partner reported using an alternative cover gas, it was not assumed it was used. Emissions of alternate gases were also estimated through linear interpolation where possible.

[86] See https://www.ipcc-nggip.iges.or.jp/public/2006gl/pdf/3_Volume3/V3_4_Ch4_Metal_Industry.pdf.

The die casting emission estimates for 1999 through 2010 were also based on information supplied by industry Partners. When a Partner was determined to be no longer in production, its metal production and usage rates were set to zero. Missing data on emissions or metal input was either interpolated or held constant at the last available reported value. In 1999 through 2010, Partners were assumed to account for all die casting tracked by USGS. For 1999, die casters who were not Partners were assumed to be similar to Partners who cast small parts. Due to process requirements, these casters consume larger quantities of SF_6 per metric ton of processed magnesium than casters that process large parts. Consequently, emission estimates from this group of die casters were developed using an average emission factor of 5.2 kg SF_6 per metric ton of magnesium. This emission factor was developed using magnesium production and SF_6 usage data for the year 1999. In 2008, the derived emission factor for die casting began to increase after many years of largely decreasing emission factors. As determined through an analysis of activity data reported from the USGS, this increase is due to a temporary decrease in production at many facilities between 2008 and 2010, which reflects the change in production that occurred during the recession.

The emissions from other casting operations were estimated by multiplying emission factors (kg SF_6 per metric ton of metal produced or processed) by the amount of metal produced or consumed from USGS, with the exception of some years for which Partner sand casting emissions data are available. The emission factors for sand casting activities were acquired through the data reported by the Partnership for 2002 to 2006. For 1999 through 2001, the sandcasting emission factor was held constant at the 2002 Partner-reported level. For 2007 through 2010, the sandcasting Partner did not report and the reported emission factor from 2005 was applied to the Partner and to a non GHGRP sand casters. Activity data for 2005 was obtained from USGS (USGS 2005b). One non partner sand casting facility reported to GHGRP in 2011 and had an emission factor derived for 2011, this factor was used to back cast emissions for this facility from 1999 to 2010.

The emission factors for primary production, secondary production and sand casting for the 1999 to 2010 are not published to protect company-specific production information. However, the emission factor for primary production has not risen above the average 1995 Partner value of 1.1 kg SF_6 per metric ton. The emission factors for the other industry sectors (i.e., permanent mold, wrought, and anode casting) were based on discussions with industry representatives. The emission factors for casting activities are provided below in Table 4-111.

The emissions of HFC-134a and FK-5-1-12 were included in the estimates for only instances where Partners reported that information to the Partnership. Emissions of these alternative cover gases were not estimated for instances where emissions were not reported.

Carbon dioxide carrier gas emissions were estimated using the emission factors developed based on GHGRP-reported carrier gas and cover gas data, by production type. It was assumed that the use of carrier gas, by production type, is proportional to the use of cover gases. Therefore, an emission factor, in kg CO_2 per kg cover gas and weighted by the cover gases used, was developed for each of the production types. GHGRP data, on which these emissions factors are based, was available for primary, secondary, die casting and sand casting. The emission factors were applied to the quantity of all cover gases used (SF_6, HFC-134a, and FK-5-1-12) by production type in this time period for producers that reported CO_2 emissions from 2011-2022 through the GHGP. Carrier gas emissions for the 1999 through 2010 time period were only estimated for those Partner companies that reported using CO_2 as a carrier gas through the GHGRP. Using this approach helped ensure time-series consistency. Emissions of carrier gases for permanent mold, wrought, and anode processes were estimated using the ratio of total CO_2 emissions to total cover gas emissions for primary, secondary, die and sand in a given year and the total SF_6 emissions from each permanent mold, wrought, and anodes processes respectively in that same year. CO_2 emissions from the calcination of dolomite were estimated using the same approach as described above. At the end of 2001, the sole magnesium production plant operating in the United States that produced magnesium metal using a dolomitic process that resulted in the release of CO_2 emissions ceased its operations (USGS 1995b through 2023).

Table 4-111: SF_6 Emission Factors (kg SF_6 per metric ton of magnesium)

Year	Die Casting[a]	Permanent Mold	Wrought	Anodes
1999	1.75[b]	2	1	1
2000	0.72	2	1	1
2001	0.72	2	1	1
2002	0.71	2	1	1
2003	0.81	2	1	1
2004	0.79	2	1	1
2005	0.77	2	1	1
2006	0.88	2	1	1
2007	0.64	2	1	1
2008	0.97	2	1	1
2009	1.41	2	1	1
2010	1.43	2	1	1

[a] Weighted average includes all die casters, Partners and non-Partners. For the majority of the time series (2000 through 2010), Partners made up 100 percent of die casters in the United States.

[b] Weighted average that includes an estimated emission factor of 5.2 kg SF_6 per metric ton of magnesium for die casters that do not participate in the Partnership.

2011 through 2022

For 2011 through 2022, for the primary and secondary producers, GHGRP-reported cover and carrier gases emissions data were used. For sand and die casting, some emissions data was obtained through EPA's GHGRP. Additionally, in 2018 a new GHGRP reporter began reporting permanent mold emissions. The balance of the emissions for this industry segment was estimated based on previous Partner reporting (i.e., for Partners that did not report emissions through EPA's GHGRP) or were estimated by multiplying emission factors by the amount of metal produced or consumed. Partners who did not report through EPA's GHGRP were assumed to have continued to emit SF_6 at the last reported level, which was from 2010 in most cases, unless publicly available sources indicated that these facilities have closed or otherwise eliminated SF_6 emissions from magnesium production (ARB 2015). Many Partners that did report through the GHGRP showed increases in SF_6 emissions driven by increased production related to a continued economic recovery after the 2008 recession. One Partner in particular reported an anonymously large increase in SF_6 emissions from 2010 to 2011, further driving increases in emissions between the two time periods of inventory estimates. All Partners were assumed to have continued to consume magnesium at the last reported level. Where the total metal consumption estimated for the Partners fell below the U.S. total reported by USGS, the difference was multiplied by the emission factors discussed in the section above, i.e., non-partner emission factors. For the other types of production and processing (i.e., permanent mold, wrought, and anode casting), emissions were estimated by multiplying the industry emission factors with the metal production or consumption statistics obtained from USGS (USGS 1995b-2023). USGS data for 2022 were not yet available at the time of the analysis, so the 2021 values were held constant through 2022 as an estimate.

Emissions of carrier gases for permanent mold, wrought, and anode processes were estimated using an approach consistent with the 1999 through 2010 time series.

Methodological approaches were applied to the entire time series to ensure time-series consistency from 1990 through 2022. 2006 IPCC Guidance methodologies were used throughout the time series, mainly either a Tier 2 or Tier 3 approach depending on available data.

Uncertainty

Uncertainty surrounding the total estimated emissions in 2022 is attributed to the uncertainties around SF_6, HFC-134a, and CO_2 emission estimates. To estimate the uncertainty surrounding the estimated 2022 SF_6 emissions from

magnesium production and processing, the uncertainties associated with three variables were estimated: (1) emissions reported by magnesium producers and processors for 2022 through EPA's GHGRP, (2) emissions estimated for magnesium producers and processors that reported via the Partnership in prior years but did not report 2022 emissions through EPA's GHGRP, and (3) emissions estimated for magnesium producers and processors that did not participate in the Partnership or report through EPA's GHGRP. An uncertainty of 5 percent was assigned to the emissions (usage) data reported by each GHGRP reporter for all the cover and carrier gases (per the *2006 IPCC Guidelines*). If facilities did not report emissions data during the current reporting year through EPA's GHGRP, SF_6 emissions data were held constant at the most recent available value reported through the Partnership. The uncertainty associated with these values was estimated to be 30 percent for each year of extrapolation (per the *2006 IPCC Guidelines*). The uncertainty of the total inventory estimate remained relatively constant between 2021 and 2022.

Alternate cover gas and carrier gases data was set equal to zero if the facilities did not report via the GHGRP. For those industry processes that are not represented in the Partnership, such as permanent mold and wrought casting, SF_6 emissions were estimated using production and consumption statistics reported by USGS and estimated process-specific emission factors (see Table 4-111). The uncertainties associated with the emission factors and USGS-reported statistics were assumed to be 75 percent and 25 percent, respectively. Emissions associated with die casting and sand casting activities utilized emission factors based on Partner reported data with an uncertainty of 75 percent. In general, where precise quantitative information was not available on the uncertainty of a parameter, a conservative (upper-bound) value was used.

Additional uncertainties exist in these estimates that are not addressed in this methodology, such as the basic assumption that SF_6 neither reacts nor decomposes during use. The melt surface reactions and high temperatures associated with molten magnesium could potentially cause some gas degradation. Previous measurement studies have identified SF_6 cover gas degradation in die casting applications on the order of 20 percent (Bartos et al. 2007). Sulfur hexafluoride may also be used as a cover gas for the casting of molten aluminum with high magnesium content; however, the extent to which this technique is used in the United States is unknown.

The results of this Approach 2 quantitative uncertainty analysis are summarized in Table 4-112. Total emissions associated with magnesium production and processing were estimated to be between 1.06 and 1.24 MMT CO_2 Eq. at the 95 percent confidence level. This indicates a range of approximately 7.9 percent below to 7.7 percent above the 2022 emission estimate of 1.15 MMT CO_2 Eq. The uncertainty estimates for 2022 are slightly higher to the uncertainty reported for 2021 in the previous *Inventory*. This increase in uncertainty is attributed to the increased number of facilities with interpolated emissions and the increasing number of years for facilities with emissions held constant.

Table 4-112: Approach 2 Quantitative Uncertainty Estimates for SF_6, HFC-134a and CO_2 Emissions from Magnesium Production and Processing (MMT CO_2 Eq. and Percent)

Source	Gas	2022 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Magnesium Production	SF_6, HFC-134a, CO_2	1.2	1.1	1.2	-7.9%	+7.7%

[a] Range of emission estimates predicted by Monte Carlo stochastic simulation for a 95 percent confidence interval.

QA/QC and Verification

General quality assurance/quality control (QA/QC) procedures were applied consistent with the U.S. Inventory QA/QC plan, which is in accordance with Volume 1, Chapter 6 of *2006 IPCC Guidelines* as described in the

introduction of the IPPU chapter (see Annex 8 for more details). For the GHGRP data, EPA verifies annual facility-level reports through a multi-step process (e.g., including a combination of pre-and post-submittal electronic checks and manual reviews by staff) to identify potential errors and ensure that data submitted to EPA are accurate, complete, and consistent (EPA 2015).[87] Based on the results of the verification process, EPA follows up with facilities to resolve mistakes that may have occurred. The post-submittals checks are consistent with a number of general and category-specific QC procedures, including: range checks, statistical checks, algorithm checks, and year-to-year checks of reported data and emissions.

Recalculations Discussion

One die casting facility which had previously had emissions back cast at a constant level had its back casting methodology updated using linear growth from 0 to reported emissions levels between 2001 and 2014, resulting in decreases in SF_6 emissions across 2001 to 2013.

Sand Casting Emissions for 2021 were updated based on 2021 specific data available in the 2021 data tables release from USGS's Mineral Yearbook. 2021 data was previously held constant at 2020 levels due to USGS Mineral Yearbook data only going through 2020. The updated production of sand cast magnesium was larger than what was estimated for 2021 in the previous *Inventory* cycle leading to an increase in SF_6 emissions in 2021.

One sand casting facility, which had previously only been estimated from 2011 onward, was confirmed to have emissions across the time series, an updated emission factor for 2011 was calculated and used to back cast emissions from 1990 to 2010.

Review of facility responses indicate that changes over time in the emission factors for this industry have occurred as facilities switch to using systems with cover gases other than SF_6 (e.g. SO_2) and also during time-periods where back-up SF_6-based systems are used due to the failure of the primary (non-SF_6) system have occurred, leading to the periodic spike in SF_6 usage rates.

Planned Improvements

Cover gas research conducted over the last decade has found that SF_6 used for magnesium melt protection can have degradation rates on the order of 20 percent in die casting applications (Bartos et al. 2007). Current emission estimates assume (per the *2006 IPCC Guidelines*) that all SF_6 utilized is emitted to the atmosphere. Additional research may lead to a revision of the *2006 IPCC Guidelines* to reflect this phenomenon and until such time, developments in this sector will be monitored for possible application to the *Inventory* methodology.

Additional emissions are generated as byproducts from the use of alternate cover gases, which are not currently accounted for. Research on this topic is developing, and as reliable emission factors become available, these emissions will be incorporated into the *Inventory.*

4.22 Lead Production (CRT Source Category 2C5)

In 2022, lead was produced in the United States using only secondary production processes. Until 2014, lead production in the United States involved both primary and secondary processes—both of which emit carbon

[87] GHGRP Report Verification Factsheet. See https://www.epa.gov/sites/production/files/2015-07/documents/ghgrp_verification_factsheet.pdf.

dioxide (CO_2) (Sjardin 2003). This reporting category (2C5) includes emissions from the production of lead. Per the IPCC methodological guidance, emissions from fuels consumed for energy purposes during the production of lead are accounted for as part of fossil fuel combustion in the industrial end-use sector reported under the Energy chapter.

Primary production of lead through the direct smelting of lead concentrate produces CO_2 emissions as the lead concentrates are reduced in a furnace using metallurgical coke (Sjardin 2003). Primary lead production, in the form of direct smelting, previously occurred at a single smelter in Missouri. This primary lead smelter was closed at the end of 2013, and a small amount of residual lead was processed during demolition of the facility in 2014 (USGS 2015). Beginning in 2015, primary lead production no longer occurred in the United States.

Similar to primary lead production, CO_2 emissions from secondary lead production result when a reducing agent, usually metallurgical coke, is added to the smelter to aid in the reduction process. Carbon dioxide emissions from secondary production also occur through the treatment of secondary raw materials (Sjardin 2003). Secondary production primarily involves the recycling of lead acid batteries and post-consumer scrap at secondary smelters. Secondary lead production in the United States has fluctuated over the past 20 years, reaching a high of 1,180,000 metric tons in 2007 and again in 2019. In 2022, secondary lead production accounted for 100 percent of total U.S. lead production. The lead-acid battery industry accounted for about 92 percent of the reported U.S. lead consumption in 2022 (USGS 2023a).

In 2022, secondary lead production in the United States decreased by approximately 3 percent compared to 2021 (USGS 2023a). Secondary lead production in 2022 is 3 percent higher than in 1990 (USGS 1994 and 2023a). The United States has become more reliant on imported refined lead, owing to the closure of the last primary lead smelter in 2013. Exports of spent starting-lighting-ignition (SLI) batteries decreased between 2014 and 2017, and subsequently recovered beginning in 2018. Exports were 10 percent higher in the first 9 months of 2021 compared to the same time period in 2014 (USGS 2015 through 2023b). In the first 9 months of 2022, 24.6 million spent SLI lead-acid batteries were exported, 4 percent less than that in the same time period in 2021 (USGS 2023b).

Emissions of CO_2 from lead production in 2022 were 0.4 MMT CO_2 Eq. (428 kt), which is a 3 percent decrease compared to 2021 and a 17 percent decrease compared to 1990 (see Table 4-113 and Table 4-114) (USGS 1994; USGS 2023a; USGS 2023b).

The United States was the third largest mine producer of lead in the world, behind China and Australia, and accounted for approximately 6 percent of world production in 2022 (USGS 2023a).

Table 4-113: CO_2 Emissions from Lead Production (MMT CO_2 Eq.)

Year	1990	2005	2018	2019	2020	2021	2022
Lead Production	0.5	0.6	0.5	0.5	0.5	0.4	0.4

Table 4-114: CO_2 Emissions from Lead Production (kt CO_2)

Year	1990	2005	2018	2019	2020	2021	2022
Lead Production	516	553	527	531	450	439	428

Methodology and Time-Series Consistency

Carbon dioxide emissions from lead production[88] are calculated based on Sjardin's work (Sjardin 2003) for lead production emissions and use Tier 1 methods from the *2006 IPCC Guidelines*, in accordance with the IPCC methodological decision tree and available data. The Tier 1 equation is as follows:

Equation 4-16: *2006 IPCC Guidelines* Tier 1: CO_2 Emissions From Lead Production (Equation 4.32)

$$CO_2\ Emissions = (DS\ \times EF_{DS})\ + (S\ \times EF_S)$$

where,

DS	=	Lead produced by direct smelting, metric ton
S	=	Lead produced from secondary materials
EF_{DS}	=	Emission factor for direct smelting, metric tons CO_2/metric ton lead product
EF_S	=	Emission factor for secondary materials, metric tons CO_2/metric ton lead product

For primary lead production using direct smelting, Sjardin (2003) and the *2006 IPCC Guidelines* provide an emission factor of 0.25 metric tons CO_2/metric ton lead. For secondary lead production, Sjardin (2003) and the *2006 IPCC Guidelines* provide an emission factor of 0.25 metric tons CO_2/metric ton lead for direct smelting, as well as an emission factor of 0.2 metric tons CO_2/metric ton lead produced for the treatment of secondary raw materials (i.e., pretreatment of lead acid batteries). Since the secondary production of lead involves both the use of the direct smelting process and the treatment of secondary raw materials, Sjardin recommends an additive emission factor to be used in conjunction with the secondary lead production quantity. The direct smelting factor (0.25) and the sum of the direct smelting and pretreatment emission factors (0.45) are multiplied by total U.S. primary and secondary lead production, respectively, to estimate CO_2 emissions.

The production and use of coking coal for lead production is adjusted for within the Energy chapter as this fuel was consumed during non-energy related activities. Additional information on the adjustments made within the Energy sector for Non-Energy Use of Fuels is described in both the Methodology section of CO_2 from Fossil Fuel Combustion (Section 3.1 Fossil Fuel Combustion (CRT Source Category 1A)) and Annex 2.1, Methodology for Estimating Emissions of CO_2 from Fossil Fuel Combustion.

The 1990 through 2022 activity data for primary and secondary lead production (see Table 4-115) were obtained from the U.S. Geological Survey (USGS 1994 through 2023a).

Table 4-115: Lead Production (Metric Tons)

Year	1990	2005	2018	2019	2020	2021	2022
Primary	404,000	143,000	0	0	0	0	0
Secondary	922,000	1,150,000	1,170,000	1,180,000	1,000,000	975,000	950,000

Methodological approaches discussed below were applied to applicable years to ensure time-series consistency in emissions from 1990 through 2022.

[88] EPA has not integrated aggregated facility-level Greenhouse Gas Reporting Program (GHGRP) information to inform these estimates. The aggregated information (e.g., activity data and emissions) associated with Lead Production did not meet criteria to shield underlying confidential business information (CBI) from public disclosure.

Uncertainty

Uncertainty associated with lead production relates to the emission factors and activity data used. The direct smelting emission factor used in primary production is taken from Sjardin (2003) who averaged the values provided by three other studies (Dutrizac et al. 2000; Morris et al. 1983; Ullman 1997). For secondary production, Sjardin (2003) added a CO_2 emission factor associated with battery treatment. The applicability of these emission factors to plants in the United States is uncertain. EPA assigned an uncertainty range of ±20 percent for these emission factors, and using this suggested uncertainty provided in Table 4.23 of the *2006 IPCC Guidelines* for a Tier 1 emission factor by process type is appropriate based on expert judgment (RTI 2023). Per this expert judgment, a triangular probability density function was assumed for emission factors.

There is also a smaller level of uncertainty associated with the accuracy of primary and secondary production data provided by the USGS which is collected via voluntary surveys; the uncertainty of the activity data is a function of the reliability of reported plant-level production data and the completeness of the survey response. EPA currently uses an uncertainty range of ±10 percent for primary and secondary lead production, and using this suggested uncertainty provided in Table 4.23 of the *2006 IPCC Guidelines* for Tier 1 national production data is appropriate based on expert judgment (RTI 2023). Per this expert judgment, a normal probability density function was assumed for all activity data.

The results of the Approach 2 quantitative uncertainty analysis are summarized in Table 4-116. Lead production CO_2 emissions in 2022 were estimated to be between 0.4 and 0.5 MMT CO_2 Eq. at the 95 percent confidence level. This indicates a range of approximately 15 percent below and 16 percent above the emission estimate of 0.4 MMT CO_2 Eq.

Table 4-116: Approach 2 Quantitative Uncertainty Estimates for CO_2 Emissions from Lead Production (MMT CO_2 Eq. and Percent)

Source	Gas	2022 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Lead Production	CO_2	0.4	0.4	0.5	-15%	+16%

[a] Range of emission estimates predicted by Monte Carlo stochastic simulation for a 95 percent confidence interval.

QA/QC and Verification

General quality assurance/quality control (QA/QC) procedures were applied consistent with the U.S. Inventory QA/QC plan, which is in accordance with Volume 1, Chapter 6 of *2006 IPCC Guidelines* as described in the introduction of the IPPU chapter (see Annex 8 for more details).

Initial review of activity data show that EPA's GHGRP Subpart R lead production data and resulting emissions are fairly consistent with those reported by USGS. EPA is still reviewing available GHGRP data, reviewing QC analysis to understand differences in data reporting (i.e., threshold implications), and assessing the possibility of including this planned improvement in future *Inventory* reports (see Planned Improvements section below). Currently, GHGRP data are used for QA purposes only.

Recalculations Discussion

Recalculations were implemented for 2020 and 2021 based on revised USGS data for secondary lead production. Compared to the previous *Inventory*, emissions decreased by 3 percent (14 kt CO_2) for 2020 and by 2 percent (7 kt CO_2) for 2021 (USGS 2023b).

Planned Improvements

Pending resources and prioritization of improvements for more significant sources, EPA will continue to evaluate and analyze data reported under EPA's GHGRP that would be useful to improve the emission estimates and category-specific QC for the Lead Production source category, in particular considering completeness of reported lead production given the reporting threshold. Particular attention will be made to ensuring time-series consistency of the emissions estimates presented in future *Inventory* reports, consistent with IPCC and UNFCCC guidelines. This is required as the facility-level reporting data from EPA's GHGRP, with the program's initial requirements for reporting of emissions in calendar year 2010, are not available for all inventory years (i.e., 1990 through 2009) as required for this *Inventory*. In implementing improvements and integration of data from EPA's GHGRP, the latest guidance from the IPCC on the use of facility-level data in national inventories will be relied upon.[89]

4.23 Zinc Production (CRT Source Category 2C6)

Zinc production in the United States consists of both primary and secondary processes. Of the primary and secondary processes currently used in the United States, only the electrothermic and Waelz kiln secondary processes result in non-energy carbon dioxide (CO_2) emissions (Viklund-White 2000). This reporting category (2C6) includes emissions from the production of zinc. Per the IPCC methodological guidance, emissions from fuels consumed for energy purposes during the production of zinc are accounted for as part of fossil fuel combustion in the industrial end-use sector reported under the Energy chapter.

The majority of zinc produced in the United States is used for galvanizing. Galvanizing is a process where zinc coating is applied to steel in order to prevent corrosion. Zinc is used extensively for galvanizing operations in the automotive and construction industry. Zinc is also used in the production of zinc alloys and brass and bronze alloys (e.g., brass mills, copper foundries, and copper ingot manufacturing). Zinc compounds and dust are also used, to a lesser extent, by the agriculture, chemicals, paint, and rubber industries.

Production of zinc can be conducted with a range of pyrometallurgical (e.g., electrothermic furnace, Waelz kiln, flame reactor, batch retorts, Pinto process, and PIZO process) and hydrometallurgical (e.g., hydrometallurgical recovery, solvent recovery, solvent extraction-electrowinning, and electrolytic) processes. Hydrometallurgical production processes are assumed to be non-emissive since no carbon is used in these processes (Sjardin 2003). Primary production in the United States is conducted through the non-emissive electrolytic process, while secondary techniques include the electrothermic and Waelz kiln processes, as well as a range of other processes. Worldwide primary zinc production also employs a pyrometallurgical process using an Imperial Smelting Furnace; however, this process is not used in the United States (Sjardin 2003).

In the electrothermic process, roasted zinc concentrate and secondary zinc products enter a sinter feed where they are burned to remove impurities before entering an electric retort furnace. Metallurgical coke is added to the electric retort furnace as a carbon-containing reductant. This concentration step, using metallurgical coke and high temperatures, reduces the zinc oxides and produces vaporized zinc, which is then captured in a vacuum condenser. This reduction process also generates non-energy CO_2 emissions.

$$ZnO + C \rightarrow Zn(gas) + CO_2 \qquad \text{(Reaction 1)}$$

[89] See http://www.ipcc-nggip.iges.or.jp/public/tb/TFI_Technical_Bulletin_1.pdf.

$$ZnO + CO \rightarrow Zn(gas) + CO_2 \quad \text{(Reaction 2)}$$

In the Waelz kiln process, electric arc furnace (EAF) dust, which is captured during the recycling of galvanized steel, enters a kiln along with a reducing agent (typically carbon-containing metallurgical coke). When kiln temperatures reach approximately 1,100 to 1,200 degrees Celsius, zinc fumes are produced, which are combusted with air entering the kiln. This combustion forms zinc oxide, which is collected in a baghouse or electrostatic precipitator, and is then leached to remove chloride and fluoride. The use of carbon-containing metallurgical coke in a high-temperature fuming process results in non-energy CO_2 emissions. Through this process, approximately 0.33 metric tons of zinc is produced for every metric ton of EAF dust treated (Viklund-White 2000).

In the flame reactor process, a waste feed stream, which can include EAF dust, is processed in a high-temperature environment (greater than 2,000 °C) created by the combustion of natural gas or coal and oxygen-enriched air. Volatile metals, including zinc, are forced into the gas phase and drawn into a combustion chamber, where air is introduced and oxidation occurs. The metal oxide product is then collected in a dust collection system (EPA 1992).

In 2022, the only companies in the United States that used emissive technology to produce secondary zinc products were Befesa Holding US Inc (Befesa) and Steel Dust Recycling (SDR). The secondary zinc facilities operated by Befesa were acquired from American Zinc Recycling (AZR) (formerly "Horsehead Corporation") in 2021. PIZO Operating Company, LLC (PIZO) operated a secondary zinc production facility that processed EAF dust in Blytheville, AR from 2009 to 2012.

For Befesa, EAF dust is recycled in Waelz kilns at their Calumet, IL; Palmerton, PA; Rockwood, TN; and Barnwell, SC facilities. The former AZR facility in Beaumont, TX processed EAF dust via flame reactor from 1993 through 2009 (AZR 2021, Horsehead 2014). These Waelz kiln and flame reactor facilities produce intermediate zinc products (crude zinc oxide or calcine). Prior to 2014, most of output from these facilities were transported to their Monaca, PA facility where the products were smelted into refined zinc using electrothermic technology. In April 2014, the Monaca smelter was permanently closed and replaced by a new facility in Mooresboro, NC in 2014.

The Mooresboro facility uses a hydrometallurgical process (i.e., solvent extraction with electrowinning technology) to produce zinc products, which is assumed to be non-emissive as described above. Production at the Mooresboro facility was idled in April 2016 and re-started in March 2020 (Recycling Today 2020). Direct consumption of coal, coke, and natural gas were replaced with electricity consumption (Horsehead 2012b). The Mooresboro facility uses leaching and solvent extraction (SX) technology combined with electrowinning, melting, and casting technology. In this process, Waelz Oxide (WOX) is first washed in water to remove soluble elements such as chlorine, potassium, and sodium, and then is leached in a sulfuric acid solution to dissolve the contained zinc creating a pregnant liquor solution (PLS). The PLS is then processed in a solvent extraction step in which zinc is selectively extracted from the PLS using an organic solvent creating a purified zinc-loaded electrolyte solution. The loaded electrolyte solution is then fed into the electrowinning process in which electrical energy is applied across a series of anodes and cathodes submerged in the electrolyte solution causing the zinc to deposit on the surfaces of the cathodes. As the zinc metal builds up on these surfaces, the cathodes are periodically harvested in order to strip the zinc from their surfaces (Horsehead 2015).

SDR recycles EAF dust into intermediate zinc products using Waelz kilns and sells the intermediate products to companies who smelt it into refined products.

Emissions of CO_2 from zinc production in 2022 were estimated to be 0.9 MMT CO_2 Eq. (947 kt CO_2) (see Table 4-117). All 2022 CO_2 emissions resulted from secondary zinc production processes. Emissions from zinc production in the United States have increased overall since 1990 due to a gradual shift from non-emissive primary production to emissive secondary production. In 2022, emissions were estimated to be 50 percent higher than they were in 1990. Emissions decreased 6 percent from 2021 levels.

Table 4-117: CO_2 Emissions from Zinc Production (MMT CO_2 Eq.)

Year	1990	2005	2018	2019	2020	2021	2022
Zinc Production	0.6	1.0	1.0	1.0	1.0	1.0	0.9

Table 4-118: CO_2 Emissions from Zinc Production (kt CO_2)

Year	1990	2005	2018	2019	2020	2021	2022
Zinc Production	632	1,030	999	1,026	977	1,007	947

U.S. zinc mine production increased by 9 percent in 2022 compared to 2021, due in part to higher mill throughput and zinc ore grades at the Red Dog Mine in Alaska, the largest zinc mine in the United States. In 2022, United States primary and secondary refined zinc production were estimated to total 220,000 metric tons (USGS 2023) (see Table 4-119), remaining at approximately the same production level as in 2021. Secondary zinc production fell to its lowest point in the time series in 2019, following the closure of the Monaca, PA smelter in 2014 and issues with the AZR secondary zinc refinery in Mooresboro, NC. Secondary zinc production has increased significantly since the reopening of the idled Mooresboro facility in March 2020 (USGS 2021; AZP 2021).

Table 4-119: Zinc Production (Metric Tons)

Year	1990	2005	2018	2019	2020	2021	2022
Primary	262,704	191,120	101,000	101,000	101,000	101,000	101,000
Secondary	95,708	156,000	15,000	14,000	79,000	119,000	119,000
Total	**358,412**	**347,120**	**116,000**	**115,000**	**180,000**	**220,000**	**220,000**

Note: Totals may not sum due to independent rounding.

Methodology and Time-Series Consistency

Emissions of CO_2 emissions from zinc production[90] using the electrothermic primary production and Waelz kiln secondary production processes are calculated using a Tier 1 method from the *2006 IPCC Guidelines*, in accordance with the IPCC methodological decision tree and available data (IPCC 2006). The Tier 1 equation used to estimate emissions from zinc production is as follows:

Equation 4-17: *2006 IPCC Guidelines* Tier 1: CO_2 Emissions from Zinc Production (Equation 4.33)

$$E_{CO2} = Zn \times EF_{default}$$

where,

E_{CO_2} = CO_2 emissions from zinc production, metric tons

Zn = Quantity of zinc produced, metric tons

$EF_{default}$ = Default emission factor, metric tons CO_2/metric ton zinc produced

The Tier 1 emission factors provided by IPCC for Waelz kiln-based secondary production were derived from metallurgical coke consumption factors and other data presented in Vikland-White (2000). These coke consumption factors as well as other inputs used to develop the Waelz kiln emission factors are shown below. IPCC does not provide an emission factor for electrothermic processes due to limited information; therefore, the Waelz kiln-specific emission factors were also applied to zinc produced from electrothermic processes. Starting in 2014, refined zinc produced in the United States used hydrometallurgical processes and is assumed to be non-emissive.

[90] EPA has not integrated aggregated facility-level Greenhouse Gas Reporting Program (GHGRP) information to inform these estimates. The aggregated information (e.g., activity data and emissions) associated with Zinc Production did not meet criteria to shield underlying confidential business information (CBI) from public disclosure.

For Waelz kiln-based production, IPCC recommends the use of emission factors based on EAF dust consumption, if possible, rather than the amount of zinc produced since the amount of reduction materials used is more directly dependent on the amount of EAF dust consumed. Since only a portion of emissive zinc production facilities consume EAF dust, the emission factor based on zinc production is applied to the non-EAF dust consuming facilities, while the emission factor based on EAF dust consumption is applied to EAF dust consuming facilities.

The Waelz kiln emission factor based on the amount of zinc produced was developed based on the amount of metallurgical coke consumed for non-energy purposes per ton of zinc produced (i.e., 1.19 metric tons coke/metric ton zinc produced) (Viklund-White 2000), and the following equation:

Equation 4-18: Waelz Kiln CO_2 Emission Factor for Zinc Produced

$$EF_{Waelz\ Kiln} = \frac{1.19\ metric\ tons\ coke}{metric\ tons\ zinc} \times \frac{0.85\ metric\ tons\ C}{metric\ tons\ coke} \times \frac{3.67\ metric\ tons\ CO_2}{metric\ tons\ C} = \frac{3.70\ metric\ tons\ CO_2}{metric\ tons\ zinc}$$

Refined zinc production levels for AZR's Monaca, PA facility (utilizing electrothermic technology) were available from the company for years 2005 through 2013 (Horsehead 2008, 2011, 2012, 2013, and 2014). The Monaca facility was permanently shut down in April 2014 and replaced by AZR's new facility in Mooresboro, NC. The new facility uses hydrometallurgical process to produce refined zinc products. Hydrometallurgical production processes are assumed to be non-emissive since no carbon is used in these processes (Sjardin 2003).

Metallurgical coke consumption for non-EAF dust consuming facilities for 1990 through 2004 were extrapolated using the percentage change in annual refined zinc production at secondary smelters in the United States, as provided by the U.S. Geological Survey (USGS) *Minerals Yearbook: Zinc* (USGS 1994 through 2006). Metallurgical coke consumption for 2005 through 2013 were based on the secondary zinc production values obtained from the Horsehead Corporation Annual Report Form 10-K: 2005 through 2008 from the 2008 10-K (Horsehead Corp 2009); 2009 and 2010 from the 2010 10-K (Horsehead Corp. 2011); and 2011 through 2013 from the associated 10-K (Horsehead Corp. 2012a, 2013, 2014). Metallurgical coke consumption levels for 2014 and later were zero due to the closure of the AZR (formerly "Horsehead Corporation") electrothermic furnace facility in Monaca, PA. The secondary zinc produced values for each year were then multiplied by the 3.70 metric tons CO_2/metric ton zinc produced emission factor to develop CO_2 emission estimates for the AZR electrothermic furnace facility.

The Waelz kiln emission factor based on the amount of EAF dust consumed was developed based on the amount of metallurgical coke consumed per ton of EAF dust consumed (i.e., 0.4 metric tons coke/metric ton EAF dust consumed) (Viklund-White 2000), and the following equation:

Equation 4-19: Waelz Kiln CO_2 Emission Factor for EAF Dust Consumed

$$EF_{EAF\ Dust} = \frac{0.4\ metric\ tons\ coke}{metric\ tons\ EAF\ Dust} \times \frac{0.85\ metric\ tons\ C}{metric\ tons\ coke} \times \frac{3.67\ metric\ tons\ CO_2}{metric\ tons\ C} = \frac{1.24\ metric\ tons\ CO_2}{metric\ tons\ EAF\ Dust}$$

Metallurgical coke consumption for EAF dust consuming facilities for 1990 through 2022 were calculated based on the values of EAF dust consumed. The total amount of EAF dust consumed by the Waelz kilns currently operated by Befesa was available from AZR (formerly "Horsehead Corporation") in financial reports for years 2006 through 2015 (Horsehead 2007, 2008, 2010a, 2011, 2012a, 2013, 2014, 2015, and 2016), from correspondence with AZR for 2016 through 2019 (AZR 2020), and from correspondence with Befesa for 2020 through 2022 (Befesa 2022, 2023). The EAF dust consumption values for each year were then multiplied by the 1.24 metric tons CO_2/metric ton EAF dust consumed emission factor to develop CO_2 emission estimates for Befesa's Waelz kiln facilities.

The amount of EAF dust consumed by SDR and their total production capacity were obtained from SDR's facility in Alabama for the years 2011 through 2022 (SDR 2012, 2014, 2015, 2017, 2018, 2021, 2022, 2023). The SDR facility has been operational since 2008, underwent expansion in 2011 to include a second unit (operational since early- to mid-2012), and expanded its capacity again in 2017 (SDR 2018). Annual consumption data for SDR was not publicly

available for the years 2008, 2009, and 2010. These data were estimated using data for AZR's Waelz kilns for 2008 through 2010 (Horsehead 2007, 2008, 2010a, 2010b, 2011). Annual capacity utilization ratios were calculated using AZR's annual consumption and total capacity for the years 2008 through 2010. AZR's annual capacity utilization ratios were multiplied with SDR's total capacity to estimate SDR's consumption for each of the years, 2008 through 2010 (SDR 2013). The 1.24 metric tons CO_2/metric ton EAF dust consumed emission factor was then applied to SDR's estimated EAF dust consumption to develop CO_2 emission estimates for those Waelz kiln facilities.

PIZO's facility in Arkansas was operational from 2009 to 2012 (PIZO 2021). The amount of EAF dust consumed by PIZO's facility for 2009 through 2012 was not publicly available. EAF dust consumption for PIZO's facility for 2009 and 2010 were estimated by calculating annual capacity utilization of AZR's Waelz kilns and multiplying this utilization ratio by PIZO's total capacity (PIZO 2012). EAF dust consumption for PIZO's facility for 2011 through 2012 were estimated by applying the average annual capacity utilization rates for AZR and SDR (Grupo PROMAX) to PIZO's annual capacity (Horsehead 2012; SDR 2012; PIZO 2012). The 1.24 metric tons CO_2/metric ton EAF dust consumed emission factor was then applied to PIZO's estimated EAF dust consumption to develop CO_2 emission estimates for those Waelz kiln facilities.

The production and use of coking coal for zinc production is adjusted for within the Energy chapter as this fuel was consumed during non-energy related activities. Additional information on the adjustments made within the Energy sector for non-energy use of fuels is described in both the Methodology section of CO_2 from Fossil Fuel Combustion (3.1 Fossil Fuel Combustion (CRT Source Category 1A)) and Annex 2.1, Methodology for Estimating Emissions of CO_2 from Fossil Fuel Combustion.

Beginning with the 2017 USGS *Minerals Commodity Summary: Zinc*, United States primary and secondary refined zinc production were reported as one value, total refined zinc production. Prior to this publication, primary and secondary refined zinc production statistics were reported separately. For years 2016 through 2022, only one facility produced primary zinc. Primary zinc produced from this facility was subtracted from the USGS 2016 to 2022 total zinc production statistic to estimate secondary zinc production for these years.

Methodological approaches were applied to the entire time series to ensure consistency in emissions from 1990 through 2022.

Uncertainty

There is uncertainty associated with the amount of EAF dust consumed in the United States to produce secondary zinc using emission-intensive Waelz kilns. The estimate for the total amount of EAF dust consumed in Waelz kilns is based on combining the totals for (1) the EAF dust consumption value obtained for the kilns currently operated by Befesa (and formerly operated by AZR or Horsehead Corporation) and (2) an EAF dust consumption value obtained from the Waelz kiln facility operated by SDR. For the 1990 through 2015 estimates, EAF dust consumption values for the kilns currently operated by Befesa were obtained from annual financial reports to the Securities and Exchange Commission (SEC) by AZR. In 2016, AZR reorganized as a private company and ceased providing annual reports to the SEC (Recycling Today 2017). EAF dust consumption values for subsequent years from the Befesa kilns and SDR have been obtained from personal communication with facility representatives. Since actual EAF dust consumption information is not available for PIZO's facility (2009 through 2010) and SDR's facility (2008 through 2010), the amount is estimated by multiplying the EAF dust recycling capacity of the facility (available from the company's website) by the capacity utilization factor for AZR (which was available from Horsehead Corporation financial reports).The EAF dust consumption for PIZO's facility for 2011 through 2012 was estimated by multiplying the average capacity utilization factor developed from AZR and SDR's annual capacity utilization rates by PIZO's EAF dust recycling capacity. Therefore, there is uncertainty associated with the assumption used to estimate PIZO's annual EAF dust consumption values for 2009 through 2012 and SDR's annual EAF dust consumption values for 2008 through 2010. EPA uses an uncertainty range of ±5 percent for these EAF dust consumption data inputs, based upon expert elicitation from the USGS commodity specialist. Per this expert judgment, a normal probability density function was assigned for EAF dust consumption data inputs.

There is also uncertainty associated with the emission factors used to estimate CO_2 emissions from secondary zinc production processes. The Waelz kiln emission factors are based on materials balances for metallurgical coke and EAF dust consumed as provided by Viklund-White (2000). Therefore, the accuracy of these emission factors depends upon the accuracy of these materials balances. Data limitations prevented the development of emission factors for the electrothermic process. Therefore, emission factors for the Waelz kiln process were applied to both electrothermic and Waelz kiln production processes. Consistent with the ranges in Table 4.25 of the *2006 IPCC Guidelines*, EPA assigned an uncertainty range of ±20 percent for the Tier 1 Waelz kiln emission factors, which are provided by Viklund-White in the form of metric tons of coke per metric ton of EAF dust consumed and metric tons of coke per metric ton of zinc produced. In order to convert coke consumption rates to CO_2 emission rates, values for the heat and carbon content of coke were obtained from Table 4.2 – Tier 2 of the *2006 IPCC Guidelines*. An uncertainty range of ±10 percent was assigned to these coke data elements, and using the suggested uncertainty provided in Table 4.25, Tier 2 – National Reducing Agent & Process Materials Data of the *2006 IPCC Guidelines* is appropriate based on expert judgment (RTI 2023). Per this expert judgment, a triangular probability density function was assigned for emission factors and the heat and carbon content of coke.

The results of the Approach 2 quantitative uncertainty analysis are summarized in Table 4-120. Zinc production CO_2 emissions from 2022 were estimated to be between 0.8 and 1.1 MMT CO_2 Eq. at the 95 percent confidence level. This indicates a range of approximately 18 percent below and 20 percent above the emission estimate of 0.9 MMT CO_2 Eq.

Table 4-120: Approach 2 Quantitative Uncertainty Estimates for CO_2 Emissions from Zinc Production (MMT CO_2 Eq. and Percent)

Source	Gas	2022 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (MMT CO_2 Eq.)		Uncertainty Range Relative to Emission Estimate[a] (%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Zinc Production	CO_2	0.9	0.8	1.1	-18%	+20%

[a] Range of emission estimates predicted by Monte Carlo stochastic simulation for a 95 percent confidence interval.

QA/QC and Verification

General quality assurance/quality control (QA/QC) procedures were applied consistent with the U.S. Inventory QA/QC plan, which is in accordance with Volume 1, Chapter 6 of *2006 IPCC Guidelines* as described in the introduction of the IPPU chapter (see Annex 8 for more details).

Recalculations Discussion

Recalculations were performed for the year 2021 based on updated EAF dust consumption data. Compared to the previous *Inventory*, 2021 emissions from zinc production increased by 4 percent (38 kt CO_2).

Planned Improvements

Pending resources and prioritization of improvements for more significant sources, EPA will continue to evaluate and analyze data reported under EPA's GHGRP that would be useful to improve the emission estimates and category-specific QC for zinc production, in particular considering completeness of reported zinc production given the reporting threshold. Given the small number of facilities in the United States, particular attention will be made to risks for disclosing CBI and ensuring time-series consistency of the emissions estimates presented in future *Inventory* reports, consistent with IPCC and UNFCCC guidelines. This is required as the facility-level reporting data from EPA's GHGRP, with the program's initial requirements for reporting of emissions in calendar year 2010, are not available for all inventory years (i.e., 1990 through 2009) as required for this *Inventory*. In implementing

improvements and integration of data from EPA's GHGRP, the latest guidance from the IPCC on the use of facility-level data in national inventories will be relied upon.[91] This is a long-term planned improvement, and EPA is still assessing the possibility of including this improvement in future *Inventory* reports.

4.24 Electronics Industry (CRT Source Category 2E)

The electronics industry uses multiple greenhouse gases in its manufacturing processes. In semiconductor manufacturing, these include long-lived fluorinated greenhouse gases used for plasma etching and chamber cleaning (CRT Source Category 2E1), fluorinated heat transfer fluids used for temperature control and other applications (CRT Source Category 2E4), and nitrous oxide (N_2O) used to produce thin films through chemical vapor deposition and in other applications (reported under CRT Source Category 2H3). Similar to semiconductor manufacturing, the manufacturing of micro-electro-mechanical systems (MEMS) devices (reported under CRT Source Category 2E5 Other) and photovoltaic (PV) cells (CRT Source Category 2E3) requires the use of multiple long-lived fluorinated greenhouse gases for various processes.

The gases most commonly employed in the electronics industry are trifluoromethane (hydrofluorocarbon (HFC)-23 or CHF_3), perfluoromethane (CF_4), perfluoroethane (C_2F_6), nitrogen trifluoride (NF_3), and sulfur hexafluoride (SF_6), although other fluorinated compounds such as perfluoropropane (C_3F_8) and perfluorocyclobutane (c-C_4F_8) are also used. The exact combination of compounds is specific to the process employed.

In addition to emission estimates for these seven commonly used fluorinated gases, this *Inventory* contains emissions estimates for N_2O and other HFCs and unsaturated, low-GWP PFCs including C_5F_8, C_4F_6, HFC-32, HFC-41, and HFC-134a. These additional HFCs and PFCs are emitted from etching and chamber cleaning processes in much smaller amounts, accounting for 0.02 percent of emissions (in CO_2 Eq.) from these processes.

For semiconductors, a single 300 mm silicon wafer that yields between 400 to 600 semiconductor products (devices or chips) may require more than 100 distinct fluorinated-gas-using process steps, principally to deposit and pattern dielectric films. Plasma etching (or patterning) of dielectric films, such as silicon dioxide and silicon nitride, is performed to provide pathways for conducting material to connect individual circuit components in each device. The patterning process uses plasma-generated fluorine atoms, which chemically react with exposed dielectric film to selectively remove the desired portions of the film. The material removed as well as undissociated fluorinated gases flow into waste streams and, unless emission abatement systems are employed, into the atmosphere. Plasma enhanced chemical vapor deposition (PECVD) chambers, used for depositing dielectric films, are cleaned periodically using fluorinated and other gases. During the cleaning cycle the gas is converted to fluorine atoms in plasma, which etches away residual material from chamber walls, electrodes, and chamber hardware. Undissociated fluorinated gases and other products pass from the chamber to waste streams and, unless abatement systems are employed, into the atmosphere.

In addition to emissions of unreacted gases, some fluorinated compounds can also be transformed in the plasma processes into different fluorinated compounds which are then exhausted, unless abated, into the atmosphere. For example, when C_2F_6 is used in cleaning or etching, CF_4 is typically generated and emitted as a process byproduct. In some cases, emissions of the byproduct gas can rival or even exceed emissions of the input gas, as is the case for NF_3 used in remote plasma chamber cleaning, which often generates CF_4 as a byproduct.

[91] See http://www.ipcc-nggip.iges.or.jp/public/tb/TFI_Technical_Bulletin_1.pdf and the *2019 Refinement*, Volume 1, Chapter 2, Section 2.3, *Use of Facility Data in Inventories* at https://www.ipcc-nggip.iges.or.jp/public/2019rf/pdf/1_Volume1/19R_V1_Ch02_DataCollection.pdf.

Besides dielectric film etching and PECVD chamber cleaning, much smaller quantities of fluorinated gases are used to etch polysilicon films and refractory metal films like tungsten.

Nitrous oxide is used in manufacturing semiconductor devices to produce thin films by CVD and nitridation processes as well as for N-doping of compound semiconductors and reaction chamber conditioning (Doering 2000).

Liquid perfluorinated compounds are also used as heat transfer fluids (F-HTFs) for temperature control, device testing, cleaning substrate surfaces and other parts, and soldering in certain types of semiconductor manufacturing production processes. Leakage and evaporation of these fluids during use is a source of fluorinated gas emissions (EPA 2006). Unweighted F-HTF emissions consist primarily of perfluorinated amines, hydrofluoroethers, perfluoropolyethers (specifically, PFPMIEs), and perfluoroalkylmorpholines. Three percent or less consist of HFCs, PFCs, and SF_6 (where PFCs are defined as compounds including only carbon and fluorine). With the exceptions of the hydrofluoroethers and most of the HFCs, all of these compounds are very long-lived in the atmosphere and have global warming potentials (GWPs) near 10,000.[92]

MEMS and photovoltaic cell manufacturing require thin film deposition and etching of material with a thickness of one micron or more, so the process is less intricate and complex than semiconductor manufacturing. The manufacturing process is different than semiconductors, but generally employs similar techniques. Like semiconductors, MEMS and photovoltaic cell manufacturers use fluorinated compounds for etching, cleaning reactor chambers, and temperature control. CF_4, SF_6, and the Bosch process (which consists of alternating steps of SF_6 and C_4F_8) are used to manufacture MEMS (EPA 2010). Photovoltaic cell manufacturing predominately uses CF_4, to etch crystalline silicon wafers, and C_2F_6 or NF_3 during chamber cleaning after deposition of SiN_x films (IPCC 2006), although other F-GHGs may be used. Similar to semiconductor manufacturing, both MEMS and photovoltaic cell manufacturing use N_2O in depositing films and other manufacturing processes. MEMS and photovoltaic manufacturing may also employ HTFs for cooling process equipment (EPA 2010).

Emissions from all fluorinated greenhouse gases (including F-HTFs) and N_2O for semiconductors, MEMS and photovoltaic cells manufacturing are presented in Table 4-121 below for the years 1990, 2005, and the period 2018 to 2022. The rapid growth of the electronics industry and the increasing complexity (growing number of layers and functions)[93] of electronic products led to an increase in emissions of 152 percent between 1990 and 1999, when emissions peaked at 8.4 MMT CO_2 Eq. Emissions began to decline after 1999, reaching a low point in 2009 before rebounding to 2006 emission levels and more or less plateauing at the current level, which represents a 43 percent decline from 1999 to 2022. Together, industrial growth, adoption of emissions reduction technologies (including but not limited to abatement technologies) and shifts in gas usages resulted in a net increase in emissions of approximately 43 percent between 1990 and 2022. Total emissions from semiconductor manufacture in 2022 were lower than 2021 emissions, decreasing by 2.2 percent, largely due to a large decrease in SF_6 emissions. The decrease in SF_6 are seen in facilities that manufacture 200 mm wafer size that do not have abatement systems installed as well as 300 mm wafer size that have abatement systems installed.

For U.S. semiconductor manufacturing in 2022, total CO_2-equivalent emissions of all fluorinated greenhouse gases and N_2O from deposition, etching, and chamber cleaning processes were estimated to be 4.7 MMT CO_2 Eq. This is a

[92] The GWP of PFPMIE, a perfluoropolyether used as an F-HTF, is included in the IPCC *Fourth Assessment Report* with a value of 10,300. The GWPs of the perfluorinated amines and perfluoroalkylmorpholines that are used as F-HTFs have not been evaluated in the peer-reviewed literature. However, evaluations by the manufacturer indicate that their GWPs are near 10,000 (78 FR 20632), which is expected given that these compounds are both saturated and fully fluorinated. EPA assigns a default GWP of 10,000 to compounds that are both saturated and fully fluorinated and that do not have chemical-specific GWPs in either the Fourth or the Fifth Assessment Reports.

[93] Complexity is a term denoting the circuit required to connect the active circuit elements (transistors) on a chip. Increasing miniaturization, for the same chip size, leads to increasing transistor density, which, in turn, requires more complex interconnections between those transistors. This increasing complexity is manifested by increasing the levels (i.e., layers) of wiring, with each wiring layer requiring fluorinated gas usage for its manufacture.

decrease in emissions from 1999 of 44 percent, and an increase in emissions from 1990 of 42 percent. These trends are driven by the above stated reasons.

Photovoltaic cell and MEMS manufacturing emissions of all fluorinated greenhouse gases are in Table 4-121. While EPA has developed a simple methodology to estimate emissions from non-reporters and to back-cast emissions from these sources for the entire time series, there is very high uncertainty associated with these emission estimates.

The emissions reported by facilities manufacturing MEMS included emissions of C_2F_6, C_3F_8, c-C_4F_8, CF_4, HFC-23, NF_3, N_2O and SF_6,[94] and were equivalent to only 0.110 percent to 0.260 percent of the total reported emissions from electronics manufacturing in 2011 to 2022. F-GHG emissions, the primary type of emissions for MEMS, ranged from 0.0003 to 0.012 MMT CO_2 Eq. from 1991 to 2022. Based upon information in the World Fab Forecast (WFF), it appears that some GHGRP reporters that manufacture both semiconductors and MEMS are reporting their emissions as only from semiconductor manufacturing (GHGRP reporters must choose a single classification per fab). Emissions from non-reporters have not been estimated.

Total CO_2-equivalent emissions from manufacturing of photovoltaic cells were estimated to range from 0.0003 MMT CO_2 Eq. to 0.0320 MMT CO_2 Eq. from 1998 to 2022 and were equivalent to between 0.003 percent to 0.77 percent of the total reported emissions from electronics manufacturing. F-GHG emissions, the primary type of emissions for photovoltaic cells, ranged from 0.0003 to 0.032 MMT CO_2 Eq. from 1998 to 2022. Emissions from manufacturing of photovoltaic cells were estimated using an emission factor developed from reported data from a single manufacturer between 2015 and 2016. This emission factor was then applied to production capacity estimates from non-reporting facilities. Reported emissions from photovoltaic cell manufacturing consisted of CF_4, C_2F_6, c-C_4F_8, CHF_3, NF_3, and N_2O.[95]

Emissions of F-HTFs, grouped by HFCs, PFCs or SF_6 are presented in Table 4-121. Emissions of F-HTFs that are not HFCs, PFCs or SF_6 are not included in inventory totals and are included for informational purposes only.

Since reporting of F-HTF emissions began under EPA's GHGRP in 2011, total F-HTF emissions (reported and estimated non-reported) have fluctuated between 0.4 MMT CO_2 Eq. and 0.9 MMT CO_2 Eq., with an overall declining trend between 2011 to 2022. An analysis of the data reported to EPA's GHGRP indicates that F-HTF emissions account for anywhere between 9 percent and 17 percent of total annual emissions (F-GHG, N_2O and F-HTFs) from semiconductor manufacturing.[96] Table 4-123 shows F-HTF emissions in tons by compound group based on reporting to EPA's GHGRP and the interpolated share of F-HTF emissions to F-GHG emissions for select years prior to reporting. [97]

[94] Gases not reported by MEMS manufacturers to the GHGRP are currently listed as "NE" in the CRTs. Since no facilities report using these gases, emissions of these gases are not estimated for this sub-sector. However, there is insufficient data to definitively conclude that they are not used by non-reporting facilities.

[95] Gases not reported by PV manufacturers to the GHGRP are currently listed as "NE" in the CRTs. Since no facilities report using these gases, emissions of these gases are not estimated for this sub-sector. However, there is insufficient data to definitively conclude that they are not used by non-reporting facilities.

[96] Emissions data for HTFs (in tons of gas) from the semiconductor industry from 2011 through 2022 were obtained from the EPA GHGRP annual facility emissions reports.

[97] Many fluorinated heat transfer fluids consist of perfluoropolymethylisopropyl ethers (PFPMIEs) of different molecular weights and boiling points that are distilled from a mixture. "BP 200 °C" (and similar terms below) indicate the boiling point of the fluid in degrees Celsius. For more information, see https://www.regulations.gov/document?D=EPA-HQ-OAR-2009-0927-0276.

Table 4-121: PFC, HFC, SF_6, NF_3, and N_2O Emissions from Electronics Industry (MMT CO_2 Eq.)

Year	1990	2005	2018	2019	2020	2021	2022
CF_4	0.8	1.0	1.6	1.5	1.5	1.6	1.6
C_2F_6	1.8	1.8	1.1	0.9	0.8	0.9	0.9
C_3F_8	+	0.1	0.1	0.1	0.1	0.1	0.1
C_4F_8	0.0	0.1	0.1	0.1	0.1	0.1	0.1
HFC-23	0.2	0.2	0.3	0.3	0.3	0.4	0.3
SF_6	0.5	0.8	0.8	0.8	0.8	0.9	0.7
NF_3	+	0.4	0.5	0.5	0.6	0.6	0.6
C_4F_6	+	+	+	+	+	+	+
C_5F_8	+	+	+	+	+	+	+
CH_2F_2	+	+	+	+	+	+	+
CH_3F	+	+	+	+	+	+	+
CH_2FCF_3	+	+	+	+	+	+	0.0
Total Semiconductors	**3.3**	**4.3**	**4.5**	**4.2**	**4.2**	**4.5**	**4.4**
CF_4	0.0	+	+	+	+	+	+
C_2F_6	0.0	+	+	+	+	+	+
C_3F_8	0.0	+	0.0	0.0	0.0	0.0	0.0
C_4F_8	0.0	+	+	+	+	+	+
HFC-23	0.0	+	+	+	+	+	+
SF_6	0.0	+	+	+	+	+	+
NF_3	0.0	0.0	+	+	+	+	+
Total MEMS	**0.0**	**+**	**+**	**+**	**+**	**+**	**+**
CF_4	0.0	+	+	+	+	+	+
C_2F_6	0.0	+	+	+	+	+	+
C_4F_8	0.0	+	+	+	+	+	+
HFC-23	0.0	+	+	+	+	+	+
SF_6	0.0	0.0	0.0	0.0	0.0	0.0	0.0
NF_3	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Total PV	**0.0**	**+**	**+**	**+**	**+**	**+**	**+**
N_2O (Semiconductors)	+	0.1	0.2	0.2	0.3	0.3	0.3
N_2O (MEMS)	0.0	+	+	+	+	+	+
N_2O (PV)	0.0	+	+	+	+	+	+
Total N_2O	**+**	**0.1**	**0.2**	**0.2**	**0.3**	**0.3**	**0.3**
HFC, PFC and SF_6 F-HTFs	0.0	+	+	+	+	+	+
Total Electronics Industry	**3.3**	**4.5**	**4.8**	**4.5**	**4.5**	**4.8**	**4.7**

+ Does not exceed 0.05 MMT CO_2 Eq.

Table 4-122: PFC, HFC, SF_6, NF_3, and N_2O Emissions from Semiconductor Manufacture (Metric Tons)

Year	1990	2005	2018	2019	2020	2021	2022
CF_4	114.8	145.3	236.7	223.9	227.6	238.2	247.2
C_2F_6	160.0	163.4	99.1	85.0	75.9	78.7	81.6
C_3F_8	0.4	7.3	12.2	10.7	9.6	11.2	13.6
C_4F_8	0.0	10.9	6.0	5.7	5.8	6.3	6.1
HFC-23	14.6	14.1	26.5	25.7	26.6	30.4	25.2
SF_6	21.7	33.4	33.4	33.3	32.3	38.4	31.4
NF_3	2.8	26.2	34.1	33.5	36.2	39.2	39.4
C_4F_6	0.7	0.9	0.8	0.9	0.8	1.0	0.9
C_5F_8	0.5	0.6	0.5	0.4	0.4	0.4	0.4
CH_2F_2	0.6	0.8	0.9	1.0	1.0	1.0	1.0
CH_3F	1.4	1.8	2.4	2.5	2.8	2.9	2.4
CH_2FCF_3	+	+	+	+	+	+	0.0
N_2O	135.9	463.3	883.4	816.0	1,020.8	1,083.0	1,113.2

+ Does not exceed 0.05 MT.

Table 4-123: F-HTF Emissions from Electronics Manufacture by Compound Group (kt CO_2 Eq.)

Year	1990	2005	2018	2019	2020	2021	2022
HFCs	0.0	0.9	2.7	1.1	0.9	1.1	1.5
PFCs	0.0	3.8	10.0	8.5	7.8	5.5	7.4
SF_6	0.0	5.6	13.2	6.1	12.9	9.0	4.2
HFEs	0.0	39.4	4.6	1.3	5.4	3.8	14.4
PFPMIEs	0.0	110.5	182.8	174.8	151.0	149.4	165.3
Perfluoalkylromorpholines	0.0	66.4	58.4	57.1	61.3	53.7	19.7
Perfluorotrialkylamines	0.0	209.9	413.7	367.5	382.0	367.5	237.1
Total F-HTFs	**0.0**	**436.5**	**685.4**	**616.5**	**621.2**	**590.1**	**449.6**

Note: Emissions of F-HTFs that are not HFCs, PFCs or SF_6 are not included in inventory totals and are included for informational purposes only. Emissions presented for informational purposes include HFEs, PFPMIEs, perfluoroalkylmorpholines, and perfluorotrialkylamines.

Methodology and Time-Series Consistency

Emissions are based on data reported through Subpart I, Electronics Manufacture, of EPA's GHGRP, semiconductor manufacturing Partner-reported emissions data received through EPA's PFC[98] Reduction/Climate Partnership, EPA's PFC Emissions Vintage Model (PEVM)—a model that estimates industry emissions from etching and chamber cleaning processes in the absence of emission control strategies (Burton and Beizaie 2001)[99]—and estimates of industry activity (i.e., total manufactured layer area and manufacturing capacity). The availability and applicability of reported emissions data from the EPA Partnership and EPA's GHGRP and activity data differ across the 1990 through 2022 time series. Consequently, fluorinated greenhouse gas (F-GHG) emissions from etching and chamber cleaning processes for semiconductors were estimated using seven distinct methods, one each for the periods 1990 through 1994, 1995 through 1999, 2000 through 2006, 2007 through 2010, 2011 and 2012, 2013 and 2014, and 2015 through 2022. Nitrous oxide emissions were estimated using five distinct methods, one each for the period 1990 through 1994, 1995 through 2010, 2011 and 2012, 2013 and 2014, and 2015 through 2022. The methodology discussion below for these time periods focuses on semiconductor emissions from etching, chamber cleaning, and uses of N_2O. Other emissions for MEMS, photovoltaic cells, and HTFs were estimated using the approaches described immediately below.

MEMS

GHGRP-reported emissions (F-GHG and N_2O) from the manufacturing of MEMS are available for the years 2011 to 2022. Emissions from manufacturing of MEMS for years prior to 2011 were calculated by linearly interpolating emissions between 1990 (at zero MMT CO_2 Eq.) and 2011, the first year where emissions from manufacturing of MEMS was reported to the GHGRP. Based upon information in the World Fab Forecast (WFF), it appears that some GHGRP reporters that manufacture both semiconductors and MEMS are reporting their emissions as only from semiconductor manufacturing; however, emissions from MEMS manufacturing are likely being included in semiconductor totals. Emissions were not estimated for non-reporters.

[98] In the context of the EPA Partnership and PEVM, PFC refers to perfluorocompounds, not perfluorocarbons.

[99] A Partner refers to a participant in the U.S. EPA PFC Reduction/Climate Partnership for the Semiconductor Industry. Through a Memorandum of Understanding (MoU) with the EPA, Partners voluntarily reported their PFC emissions to the EPA by way of a third party, which aggregated the emissions through 2010.

Photovoltaic Cells

GHGRP-reported emissions (F-GHG and N_2O) from the manufacturing of photovoltaic cells are available for 2011, 2012, 2015, and 2016 from two manufacturers. EPA estimates the emissions from manufacturing of PVs from non-reporting facilities by multiplying the estimated capacity of non-reporters by a calculated F-GHG emission factor and N_2O emission factor based on GHGRP reported emissions from the manufacturer (in MMT CO_2 Eq. per megawatt) that reported emissions in 2015 and 2016. This manufacture's emissions are expected to be more representative of emissions from the sector, as their emissions were consistent with consuming only CF_4 for etching processes and are a large-scale manufacturer, representing 28 percent of the U.S. production capacity in 2016. The second photovoltaic manufacturer only produced a small fraction of U.S. production (<4 percent). They also reported the use of NF_3 in remote plasma cleaning processes, which does not have an emission factor in Part 98 for PV manufacturing, requiring them to report emissions equal to consumption. The total F-GHG emissions from non-reporters are then disaggregated into individual gases using the gas distribution from the 2015 to 2016 manufacturer. Manufacturing capacities in megawatts were drawn from DisplaySearch, a 2015 Congressional Research Service Report on U.S. Solar Photovoltaic Manufacturing, and self-reported capacity by GHGRP reporters. EPA estimated that during the 2015 to 2016 period, 28 percent of manufacturing capacity in the United States was represented through reported GHGRP emissions. Capacities are estimated for the full time series by linearly scaling the total U.S. capacity between zero in 1997 to the total capacity reported of crystalline silicon (c-Si) PV manufacturing in 2000 in DisplaySearch and then linearly scaling between the total capacity of c-Si PV manufacturing in DisplaySearch in 2009 to the total capacity of c-Si PV manufacturing reported in the Congressional Research Service report in 2012. Capacities were held constant for non-reporters for 2012 to 2019. In 2020, non-reporter capacity declined due to the closure of several PV manufacturing plants. This capacity was held constant for 2021 and 2022. Average emissions per MW from the GHGRP reporter in 2015 and 2016 were then applied to the total capacity prior to 2015. Emissions for 2014 from the GHGRP reporter that reported in 2015 and 2016 were scaled to the number of months open in 2014. For 1998 through 2022, emissions per MW (capacity) from the GHGRP reporter were applied to the non-reporters. For 2017 through 2022, there are no reported PV emissions. Therefore, emissions were estimated using the EPA-derived emission factor and estimated manufacturing capacity from non-reporters only.

HTFs

Facility emissions of F-HTFs from semiconductor manufacturing are reported to EPA under its GHGRP and are available for the years 2011 through 2022. EPA estimates the emissions of F-HTFs from non-reporting semiconductor facilities by calculating the ratio of GHGRP-reported fluorinated HTF emissions to GHGRP reported F-GHG emissions from etching and chamber cleaning processes, and then multiplying this ratio by the F-GHG emissions from etching and chamber cleaning processes estimated for non-reporting facilities. Fluorinated HTF use in semiconductor manufacturing is assumed to have begun in the early 2000s and to have gradually displaced other HTFs (e.g., de-ionized water and glycol) in semiconductor manufacturing (EPA 2006). For time-series consistency, EPA interpolated the share of F-HTF emissions to F-GHG emissions between 2000 (at 0 percent) and 2011 (at 17 percent) and applied these shares to the unadjusted F-GHG emissions during those years to estimate the emissions.

Semiconductors

1990 through 1994

From 1990 through 1994, Partnership data were unavailable, and emissions were modeled using PEVM (Burton

and Beizaie 2001).[100] The 1990 to 1994 emissions are assumed to be uncontrolled, since reduction strategies such as chemical substitution and abatement were yet to be developed.

PEVM is based on the recognition that fluorinated greenhouse gas emissions from semiconductor manufacturing vary with: (1) the number of layers that comprise different kinds of semiconductor devices, including both silicon wafer and metal interconnect layers, and (2) silicon consumption (i.e., the area of semiconductors produced) for each kind of device. The product of these two quantities, Total Manufactured Layer Area (TMLA), constitutes the activity data for semiconductor manufacturing. PEVM also incorporates an emission factor that expresses emissions per unit of manufactured layer-area. Emissions are estimated by multiplying TMLA by this emission factor.

PEVM incorporates information on the two attributes of semiconductor devices that affect the number of layers: (1) linewidth technology (the smallest manufactured feature size),[101] and (2) product type (discrete, memory or logic).[102] For each linewidth technology, a weighted average number of layers is estimated using VLSI product-specific worldwide silicon demand data in conjunction with complexity factors (i.e., the number of layers per Integrated Circuit (IC) specific to product type (Burton and Beizaie 2001; ITRS 2007). PEVM derives historical consumption of silicon (i.e., square inches) by linewidth technology from published data on annual wafer starts and average wafer size (VLSI Research, Inc. 2012).

The emission factor in PEVM is the average of four historical emission factors, each derived by dividing the total annual emissions reported by the Partners for each of the four years between 1996 and 1999 by the total TMLA estimated for the Partners in each of those years. Over this period, the emission factors varied relatively little (i.e., the relative standard deviation for the average was 5 percent). Since Partners are believed not to have applied significant emission reduction measures before 2000, the resulting average emission factor reflects uncontrolled emissions and hence may be use here to estimate 1990 through 1994 emissions. The emission factor is used to estimate U.S. uncontrolled emissions using publicly available data on world (including U.S.) silicon consumption.

As it was assumed for this time period that there was no consequential adoption of fluorinated-gas-reducing measures, a fixed distribution of fluorinated-gas use was assumed to apply to the entire U.S. industry to estimate gas-specific emissions. This distribution was based upon the average fluorinated-gas purchases made by semiconductor manufacturers during this period and the application of IPCC default emission factors for each gas (Burton and Beizaie 2001).

PEVM only addressed the seven main F-GHGs (CF_4, C_2F_6, C_3F_8, c-C_4F_8, HFC-23, SF_6, and NF_3) used in semiconductor manufacturing. Through reporting under Subpart I of EPA's GHGRP, data on other F-GHGs (C_4F_6, C_5F_8, HFC-32, HFC-41, HFC-134a) used in semiconductor manufacturing became available and EPA was therefore able to extrapolate this data across the entire 1990 to 2022 timeseries. To estimate emissions for these "other F-GHGs", emissions data from Subpart I between 2014 to 2016 were used to estimate the average share or percentage contribution of these gases as compared to total F-GHG emissions. Subpart I emission factors were updated for 2014 by EPA as a

[100] Various versions of the PEVM exist to reflect changing industrial practices. From 1990 to 1994 emissions estimates are from PEVM v1.0, completed in September 1998. The emission factor used to estimate 1990 to 1994 emissions is an average of the 1995 and 1996 emissions factors, which were derived from Partner reported data for those years.

[101] By decreasing features of Integrated Circuit components, more components can be manufactured per device, which increases its functionality. However, as those individual components shrink it requires more layers to interconnect them to achieve the functionality. For example, a microprocessor manufactured with 65 nm feature sizes might contain as many as 1 billion transistors and require as many as 11 layers of component interconnects to achieve functionality, while a device manufactured with 130 nm feature size might contain a few hundred million transistors and require 8 layers of component interconnects (ITRS 2007).

[102] Memory devices manufactured with the same feature sizes as microprocessors (a logic device) require approximately one-half the number of interconnect layers, whereas discrete devices require only a silicon base layer and no interconnect layers (ITRS 2007). Since discrete devices did not start using PFCs appreciably until 2004, they are only accounted for in the PEVM emissions estimates from 2004 onwards.

result of a larger set of emission factor data becoming available, so reported data from 2011 through 2013 was not utilized for the average. To estimate non-reporter emissions from 2011-2022, the average emissions data from Subpart I of 2011 to 2022 was used.

To estimate N_2O emissions, it was assumed the proportion of N_2O emissions estimated for 1995 (discussed below) remained constant for the period of 1990 through 1994.

1995 through 1999

For 1995 through 1999, total U.S. emissions were extrapolated from the total annual emissions reported by the Partners (1995 through 1999). Partner-reported emissions are considered more representative (e.g., in terms of capacity utilization in a given year) than PEVM-estimated emissions and are used to generate total U.S. emissions when applicable. The emissions reported by the Partners were divided by the ratio of the total capacity of the plants operated by the Partners and the total capacity of all of the semiconductor plants in the United States; this ratio represents the share of capacity attributable to the Partnership. This method assumes that Partners and non-Partners have identical capacity utilizations and distributions of manufacturing technologies. Plant capacity data is contained in the World Fab Forecast (WFF) database and its predecessors, which is updated quarterly. Gas-specific emissions were estimated using the same method as for 1990 through 1994.

For this time period emissions of other F-GHGs (C_4F_6, C_5F_8, HFC-32, HFC-41, HFC-134a) were estimated using the method described above for 1990 to 1994.

For this time period, the N_2O emissions were estimated using an emission factor that was applied to the annual, total U.S. TMLA manufactured. The emission factor was developed using a regression-through-the-origin (RTO) model: GHGRP reported N_2O emissions were regressed against the corresponding TMLA of facilities that reported no use of abatement systems. Details on EPA's GHGRP reported emissions and development of emission factor using the RTO model are presented in the 2011 through 2012 section. The total U.S. TMLA for 1995 through 1999 was estimated using PEVM.

2000 through 2006

Emissions for the years 2000 through 2006—the period during which Partners began the consequential application of fluorinated greenhouse gas-reduction measures—were estimated using a combination of Partner-reported emissions and adjusted PEVM modeled emissions. The emissions reported by Partners for each year were accepted as the quantity emitted from the share of the industry represented by those Partners. Remaining emissions, those from non-Partners, were estimated using PEVM, with one change. To ensure time-series consistency and to reflect the increasing use of remote clean technology (which increases the efficiency of the production process while lowering emissions of fluorinated greenhouse gases), the average non-Partner emission factor (PEVM emission factor) was assumed to begin declining gradually during this period. Specifically, the non-Partner emission factor for each year was determined by linear interpolation, using the end points of 1999 (the original PEVM emission factor) and 2011 (a new emission factor determined for the non-Partner population based on GHGRP-reported data, described below).

The portion of the U.S. total emissions attributed to non-Partners is obtained by multiplying PEVM's total U.S. emissions figure by the non-Partner share of U.S. total silicon capacity for each year as described above.[103] Gas-specific emissions from non-Partners were estimated using linear interpolation between the gas-specific emissions distributions of 1999 (assumed to be the same as that of the total U.S. Industry in 1994) and 2011 (calculated from a subset of non-Partners that reported through the GHGRP as a result of emitting more than 25,000 MT CO_2 Eq. per year). Annual updates to PEVM reflect published figures for actual silicon consumption from VLSI Research, Inc., revisions and additions to the world population of semiconductor manufacturing plants, and changes in IC

[103] This approach assumes that the distribution of linewidth technologies is the same between Partners and non-Partners. As discussed in the description of the method used to estimate 2007 emissions, this is not always the case.

fabrication practices within the semiconductor industry (see ITRS 2008 and Semiconductor Equipment and Materials Industry 2011).[104, 105, 106] For this time period emissions of other F-GHGs (C_4F_6, C_5F_8, HFC-32, HFC-41, HFC-134a) were estimated using the method described above for 1990 to 1994.

Nitrous oxide emissions were estimated using the same methodology as the 1995 through 1999 methodology.

2007 through 2010

For the years 2007 through 2010, emissions were also estimated using a combination of Partner reported emissions and adjusted PEVM modeled emissions to provide estimates for non-Partners; however, two improvements were made to the estimation method employed for the previous years in the time series. First, the 2007 through 2010 emission estimates account for the fact that Partners and non-Partners employ different distributions of manufacturing technologies, with the Partners using manufacturing technologies with greater transistor densities and therefore greater numbers of layers.[107] Second, the scope of the 2007 through 2010 estimates was expanded relative to the estimates for the years 2000 through 2006 to include emissions from research and development (R&D) fabs. This additional enhancement was feasible through the use of more detailed data published in the WFF. PEVM databases were updated annually as described above. The published world average capacity utilization for 2007 through 2010 was used for production fabs, while for R&D fabs a 20 percent figure was assumed (SIA 2009).

In addition, publicly available utilization data was used to account for differences in fab utilization for manufacturers of discrete and IC products for 2010 emissions for non-Partners. The Semiconductor Capacity Utilization (SICAS) Reports from SIA provides the global semiconductor industry capacity and utilization, differentiated by discrete and IC products (SIA 2009 through 2011). PEVM estimates were adjusted using technology-weighted capacity shares that reflect the relative influence of different utilization. Gas-specific emissions for non-Partners were estimated using the same method as for 2000 through 2006.

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[104] Special attention was given to the manufacturing capacity of plants that use wafers with 300 mm diameters because the actual capacity of these plants is ramped up to design capacity, typically over a 2 to 3 year period. To prevent overstating estimates of partner-capacity shares from plants using 300 mm wafers, *design* capacities contained in WFF were replaced with estimates of *actual installed* capacities for 2004 published by Citigroup Smith Barney (2005). Without this correction, the partner share of capacity would be overstated, by approximately 5 percent. For perspective, approximately 95 percent of all new capacity additions in 2004 used 300 mm wafers, and by year-end those plants, on average, could operate at approximately 70 percent of the design capacity. For 2005, actual installed capacities were estimated using an entry in the World Fab Watch database (April 2006 Edition) called "wafers/month, 8-inch equivalent," which denoted the actual installed capacity instead of the fully-ramped capacity. For 2006, actual installed capacities of new fabs were estimated using an average monthly ramp rate of 1100 wafer starts per month (wspm) derived from various sources such as semiconductor fabtech, industry analysts, and articles in the trade press. The monthly ramp rate was applied from the first-quarter of silicon volume (FQSV) to determine the average design capacity over the 2006 period.

[105] In 2006, the industry trend in co-ownership of manufacturing facilities continued. Several manufacturers, who are Partners, now operate fabs with other manufacturers, who in some cases are also Partners and in other cases are not Partners. Special attention was given to this occurrence when estimating the Partner and non-Partner shares of U.S. manufacturing capacity.

[106] Two versions of PEVM are used to model non-Partner emissions during this period. For the years 2000 to 2003 PEVM v3.2.0506.0507 was used to estimate non-Partner emissions. During this time, discrete devices did not use PFCs during manufacturing and therefore only memory and logic devices were modeled in the PEVM v3.2.0506.0507. From 2004 onwards, discrete device fabrication started to use PFCs, hence PEVM v4.0.0701.0701, the first version of PEVM to account for PFC emissions from discrete devices, was used to estimate non-Partner emissions for this time period.

[107] EPA considered applying this change to years before 2007 but found that it would be difficult due to the large amount of data (i.e., technology-specific global and non-Partner TMLA) that would have to be examined and manipulated for each year. This effort did not appear to be justified given the relatively small impact of the improvement on the total estimate for 2007 and the fact that the impact of the improvement would likely be lower for earlier years because the estimated share of emissions accounted for by non-Partners is growing as Partners continue to implement emission-reduction efforts.

For this time period emissions of other F-GHGs (C_5F_8, CH_2F_2, CH_3F, CH_2FCF_3, $C_2H_2F_4$) were estimated using the method described above for 1990 to 1994. Nitrous oxide emissions were estimated using the same methodology as the 1995 through 1999 methodology.

2011 through 2012

The fifth method for estimating emissions from semiconductor manufacturing covers the period 2011 through 2012. This methodology differs from previous years because the EPA's Partnership with the semiconductor industry ended (in 2010) and reporting under EPA's GHGRP began. Manufacturers whose estimated uncontrolled emissions equal or exceed 25,000 MT CO_2 Eq. per year (based on default F-GHG-specific emission factors and total capacity in terms of substrate area) are required to report their emissions to EPA. This population of reporters to EPA's GHGRP included both historical Partners of EPA's PFC Reduction/Climate Partnership as well as non-Partners some of which use gallium arsenide (GaAs) technology in addition to Si technology.[108] Emissions from the population of manufacturers that were below the reporting threshold were also estimated for this time period using EPA-developed emission factors and estimates of facility-specific production obtained from WFF. Inventory totals reflect the emissions from both reporting and non-reporting populations.

Under EPA's GHGRP, semiconductor manufacturing facilities report emissions of F-GHGs (for all types of F-GHGs) used in etch and clean processes as well as emissions of fluorinated heat transfer fluids. (Fluorinated heat transfer fluids are used to control process temperatures, thermally test devices, and clean substrate surfaces, among other applications.) They also report N_2O emissions from CVD and other processes. The F-GHGs and N_2O were aggregated, by gas, across all semiconductor manufacturing GHGRP reporters to calculate gas-specific emissions for the GHGRP-reporting segment of the U.S. industry. At this time, emissions that result from heat transfer fluid use that are HFC, PFC and SF_6 are included in the total emission estimates from semiconductor manufacturing, and these GHGRP-reported emissions have been compiled and presented in Table 4-121. F-HTF emissions resulting from other types of gases (e.g., HFEs) are not presented in semiconductor manufacturing totals in Table 4-121 and Table 4-122 but are shown in Table 4-123 for informational purposes.

Changes to the default emission factors and default destruction or removal efficiencies (DREs) used for GHGRP reporting affected the emissions trend between 2013 and 2014. These changes did not reflect actual emission rate changes but data improvements. Therefore, for the current *Inventory*, EPA adjusted the time series of GHGRP-reported data for 2011 through 2013 to ensure time-series consistency using a series of calculations that took into account the characteristics of a facility (e.g., wafer size and abatement use). To adjust emissions for facilities that did not report abatement in 2011 through 2013, EPA simply applied the revised emission factors to each facility's estimated gas consumption by gas, process type and wafer size. In 2014, EPA also started collecting information on fab-wide DREs and the gases abated by process type, which were used in calculations for adjusting emissions from facilities that abated F-GHGs in 2011 through 2013.

- To adjust emissions for facilities that abated emissions in 2011 through 2013, EPA first calculated the quantity of gas abated in 2014 using reported F-GHG emissions, the revised default DREs (or the estimated site-specific DRE,[109] if a site-specific DRE was indicated), and the fab-wide DREs reported in 2014.[110] To adjust emissions for facilities that abated emissions in 2011 through 2013, EPA first estimated

[108] GaAs and Si technologies refer to the wafer on which devices are manufactured, which use the same PFCs but in different ways.

[109] EPA generally assumed site-specific DREs were as follows: CF_4, Etch (90 percent); all other gases, Etch (98 percent); NF_3, Clean (95 percent); CF_4, Clean (80 percent), and all other gases, Clean (80 percent). There were a few exceptions where a higher DRE was assumed to ensure the calculations operated correctly when there was 100 percent abatement.

[110] If abatement information was not available for 2014 or the reported incorrectly in 2014, data from 2015 or 2016 was substituted.

the percentage of gas passing through abatement systems for remote plasma clean in 2014 using the ratio of emissions reported for CF_4 and NF_3.

- EPA then estimated the quantity of NF_3 abated for remote plasma clean in 2014 using the ratio of emissions reported for CF_4 (which is not abated) and NF_3. This abated quantity was then subtracted from the total abated quantity calculated as described in the bullet above.
- To account for the resulting remaining abated quantity, EPA assumed that the percentage of gas passing through abatement systems was the same across all remaining gas and process type combinations where abatement was reported for 2014.
- The percentage of gas abated was then assumed to be the same in 2011 through 2013 (if the facility claimed abatement that year) as in 2014 for each gas abated in 2014.

The revised emission factors and DREs were then applied to the estimated gas consumption for each facility by gas, process type and wafer size.[111]

For the segment of the semiconductor industry that is below EPA's GHGRP reporting threshold, and for R&D facilities, which are not covered by EPA's GHGRP, emission estimates are based on EPA-developed emission factors for the F-GHGs and N_2O and estimates of manufacturing activity. The new emission factors (in units of mass of CO_2 Eq./TMLA [million square inches (MSI)]) are based on the emissions reported under EPA's GHGRP by facilities without abatement and on the TMLA estimates for these facilities based on the WFF (SEMI 2012, 2013).[112] In a refinement of the method used to estimate emissions for the non-Partner population for prior years, different emission factors were developed for different subpopulations of fabs, disaggregated by wafer size (200 mm and 300 mm). For each of these groups, a subpopulation-specific emission factor was obtained using a regression-through-the-origin (RTO) model: facility-reported aggregate emissions of seven F-GHGs (CF_4, C_2F_6, C_3F_8, c-C_4F_8, CHF_3, SF_6 and NF_3)[113] were regressed against the corresponding TMLA to estimate an aggregate F-GHG emissions factor (CO_2 Eq./MSI TMLA), and facility-reported N_2O emissions were regressed against the corresponding TMLA to estimate a N_2O emissions factor (CO_2 Eq./MSI TMLA). For each subpopulation, the slope of the RTO model is the emission factor for that subpopulation. Information on the use of point-of-use abatement by non-reporting fabs was not available; thus, EPA conservatively assumed that non-reporting facilities did not use point-of-use abatement.

For 2011 and 2012, estimates of TMLA relied on the capacity utilization of the fabs published by the U.S. Census Bureau's Historical Data Quarterly Survey of Plant Capacity Utilization (USCB 2011, 2012). Similar to the assumption for 2007 through 2010, facilities with only R&D activities were assumed to utilize only 20 percent of their manufacturing capacity. All other facilities in the United States are assumed to utilize the average percent of the manufacturing capacity without distinguishing whether fabs produce discrete products or logic products.

Non-reporting fabs were then broken out into subpopulations by wafer size (200 mm and 300 mm). using information available through the WFF. The appropriate emission factor was applied to the total TMLA of each subpopulation of non-reporting facilities to estimate the CO_2-equivalent emissions of that subpopulation.

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[111] Since facilities did not report by fab before 2014, fab-wide DREs were averaged if a facility had more than one fab. For facilities that reported more than one wafer size per facility, the percentages of a facility's emissions per wafer size were estimated in 2014 and applied to earlier years, if possible. If the percentage of emissions per wafer size were unknown, a 50/50 split was used.

[112] EPA does not have information on fab-wide DREs for this time period, so it is not possible to estimate uncontrolled emissions from fabs that reported point-of-use abatement. These fabs were therefore excluded from the regression analysis. (They are still included in the national totals.)

[113] Only seven gases were aggregated because inclusion of F-GHGs that are not reported in the *Inventory* results in overestimation of emission factor that is applied to the various non-reporting subpopulations.

Gas-specific, CO_2-equivalent emissions for each subpopulation of non-reporting facilities were estimated using the corresponding reported distribution of gas-specific, CO_2-equivalent emissions from which the aggregate emission factors, based on GHGRP-reported data, were developed. Estimated in this manner, the non-reporting population accounted for 4.9 and 5.0 percent of U.S. emissions in 2011 and 2012, respectively. The GHGRP-reported emissions and the calculated non-reporting population emissions are summed to estimate the total emissions from semiconductor manufacturing.

2013 and 2014

For 2013 and 2014, as for 2011 and 2012, F-GHG and N_2O emissions data received through EPA's GHGRP were aggregated, by gas, across all semiconductor-manufacturing GHGRP reporters to calculate gas-specific emissions for the GHGRP-reporting segment of the U.S. industry. However, for these years WFF data was not available. Therefore, an updated methodology that does not depend on the WFF derived activity data was used to estimate emissions for the segment of the industry that are not covered by EPA's GHGRP. For the facilities that did not report to the GHGRP (i.e., which are below EPA's GHGRP reporting threshold or are R&D facilities), emissions were estimated based on the proportion of total U.S. emissions attributed to non-reporters for 2011 and 2012. EPA used a simple averaging method by first estimating this proportion for both F-GHGs and N_2O for 2011, 2012, and 2015 and 2016, resulting in one set of proportions for F-GHGs and one set for N_2O, and then applied the average of each set to the 2013 and 2014 GHGRP reported emissions to estimate the non-reporters' emissions. Fluorinated gas-specific, CO_2-equivalent emissions for non-reporters were estimated using the corresponding reported distribution of gas-specific, CO_2-equivalent emissions reported through EPA's GHGRP for 2013 and 2014.

GHGRP-reported emissions in 2013 were adjusted to capture changes to the default emission factors and default destruction or removal efficiencies used for GHGRP reporting, affecting the emissions trend between 2013 and 2014. EPA used the same method to make these adjustments as described above for 2011 and 2012 GHGRP data.

2015 through 2022

Similar to the methods described above for 2011 and 2012, and 2013 and 2014, EPA relied upon emissions data reported directly through the GHGRP. For 2015 through 2022, EPA took an approach similar to the one used for 2011 and 2012 to estimate emissions for the segment of the semiconductor industry that is below EPA's GHGRP reporting threshold, and for R&D facilities, which are not covered by EPA's GHGRP. However, in a change from previous years, EPA was able to develop new annual emission factors for 2015 through 2022 using TMLA from WFF and a more comprehensive set of emissions, i.e., fabs with as well as without abatement control, as new information about the use of abatement in GHGRP fabs and fab-wide were available. Fab-wide DREs represent total fab CO_2 Eq.-weighted controlled F-GHG and N_2O emissions (emissions after the use of abatement) divided by total fab CO_2 Eq.-weighted uncontrolled F-GHG and N_2O emissions (emission prior to the use of abatement).

Using information about reported emissions and the use of abatement and fab-wide DREs, EPA was able to calculate uncontrolled emissions (each total F-GHG and N_2O) for every GHGRP reporting fab. Using this, coupled with TMLA estimated using methods described above (see 2011 through 2012), EPA derived emission factors by year, gas type (F-GHG or N_2O), and wafer size (200 mm and less or 300 mm) by dividing the total annual emissions reported by GHGRP reporters by the total TMLA estimated for those reporters. These emission factors were multiplied by estimates of non-reporter TMLA to arrive at estimates of total F-GHG and N_2O emissions for non-reporters for each year. For each wafer size, the total F-GHG emissions were disaggregated into individual gases using the shares of total emissions represented by those gases in the emissions reported to the GHGRP by unabated fabs producing that wafer size.

Data Sources

GHGRP reporters, which consist of former EPA Partners and non-Partners, estimated their emissions using a default emission factor method established by EPA. Like the Tier 2c Method in the *2019 Refinement to the 2006 IPCC Guidelines*, this method uses different emission and byproduct generation factors for different F-GHGs and process types and uses factors for different wafer sizes (i.e., 300mm vs. 150 and 200mm) and CVD clean subtypes

(in situ thermal, in situ plasma, and remote plasma). Starting with 2014 reported emissions, EPA's GHGRP required semiconductor manufacturers to apply updated emission factors to estimate their F-GHG emissions. For the years 2011 through 2013 reported emissions, semiconductor manufacturers used older emission factors to estimate their F-GHG emissions (Federal Register / Vol. 75, No. 230 /December 1, 2010, 74829). Subpart I emission factors were updated for 2014 by EPA as a result of a larger set of emission factor data becoming available as part of the Subpart I petition process, which took place from 2011 through 2013. In addition to semiconductor manufacturing, GHGRP also includes reported emissions from MEMS and PV producers.

Historically, semiconductor industry partners estimated and reported their emissions using a range of methods and uneven documentation. It is assumed that most Partners used a method at least as accurate as the IPCC's Tier 2a Methodology, recommended in the *2006 IPCC Guidelines*. Partners are estimated to have accounted for between 56 and 79 percent of F-GHG emissions from U.S. semiconductor manufacturing between 1995 and 2010, with the percentage declining in recent years as Partners increasingly implemented abatement measures.

Estimates of operating plant capacities and characteristics for Partners and non-Partners were derived from the Semiconductor Equipment and Materials Industry (SEMI) WFF (formerly World Fab Watch) database (1996 through 2012, 2013, 2016, 2018, 2021, and 2023) (e.g., Semiconductor Materials and Equipment Industry 2021). Actual worldwide capacity utilizations for 2008 through 2010 were obtained from Semiconductor International Capacity Statistics (SICAS) (SIA 2009 through 2011). Estimates of the number of layers for each linewidth was obtained from International Technology Roadmap for Semiconductors: 2013 Edition (Burton and Beizaie 2001; ITRS 2007; ITRS 2008; ITRS 2011; ITRS 2013). PEVM utilized the WFF, SICAS, and ITRS, as well as historical silicon consumption estimates published by VLSI. Actual quarterly U.S. capacity utilizations for 2011, 2012, 2014 to 2022 were obtained from the U.S. Census Bureau's Historical Data Quarterly Survey of Plant Capacity Utilization (USCB 2011, 2012, 2015, 2016, 2017, 2018, 2019, 2020, 2021, 2022).

Estimates of PV manufacturing capacity, which are used to calculate emissions from non-reporting facilities, are based on data from two sources. A historical market analysis from DisplaySearch provided estimates of U.S. manufacturing capacity from 2000 to 2009 (DisplaySearch 2010). Domestic PV cell production for 2012 was obtained from a Congressional Research Service report titled *U.S. Solar Photovoltaic Manufacturing: Industry Trends, Global Competition, Federal Support* (Platzer 2015).

Uncertainty

A quantitative uncertainty analysis of this source category was performed using the IPCC-recommended Approach 2 uncertainty estimation methodology, the Monte Carlo stochastic simulation technique. The Monte Carlo stochastic simulation was performed on the total emissions estimate from the electronics industry, represented in equation form as:

Equation 4-20: Total Emissions from Electronics Industry

$$\begin{aligned}\text{Total Emissions } (\mathrm{E}_T) &= \text{Semiconductors F-GHG and } \mathrm{N_2O} \text{ Emissions } (\mathrm{E}_{Semi}) \\ &+ \text{MEMS F-GHG and } \mathrm{N_2O} \text{ Emissions } (\mathrm{E}_{MEMS}) + \text{PV F-GHG and } \mathrm{N_2O} \text{ Emissions } (\mathrm{E}_{PV}) \\ &+ \text{HFC, PFC and } \mathrm{SF_6} \text{ F-HTFs Emissions } (\mathrm{E}_{HTF})\end{aligned}$$

The uncertainty in the total emissions for the electronics industry, presented in Table 4-124 below, results from the convolution of four distributions of emissions, namely from semiconductors manufacturing, MEMS manufacturing, PV manufacturing and emissions of heat transfer fluids. The approaches for estimating uncertainty in each of the sources are described below:

Semiconductors Manufacture Emission Uncertainty

The Monte Carlo stochastic simulation was performed on the emissions estimate from semiconductor manufacturing, represented in equation form as:

Equation 4-21: Total Emissions from Semiconductor Manufacturing

$$\begin{aligned}\text{Semiconductors F-GHG and } N_2O \text{ Emissions } (E_{Semi}) \\ = \text{ GHGRP Reported F-GHG Emissions } (ER,\text{F-GHG, Semi}) \\ + \text{ Non-Reporters' Estimated F-GHG Emissions } \left(E_{NR,\text{F-GHG},Semi}\right) \\ + \text{ GHGRP Reported } N_2O \text{ Emissions } \left(E_{R,N_2O,Semi}\right) \\ + \text{ Non-Reporters' Estimated } N_2O \text{ Emissions } \left(E_{NR,N_2O,Semi}\right)\end{aligned}$$

The uncertainty in E_{Semi} results from the convolution of four distributions of emissions, $E_{R,F\text{-}GHG,Semi}$ $E_{R,N2O,Semi}$ $E_{NR,F\text{-}GHG,Semi}$ and $E_{NR,N2O,Semi}$. The approaches for estimating each distribution and combining them to arrive at the reported 95 percent confidence interval (CI) for E_{Semi} are described in the remainder of this section.

The uncertainty estimate of $E_{R,\ F\text{-}GHG,Semi}$, or GHGRP-reported F-GHG emissions, is developed based on gas-specific uncertainty estimates of emissions for two industry segments, one processing 200 mm or less wafers and one processing 300 mm wafers. Uncertainties in emissions for each gas and industry segment are based on an uncertainty analysis conducted during the assessment of emission estimation methods for the Subpart I rulemaking in 2012 (see Technical Support for Modifications to the Fluorinated Greenhouse Gas Emission Estimation Method Option for Semiconductor Facilities under Subpart I, docket EPA–HQ–OAR–2011–0028).[114] This assessment relied on facility-specific gas information by gas and wafer size, and incorporated uncertainty associated with both emission factors and gas consumption quantities. The 2012 analysis did not consider the use of abatement.

For the industry segment that manufactured 200 mm wafers, estimates of uncertainty at a 95 percent CI ranged from ±29 percent for C_3F_8 to ±10 percent for CF_4. For the corresponding 300 mm industry segment, estimates of uncertainty at the 95 percent CI ranged from ±36 percent for C_4F_8 to ±16 percent for CF_4. For gases for which uncertainty was not analyzed in the 2012 assessment (e.g., CH_2F_2), EPA applied the 95 percent CI range equivalent to the range for the gas and industry segment with the highest uncertainty from the 2012 assessment. These gas and wafer-specific uncertainty estimates were developed to represent uncertainty at a facility-level, but they are applied to the total emissions across all the facilities that did not abate emissions as reported under EPA's GHGRP at a national-level. Hence, it is noted that the uncertainty estimates used may be overestimating the uncertainties at a national-level.

For those facilities reporting abatement of emissions under EPA's GHGRP, estimates of uncertainties for the no abatement industry segments are modified to reflect the use of full abatement (abatement of all gases from all cleaning and etching equipment) and partial abatement. These assumptions used to develop uncertainties for the partial and full abatement facilities are identical for 200 mm and 300 mm wafer processing facilities. For all facilities reporting gas abatement, a triangular distribution of destruction or removal efficiency is assumed for each gas. The triangular distributions range from an asymmetric and highly uncertain distribution of zero percent minimum to 90 percent maximum with 70 percent most likely value for CF_4 to a symmetric and less uncertain distribution of 85 percent minimum to 95 percent maximum with 90 percent most likely value for C_4F_8, NF_3, and SF_6. For facilities reporting partial abatement, the distribution of fraction of the gas fed through the abatement device, for each gas, is assumed to be triangularly distributed as well. It is assumed that no more than 50 percent

[114] On November 13, 2013, EPA published a final rule revising Subpart I (Electronics Manufacturing) of the GHGRP (78 FR 68162). The revised rule includes updated default emission factors and updated default destruction and removal efficiencies that are slightly different from those that semiconductor manufacturers were required to use to report their 2012 emissions. The uncertainty analyses that were performed during the development of the revised rule focused on these updated defaults but are expected to be reasonably representative of the uncertainties associated with the older defaults, particularly for estimates at the country level. (They may somewhat underestimate the uncertainties associated with the older defaults at the facility level.) For simplicity, the 2012 estimates are assumed to be unbiased although in some cases, the updated (and therefore more representative) defaults are higher or lower than the older defaults. Multiple models and sensitivity scenarios were run for the Subpart I analysis. The uncertainty analysis presented here made use of the Input gas and wafer size model (Model 1) under the following conditions: Year = 2010, f = 20, n = SIA3.

of the gases are abated (i.e., the maximum value) and that 50 percent is the most likely value, and the minimum is zero percent. Consideration of abatement then resulted in four additional industry segments, two 200-mm wafer-processing segments (one fully and one partially abating each gas) and two 300-mm wafer-processing segment (one fully and the other partially abating each gas). Gas-specific emission uncertainties were estimated by convolving the distributions of unabated emissions with the appropriate distribution of abatement efficiency for fully and partially abated facilities using a Monte Carlo simulation.

The uncertainty in $E_{R,F\text{-}GHG,Semi}$ is obtained by allocating the estimates of uncertainties to the total GHGRP-reported emissions from each of the six industry segments, and then running a Monte Carlo simulation which results in the 95 percent CI for emissions from GHGRP-reporting facilities ($E_{R,F\text{-}GHG,Semi}$).

The uncertainty in $E_{R,N2O,Semi}$ is obtained by assuming that the uncertainty in the emissions reported by each of the GHGRP reporting facilities results from the uncertainty in quantity of N_2O consumed and the N_2O emission factor (or utilization). Similar to analyses completed for Subpart I (see Technical Support for Modifications to the Fluorinated Greenhouse Gas Emission Estimation Method Option for Semiconductor Facilities under Subpart I, docket EPA–HQ–OAR–2011–0028), the uncertainty of N_2O consumed was assumed to be 20 percent. Consumption of N_2O for GHGRP reporting facilities was estimated by back-calculating from emissions reported and assuming no abatement. The quantity of N_2O utilized (the complement of the emission factor) was assumed to have a triangular distribution with a minimum value of zero percent, mode of 20 percent and maximum value of 84 percent. The minimum was selected based on physical limitations, the mode was set equivalent to the Subpart I default N_2O utilization rate for chemical vapor deposition, and the maximum was set equal to the maximum utilization rate found in ISMI Analysis of Nitrous Oxide Survey Data (ISMI 2009). The inputs were used to simulate emissions for each of the GHGRP reporting, N_2O-emitting facilities. The uncertainty for the total reported N_2O emissions was then estimated by combining the uncertainties of each facilities' reported emissions using Monte Carlo simulation.

The estimate of uncertainty in $E_{NR,\ F\text{-}GHG,Semi}$ and $E_{NR,\ N2O,Semi}$ entailed developing estimates of uncertainties for the emissions factors and the corresponding estimates of TMLA.

The uncertainty in TMLA depends on the uncertainty of two variables—an estimate of the uncertainty in the average annual capacity utilization for each level of production of fabs (e.g., full scale or R&D production) and a corresponding estimate of the uncertainty in the number of layers manufactured. For both variables, the distributions of capacity utilizations and number of manufactured layers are assumed triangular for all categories of non-reporting fabs. The most probable utilization is assumed to be 82 percent, with the highest and lowest utilization assumed to be 89 percent, and 70 percent, respectively. For the triangular distributions that govern the number of possible layers manufactured, it is assumed the most probable value is one layer less than reported in the ITRS; the smallest number varied by technology generation between one and two layers less than given in the ITRS and largest number of layers corresponded to the figure given in the ITRS.

The uncertainty bounds for the average capacity utilization and the number of layers manufactured are used as inputs in a separate Monte Carlo simulation to estimate the uncertainty around the TMLA of both individual facilities as well as the total non-reporting TMLA of each sub-population.

The uncertainty around the emission factors for non-reporting facilities is the total combined uncertainties of individual gases and the TMLA of each reporting facility in that category. The combined uncertainty of emissions of individual gases from non-reporters is equal to the uncertainty of total emissions for non-reporting facilities.

The uncertainty around the emission factors for non-reporting facilities is the total combined uncertainties of individual gases (MT units) and the TMLA of each reporting facility in that category. The combined uncertainty of emissions of individual gases from non-reporters is equal to the uncertainty of total emissions for non-reporting facilities. For each wafer size for reporting facilities, emissions of individual gases were regressed on TMLA (with an intercept forced to zero) for 10,000 emission and 10,000 TMLA values in a Monte Carlo simulation, which results in 10,000 total regression coefficients (emission factors). The 2.5^{th} and the 97.5^{th} percentile of these emission factors are determined, and the bounds are assigned as the percent difference from the estimated emission factor.

The next step in estimating the uncertainty in emissions of reporting and non-reporting facilities in semiconductor

manufacture is convolving the distribution of reported emissions, emission factors, and TMLA using Monte Carlo simulation. For this Monte Carlo simulation, the distributions of the reported F-GHG gas- and wafer size-specific emissions are assumed to be normally distributed, and the uncertainty bounds are assigned at 1.96 standard deviations around the estimated mean. The were some instances, though, where departures from normality were observed for variables, including for the distributions of the gas- and wafer size-specific N_2O emissions, TMLA, and non-reporter emission factors, both for F-GHGs and N_2O. As a result, the distributions for these parameters were assumed to follow a PERT beta distribution.

MEMS Manufacture Emission Uncertainty

The Monte Carlo stochastic simulation was performed on the emissions estimate from MEMS manufacturing, represented in equation form as:

Equation 4-22: Total Emissions from MEMS Manufacturing

$$\text{MEMS F-GHG and } N_2O \text{ Emissions } (E_{MEMS}) = \text{GHGRP Reported F-GHG Emissions } (E_{R,\text{F-GHG},MEMS}) + \text{GHGRP Reported } N_2O \text{ Emissions } (E_{R,N2O,\,MEMS})$$

$$\text{MEMS F-GHG and } N_2O \text{ Emissions } (E_{MEMS}) = \text{GHGRP Reported F-GHG Emissions } \left(E_{R,\,\text{F-GHG},MEMS}\right) + \text{GHGRP Reported } N_2O \text{ Emissions } \left(E_{R,N_2O,MEMS}\right)$$

Emissions from MEMS manufacturing are only quantified for GHGRP reporters. MEMS manufacturers that report to the GHGRP all report the use of 200 mm wafers. Some MEMS manufacturers report using abatement equipment. Therefore, the estimates of uncertainty at the 95 percent CI for each gas emitted by MEMS manufacturers are set equal to the gas-specific uncertainties for manufacture of 200mm semiconductor wafers with partial abatement. The same assumption is applied for uncertainty levels for GHGRP reported MEMS N_2O emissions ($E_{R,N2O,MEMS}$).

PV Manufacture Emission Uncertainty

The Monte Carlo stochastic simulation was performed on the emissions estimate from PV manufacturing, represented in equation form as:

Equation 4-23: Total Emissions from PV Manufacturing

$$\text{PV F-GHG and } N_2O \text{ Emissions } (E_{PV}) = \text{Non-Reporters' Estimated F-GHG Emissions } (E_{NR,\text{F-GHG},PV}) + \text{Non-Reporters' Estimated } N_2O \text{ Emissions } (E_{NR,N2O,PV})$$

$$\text{PV F-GHG and } N_2O \text{ Emissions } (E_{PV}) = \text{Non-Reporters' Estimated F-GHG Emissions } \left(E_{NR,\text{F-GHG},PV}\right) + \text{Non-Reporters' Estimated N2O Emissions } \left(E_{NR,N_2O,PV}\right)$$

Emissions from PV manufacturing are only estimated for non-GHGRP reporters in 2022. There were no reported emissions from PV manufacturing in GHGRP in 2022. The "Non-Reporters' Estimated F-GHG Emissions" term in Equation 4-23 was estimated using an emission factor developed using emissions from reported data in 2015 and 2016 and total non-reporters' capacity. Due to a lack of information and data and because they represent similar physical and chemical processes, the uncertainty at the 95 percent CI level for non-reporter PV capacity is assumed to be the same as the uncertainty in non-reporter TMLA for semiconductor manufacturing. Similarly, the uncertainty for the PV manufacture emission factors are assumed to be the same as the uncertainties in emission factors used for non-reporters in semiconductor manufacture.

Heat Transfer Fluids Emission Uncertainty

There is a lack of data related to the uncertainty of emission estimates of heat transfer fluids used for electronics manufacture. Therefore, per the *2006 IPCC Guidelines* (IPCC 2006, Volume 3, Chapter 6), uncertainty bounds of 20

percent were applied to estimate uncertainty associated with the various types of heat transfer fluids, including PFCs, HFC, and SF_6, at the national level.

The results of the Approach 2 quantitative uncertainty analysis for electronics manufacturing are summarized in Table 4-124. These results were obtained by convolving—using Monte Carlo simulation—the distributions of emissions for each reporting and non-reporting facility that manufactures semiconductors, MEMS, or PVs and use heat transfer fluids. The emissions estimate for total U.S. F-GHG, N_2O, and HTF emissions from electronics manufacturing were estimated to be between 4.44 and 5.02 MMT CO_2 Eq. at a 95 percent CI level. This range represents 6 percent below to 6 percent above the 2022 emission estimate of 4.73 MMT CO_2 Eq. for all emissions from electronics manufacture. This range and the associated percentages apply to the estimate of total emissions rather than those of individual gases. Uncertainties associated with individual gases will be somewhat higher than the aggregate but were not explicitly modeled.

Table 4-124: Approach 2 Quantitative Uncertainty Estimates for HFC, PFC, SF_6, NF_3 and N_2O Emissions from Electronics Manufacture (MMT CO_2 Eq. and Percent)

Source	Gas	2022 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (MMT CO_2 Eq.)		(%)	
			Lower Bound[b]	Upper Bound[b]	Lower Bound	Upper Bound
Electronics Industry	HFC, PFC, SF_6, NF_3, and N_2O	4.7	4.4	5.0	-6%	+6%

[a] Range of emission estimates predicted by Monte Carlo stochastic simulation for a 95 percent confidence interval.
[b] Absolute lower and upper bounds were calculated using the corresponding lower and upper bounds in percentages.

QA/QC and Verification

For its GHGRP data, EPA verifies annual facility-level reports through a multi-step process (e.g., including a combination of pre-and post-submittal electronic checks and manual reviews by staff) to identify potential errors and ensure that data submitted to EPA are accurate, complete, and consistent (EPA 2015).[115] Based on the results of the verification process, EPA follows up with facilities to resolve mistakes that may have occurred. The post-submittals checks are consistent with a number of general and category-specific QC procedures including range checks, statistical checks, algorithm checks, and year-to-year checks of reported data and emissions.

For more information on the general QA/QC process applied to this source category, consistent with Volume 1, Chapter 6 of the *2006 IPCC Guidelines*, see the QA/QC and Verification Procedures section in the introduction of the IPPU chapter and Annex 8 for more details.

Recalculations Discussion

Any resubmitted emissions data reported to EPA's GHGRP from all prior years were updated in this *Inventory*. Additionally, EPA made the following changes:

- To estimate non-reporter F-GHG and N_2O emissions, EPA relies on data reported through Subpart I and the World Fab Forecast. This process requires EPA to map facilities that report through Subpart I and which are also represented in the World Fab Forecast. For this *Inventory* update, EPA identified and made

[115] GHGRP Report Verification Factsheet. See https://www.epa.gov/sites/production/files/2015-07/documents/ghgrp_verification_factsheet.pdf.

corrections to a few instances of this mapping based on new information and additional reviews of the data. This had minimal effects on emission estimates.

- EPA re-ran regression analyses for years 2010 to 2021 to reflect updates to Subpart I and the World Fab Forecast. These changes had minor effects on the emission factors, standard error, and R^2 values for all years. This resulted in the recalculation of non-reporter's F-GHG and N_2O estimates for all years.
- EPA recalculated HTF emissions for years 1990 to 2021 using IPCC *Fifth Assessment Report* (AR5) GWP values (IPCC 2013). Emission estimates were incorrectly calculated using the IPCC *Fourth Assessment Report* (AR4) GWP values (IPCC 2007) in the previous *Inventory* (EPA 2023). Overall, the impact of these recalculations led to an average decrease of 0.009 MMT CO_2 Eq. (0.19 percent) across the time series (1990 through 2021).
- EPA recalculated fluorinated GHG consumption for 2014 to 2021 using the following methodology. Fluorinated GHG consumption estimates for unabated fabs were calculated using reported GHGRP emissions data and default emission factors for Subpart I. Because certain fluorinated GHGs are generated as by-products as well as used as input gases, both input gas emission factors and by-product gas emission factors were factored into this calculation. For abated fabs, a "consumption factor" was developed by dividing the reported emissions of each fluorinated GHG from unabated fabs by the estimated consumption of each fluorinated GHG for each wafer size. Fluorinated GHG consumption for 2021 was estimated based on GDP growth of the 2020 consumption estimate. The consumption estimate will be updated with reported 2021 GHGRP emissions data.
- EPA refined the non-reporting population for 2015 to 2022 by conducting an analysis into the criteria being used to determine which fabs should be included and excluded from this population. Overall, the impact of this refinement led to an average increase in semiconductor emissions by 0.02 MMT CO_2 Eq. (0.45 percent) for the time series 2015 to 2022.
- EPA recalculated non-reporter emissions for 2015 to 2022 by developing emission factors for individual gases and calculated on an MT basis. Overall, the impact of this refinement led to an average increase in semiconductor emissions by 0.04 MMT CO_2 Eq. (0.84 percent) for the time series 2014 to 2022.

Planned Improvements

The *Inventory* methodology uses data reported through the EPA Partnership (for earlier years) and EPA's GHGRP (for later years) to extrapolate the emissions of the non-reporting population. While these techniques are well developed, the accuracy of the emissions estimates for the non-reporting population could be further increased through EPA's further investigation of and improvement upon the accuracy of estimated activity in the form of TMLA.

The *Inventory* uses utilization from two different sources for various time periods–SEMI to develop PEVM and to estimate non-Partner emissions for the period 1995 to 2010 and U.S. Census Bureau for 2011 through 2022. SEMI reported global capacity utilization for manufacturers through 2011. U.S. Census Bureau capacity utilization include U.S. semiconductor manufacturers as well as assemblers. Further analysis on the impacts of using a new and different source of utilization data could prove to be useful in better understanding of industry trends and impacts of utilization data sources on historical emission estimates.

Estimates of semiconductor non-reporter and non-Partner emissions are based on EPA-developed emission factors for the time periods pre-2010, 2011 through 2012, and 2015 through 2022. Based on the data available for these time periods, the methods used to develop emission factors for non-reporters and non-Partners are slightly inconsistent for semiconductors (e.g., how data representing emissions and TMLA from the manufacture of various wafer sizes are aggregated or disaggregated for purposes of calculating emission factors). Further analyses to support potentially adjusting the methods for developing these emission factors could be done to better ensure consistency across the time series.

The methodology for estimating semiconductor emissions from non-reporters uses data from the International Technology Roadmap for Semiconductors (ITRS) on the number of layers associated with various technology node sizes. The ITRS has now been replaced by the International Roadmap for Devices and Systems (IRDS), which has published updated data on the number of layers used in each device type and node size (in nanometers). Incorporating this updated dataset will improve the accuracy of emissions estimates from non-reporting semiconductor fabs.

4.25 Substitution of Ozone Depleting Substances (CRT Source Category 2F)

This reporting category (2F) includes emissions from the substitution of ozone-depleting substance (ODS). Hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and carbon dioxide (CO_2) are used as alternatives to several classes of ODS that are being phased out under the terms of the *Montreal Protocol* and the Clean Air Act Amendments of 1990.[116] Ozone-depleting substances—chlorofluorocarbons (CFCs), halons, carbon tetrachloride, methyl chloroform, and hydrochlorofluorocarbons (HCFCs)—are used in a variety of industrial applications including refrigeration and air conditioning equipment, solvent cleaning, foam production, sterilization, fire extinguishing, and aerosols. Although HFCs and PFCs are not harmful to the stratospheric ozone layer, they are potent greenhouse gases. On December 27, 2020, the American Innovation and Manufacturing (AIM) Act was enacted by Congress and directs EPA to address HFCs by phasing down production and consumption (i.e., production plus import minus export), maximizing reclamation and minimizing releases from equipment, and facilitating the transition to next-generation technologies through sector-based restrictions. Emission estimates for HFCs, PFCs, and CO_2 used as substitutes for ODSs are provided in Table 4-125 and Table 4-126.[117]

Table 4-125: Emissions of HFCs, PFCs, and CO_2 from ODS Substitutes (MMT CO_2 Eq.)

Gas	1990	2005	2018	2019	2020	2021	2022
HFC-23	0.0	+	+	+	+	+	+
HFC-32	0.0	0.3	6.1	6.9	7.8	9.4	10.5
HFC-125	+	8.2	48.8	53.1	57.8	66.3	72.0
HFC-134a	+	72.8	56.4	55.3	54.1	50.0	48.3
HFC-143a	+	10.0	29.7	29.9	29.9	30.0	29.8
HFC-236fa	0.0	1.0	0.8	0.7	0.7	0.6	0.6
CF_4	0.0	+	+	+	+	+	0.1
CO_2	+	+	+	+	+	+	+
Other Saturated HFCs[a]	0.3	6.9	15.9	16.0	15.9	16.3	16.8
Other PFCs and HFOs[b]	+	0.1	+	+	+	+	+
Total	**0.3**	**99.5**	**157.9**	**162.1**	**166.2**	**172.7**	**178.1**

+ Does not exceed 0.05 MMT CO_2 Eq.

[a] Other Saturated HFCs represents an unspecified mix of saturated HFCs, which includes HFC-152a, HFC-227ea, HFC-245fa, HFC-365mfc, and HFC-43-10mee.

[b] Other PFCs and HFOs represents an unspecified mix of PFCs and HFOs, which includes HCFO-1233zd(E), HFO-1234yf, HFO-1234ze(E), HFO-1336mzz(Z), C_4F_{10}, and PFC/PFPEs, the latter being a proxy for a diverse

[116] [42 U.S.C § 7671, CAA Title VI].

[117] Emissions of ODS are not included here consistent with UNFCCC reporting guidelines for national inventories noted in Box 4-1. See Annex 6.2 for more details on emissions of ODS. Emissions from CO_2 used in the food and beverage industry are separately reported in Chapter 4.16 Carbon Dioxide Consumption but does not include CO_2 in ODS substitute use sectors as a refrigerant, foam blowing agent, or fire extinguishing agent.

collection of PFCs and perfluoropolyethers (PFPEs) employed for solvent applications. For estimating purposes, the GWP value used for PFC/PFPEs was based upon n-C_6F_{14}.
Note: Totals may not sum due to independent rounding.

Table 4-126: Emissions of HFCs, PFCs, and CO_2 from ODS Substitution (Metric Tons)

Gas	1990	2005	2018	2019	2020	2021	2022
HFC-23	0	1	2	2	2	2	3
HFC-32	0	397	9,008	10,156	11,461	13,958	15,582
HFC-125	+	2,580	15,406	16,761	18,240	20,909	22,704
HFC-134a	+	56,029	43,419	42,558	41,590	38,447	37,167
HFC-143a	+	2,093	6,188	6,230	6,234	6,240	6,203
HFC-236fa	0	127	99	91	84	78	72
CF_4	0	3	5	5	4	4	4
CO_2	14	1,325	3,093	3,303	3,516	3,734	3,969
Other Saturated HFCs[a]	M	M	M	M	M	M	M
Other PFCs and HFOs[b]	M	M	M	M	M	M	M

+ Does not exceed 0.5 MT.
M (Mixture of Gases).
[a] Other Saturated HFCs represents an unspecified mix of saturated HFCs, which includes HFC-152a, HFC-227ea, HFC-245fa, HFC-365mfc, and HFC-43-10mee.
[b] Other PFCs and HFOs represents an unspecified mix of PFCs and HFOs, which includes HCFO-1233zd(E), HFO-1234yf, HFO-1234ze(E), HFO-1336mzz(Z), C_4F_{10}, and PFC/PFPEs, the latter being a proxy for a diverse collection of PFCs and perfluoropolyethers (PFPEs) employed for solvent applications. For estimating purposes, the GWP value used for PFC/PFPEs was based upon n-C_6F_{14}.

In 1990 and 1991, the only significant emissions of HFCs and PFCs as substitutes to ODSs were relatively small amounts of HFC-152a—used as an aerosol propellant and also a component of the refrigerant blend R-500 used in chillers. Beginning in 1992, HFC-134a was used in growing amounts as a refrigerant in motor vehicle air-conditioners and in refrigerant blends such as R-404A.[118] In 1993, the use of HFCs in foam production began, and in 1994 ODS substitutes for halons entered widespread use in the United States as halon production was phased out. In 1995, these compounds also found applications as solvents. Non-fluorinated ODS substitutes, such as CO_2, have been used in place of ODS in certain foam production and fire extinguishing uses since the 1990s.

The use and subsequent emissions of HFCs, PFCs, and CO_2 as ODS substitutes has been increasing from small amounts in 1990 to 178.1 MMT CO_2 Eq. emitted in 2022. This increase was in large part the result of efforts to phase out CFCs, HCFCs, and other ODSs in the United States. Use and emissions of HFCs are expected to start decreasing in the next few years and continue downward as production and consumption of HFCs are phased down to 15 percent of their baseline levels by 2036 through an allowance allocation and trading program established by EPA. Improvements in recovery practices and the use of alternative gases and technologies, through voluntary actions and in response to existing and potential future regulations under the AIM Act, will also contribute to a reduction in HFC use and emissions.

Table 4-127 presents emissions of HFCs, PFCs, and CO_2 as ODS substitutes by end-use sector for 1990 through 2022. The refrigeration and air-conditioning sector is further broken down by sub-sector. The end-use sectors that contributed the most toward emissions of HFCs, PFCs, and CO_2 as ODS substitutes in 2022 include refrigeration and air-conditioning (144.6 MMT CO_2 Eq., or approximately 81 percent), aerosols (17.0 MMT CO_2 Eq., or approximately 10 percent), and foams (11.7 MMT CO_2 Eq., or approximately 7 percent). Within the refrigeration and air-conditioning end-use sector residential unitary AC, part of the Residential Stationary Air-conditioning subsector

[118] R-404A contains HFC-125, HFC-143a, and HFC-134a.

shown below, was the highest emitting end-use (40.8 MMT CO_2 Eq.), followed by large retail food, which is part of the Commercial Refrigeration subsector. Each of the end-use sectors is described in more detail below.

Table 4-127: Emissions of HFCs, PFCs, and CO_2 from ODS Substitutes (MMT CO_2 Eq.) by Sector

Sector	1990	2005	2018	2019	2020	2021	2022
Refrigeration/Air Conditioning	**+**	**83.0**	**122.7**	**126.5**	**130.6**	**139.5**	**144.6**
Commercial Refrigeration	+	14.9	39.6	40.2	40.6	41.0	41.4
Domestic Refrigeration	+	0.2	1.2	1.2	1.2	1.1	1.0
Industrial Process Refrigeration	+	1.8	13.8	15.0	16.2	17.4	18.6
Transport Refrigeration	+	1.6	6.9	7.4	7.9	8.4	8.8
Mobile Air Conditioning	+	61.5	28.7	26.6	24.6	22.9	20.8
Residential Stationary Air Conditioning	+	1.2	26.2	29.4	33.2	41.5	46.4
Commercial Stationary Air Conditioning	+	1.7	6.2	6.6	6.9	7.3	7.6
Aerosols	**0.2**	**10.2**	**16.7**	**17.0**	**17.3**	**17.7**	**17.0**
Foams	**+**	**3.5**	**14.2**	**14.1**	**13.7**	**10.8**	**11.7**
Solvents	**+**	**1.6**	**2.0**	**2.0**	**2.0**	**2.1**	**2.1**
Fire Protection	**+**	**1.2**	**2.4**	**2.5**	**2.5**	**2.6**	**2.6**
Total	**0.3**	**99.5**	**157.9**	**162.1**	**166.2**	**172.7**	**178.1**

+ Does not exceed 0.05 MMT CO_2 Eq.

Note: Totals may not sum due to independent rounding.

Refrigeration/Air Conditioning

The refrigeration and air-conditioning sector includes a wide variety of equipment types that have historically used CFCs or HCFCs. End-uses within this sector include motor vehicle air-conditioning, retail food refrigeration, refrigerated transport (e.g., ship holds, truck trailers, railway freight cars), household refrigeration, residential and small commercial air-conditioning and heat pumps, chillers (large comfort cooling), cold storage facilities, and industrial process refrigeration (e.g., systems used in food processing, chemical, petrochemical, pharmaceutical, oil and gas, metallurgical, and other industries). As the ODS phaseout has taken effect, most equipment has been retrofitted or replaced to use HFC-based substitutes. Common HFCs in use today in refrigeration/air-conditioning equipment are HFC-134a, R-410A,[119] R-404A, and R-507A.[120] Lower-GWP options such as hydrofluoroolefin (HFO)-1234yf in motor vehicle air-conditioning, R-717 (ammonia) in cold storage and industrial applications, and R-744 (carbon dioxide) and HFC/HFO blends in retail food refrigeration, are also being used. Manufacturers of residential and commercial air conditioning have announced their plans to use HFC-32 and R-454B[121] in the future, and at least one manufacturer has announced the availability of chillers operating on HFC-32 as of 2023 (Carrier, 2023). These refrigerants are emitted to the atmosphere during equipment operation (as a result of component failure, leaks, and purges), as well as at manufacturing (if charged at the factory), installation, servicing, and disposal events.

[119] R-410A contains HFC-32 and HFC-125.

[120] R-507A, also called R-507, contains HFC-125 and HFC-143a.

[121] R-454B contains HFC-32 and HFO-1234yf.

Aerosols

Aerosol propellants are used in metered dose inhalers (MDIs) and a variety of personal care products and technical/specialty products (e.g., duster sprays and safety horns). Pharmaceutical companies that produce MDIs—a type of inhaled therapy used to treat asthma and chronic obstructive pulmonary disease—have replaced the use of CFCs with HFC-propellant alternatives. The earliest ozone-friendly MDIs were produced with HFC-134a, but the industry is using HFC-227ea as well. Conversely, since the use of CFC propellants in other types of aerosols was banned in the Unites States in 1978, most non-medical consumer aerosol products have not transitioned to HFCs, but to "not-in-kind" technologies, such as solid or roll-on deodorants and finger-pump sprays. The transition away from ODSs in specialty aerosol products has also led to the introduction of non-fluorocarbon alternatives (e.g., hydrocarbon propellants) in certain applications, in addition to HFC-134a or HFC-152a. Other low-GWP options such as HFO-1234ze(E) are being used as well. These propellants are released into the atmosphere as the aerosol products are used.

Foams

Chlorofluorocarbons and HCFCs have traditionally been used as foam blowing agents to produce polyurethane (PU), polystyrene, polyolefin, and phenolic foams, which are used in a wide variety of products and applications. Since the *Montreal Protocol*, flexible PU foams as well as other types of foam, such as polystyrene sheet, polyolefin, and phenolic foam, have transitioned almost completely away from fluorocompounds into alternatives such as CO_2 and hydrocarbons. The majority of rigid PU foams have transitioned to HFCs—primarily HFC-134a and HFC-245fa. Today, these HFCs are used to produce PU appliance, PU commercial refrigeration, PU spray, and PU panel foams—used in refrigerators, vending machines, roofing, wall insulation, garage doors, and cold storage applications. In addition, HFC-152a, HFC-134a, and CO_2 are used to produce polystyrene sheet/board foam, which is used in food packaging and building insulation. Low-GWP fluorinated foam blowing agents in use include HFO-1234ze(E) and HCFO-1233zd(E). Emissions of blowing agents occur when the foam is manufactured as well as during the foam lifetime and at foam disposal, depending on the particular foam type.

Solvents

Chlorofluorocarbons, methyl chloroform (1,1,1-trichloroethane or TCA), and to a lesser extent carbon tetrachloride (CCl_4) were historically used as solvents in a wide range of cleaning applications, including precision, electronics, and metal cleaning. Since their phaseout, metal cleaning end-use applications have primarily transitioned to non-fluorocarbon solvents and not-in-kind processes. The precision and electronics cleaning end-uses have transitioned in part to high-GWP gases, due to their high reliability, excellent compatibility, good stability, low toxicity, and selective solvency. These applications rely on HFC-43-10mee, HFC-365mfc, HFC-245fa, and to a lesser extent, PFCs. Electronics cleaning involves removing flux residue that remains after a soldering operation for printed circuit boards and other contamination-sensitive electronics applications. Precision cleaning may apply to either electronic components or to metal surfaces, and is characterized by products, such as disk drives, gyroscopes, and optical components, that require a high level of cleanliness and generally have complex shapes, small clearances, and other cleaning challenges. The use of these solvents yields fugitive emissions of these HFCs and PFCs.

Fire Protection

Fire protection applications include portable fire extinguishers ("streaming" applications) that originally used halon 1211, and total flooding applications that originally used halon 1301, as well as some halon 2402. Since the production and import of virgin halons were banned in the United States in 1994, the halon replacement agent of choice in the streaming sector has been dry chemical, although HFC-236fa is also used to a limited extent. In the total flooding sector, HFC-227ea has emerged as the primary replacement for halon 1301 in applications that require clean agents. Other HFCs, such as HFC-23 and HFC-125, are used in smaller amounts. The majority of HFC-227ea in total flooding systems is used to protect essential electronics, as well as in civil aviation, military mobile weapons systems, oil/gas/other process industries, and merchant shipping. Fluoroketone FK-5-1-12 is also used as

a low-GWP option and 2-BTP is being use in niche applications. As fire protection equipment is tested or deployed, emissions of these fire protection agents occur.

Methodology and Time-Series Consistency

Using a Tier 2 method in accordance with the IPCC methodological decision tree, a detailed Vintaging Model of ODS-containing equipment and products was used to estimate the actual—versus potential—emissions of various ODS substitutes, including HFCs, PFCs, and CO_2. The name of the model refers to the fact that it tracks the use and emissions of various compounds for the annual "vintages" of new equipment that enter service in each end-use. The Vintaging Model predicts ODS and ODS substitute use in the United States based on modeled estimates of the quantity of equipment or products sold each year containing these chemicals and the amount of the chemical required to manufacture and/or maintain equipment and products over time. Emissions for each end-use were estimated by applying annual leak rates and release profiles, which account for the lag in emissions from equipment as they leak over time. By aggregating the data for 80 different end-uses, the model produces estimates of annual use and emissions of each compound. Further information on the Vintaging Model is contained in Annex 3.9.

Methodological approaches were applied to the entire time series to ensure time-series consistency from 1990 through 2022.

Uncertainty

Given that emissions of ODS substitutes occur from thousands of different kinds of equipment and from millions of point and mobile sources throughout the United States, emission estimates must be made using analytical tools such as the Vintaging Model or the methods outlined in IPCC (2006). Though the model is more comprehensive than the IPCC default methodology, significant uncertainties still exist with regard to the levels of equipment sales, equipment characteristics, and end-use emissions profiles that were used to estimate annual emissions for the various compounds.

The uncertainty analysis quantifies the level of uncertainty associated with the aggregate emissions across the 80 end-uses in the Vintaging Model. In order to calculate uncertainty, functional forms were developed to simplify some of the complex "vintaging" aspects of some end-use sectors, especially with respect to refrigeration and air-conditioning, and to a lesser degree, fire extinguishing. These sectors calculate emissions based on the entire lifetime of equipment, not just equipment put into commission in the current year, thereby necessitating simplifying equations. The functional forms used variables that included growth rates, emission factors, transition from ODSs, change in charge size as a result of the transition, disposal quantities, disposal emission rates, and either stock (e.g., number of air conditioning units in operation) for the current year or ODS consumption before transition to alternatives began (e.g., in 1985 for most end-uses). Uncertainty was estimated around each variable within the functional forms based on expert judgment, and a Monte Carlo analysis was performed.

Inputs to the ODS substitutes uncertainty model generally take on a normal distribution with a 90 to 95 percent confidence interval but do utilize other probability density functions such as a uniform or PERT BETA distribution. The uncertainty inputs are based on conversations with industry experts and how certain assumptions are developed in the Vintaging Model. For example, if the Vintaging Model estimates are specifically aligned with actual reported data, then the uncertainty is decreased. This can be seen with the unitary AC end-use where annual stock data is aligned with sales data published by the Air-Conditioning, Heating, and Refrigeration Institute (AHRI). The stock is assumed to be fairly accurate and therefore, uncertainty range for the stock of unitary AC is set to an upper and lower bound of only 2.5 percent. The most significant sources of uncertainty for the substitution of ODS source category include the total stock of refrigerant installed in industrial process refrigeration and cold storage equipment, as well as the charge size for technical aerosols using HFC-134a. For technical aerosols, a triangular distribution is utilized to apply an asymmetrical range to the inventory value. This is to account for the

uncertainty that technical aerosols using HFC-134a might have higher market penetration than what the Vintaging Model currently estimates.

The results of the Approach 2 quantitative uncertainty analysis are summarized in Table 4-128. Substitution of ozone depleting substances HFC and PFC emissions were estimated to be between 170.8 and 205.1 MMT CO_2 Eq. at the 95 percent confidence level. This indicates a range of approximately 4.1 percent below to 15.1 percent above the emission estimate of 178.1 MMT CO_2 Eq.

Table 4-128: Approach 2 Quantitative Uncertainty Estimates for HFC and PFC Emissions from ODS Substitutes (MMT CO_2 Eq. and Percent)

Source	Gases	2022 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Substitution of Ozone Depleting Substances	HFCs and PFCs	178.1	170.8	205.1	-4.1%	+15.1%

[a] Range of emission estimates predicted by Monte Carlo stochastic simulation for a 95 percent confidence interval.

QA/QC and Verification

For more information on the general QA/QC process applied to this source category, consistent with Volume 1, Chapter 6 of the *2006 IPCC Guidelines*, see the QA/QC and Verification Procedures section in the introduction of the IPPU chapter. Category specific QA/QC findings are described below.

The QA and verification process for individual gases and sources in the Vintaging Model includes review against up-to-date market information, including equipment stock estimates, leak rates, and sector transitions to new chemicals and technologies. In addition, comparisons against published emission and consumption sources by gas and by source are performed when available as described further below. Independent peer reviews of the Vintaging Model are periodically performed, including one conducted in 2017 (EPA 2018), to confirm Vintaging Model estimates and identify updates. For the purposes of reporting emissions to protect Confidential Business Information (CBI), some HFCs and PFCs are grouped into two unspecified mixes of saturated HFCs and other PFCs and HFOs. The HFCs and PFCs within the unspecified mix of HFCs and PFCs are modelled and verified individually in the same process as all other gases and sources in the Vintaging Model.

Data from EPA's Greenhouse Gas Reporting Program (GHGRP)[122] and emissions of some fluorinated greenhouse gases estimated for the contiguous United States by scientists at the National Oceanic and Atmospheric Administration (NOAA) were used to perform additional quality control as specified in *2006 IPCC Guidelines for National Greenhouse Gas Inventories* and the *2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories (IPCC 2019)*. These comparisons are detailed further in Annex 3.9.

Recalculations Discussion

For the current *Inventory*, updates to the Vintaging Model included updating 2022 growth rates for residential and commercial unitary air-conditioning to align with annual sales estimates published by AHRI. Projected growth rates

[122] For the GHGRP data, EPA verifies annual facility-level and company-level reports through a multi-step process (e.g., including a combination of pre-and post-submittal electronic checks and manual reviews by staff) to identify potential errors and ensure that data submitted to EPA are accurate, complete, and consistent (EPA 2015). Based on the results of the verification process, EPA follows up with facilities to resolve mistakes that may have occurred. The post-submittals checks are consistent with a number of general and category-specific QC procedures, including range checks, statistical checks, algorithm checks, and year-to-year checks of reported data.

were updated for residential unitary air-conditioning to align with projected residential housing available from the Energy Information Administration (EIA) and commercial unitary air-conditioning growth rates were updated based on new commercial floorspace growth projections from EIA (EPA 2023a). Growth rates for window units were updated to align with sales data for Energy Star- and non-Energy Star-certified units (EPA 2023b).

The Vintaging Model was also updated to include the addition of two end-uses representing multi-split air-conditioning units: small ductless mini-split and multi-split air-conditioning and large ductless mini-split and multi-split air-conditioning. These end-uses were split from the existing residential unitary air-conditioning end-use. Stock for ductless mini-split and multi-split air-conditioning systems were estimated based on the EIA Residential Energy and Consumption Survey (RECS) and growth projected based on annual sales of split systems under 33,000 BTU/h (small mini/multi-splits) and split systems between 33,000 BTU/h and 65,000 BTU/h (large mini/multi-splits) published by AHRI (EPA 2023c).

In addition, the market size and growth rates of the streaming agents end-use in the Fire Suppression sector was updated, improving alignment of halon 1211 consumption with the 2022 Fire Suppression Technical Options Committee (FSTOC) estimates, the lifetime was adjusted to reflect internal inspection timelines, rather than physical extinguisher lifetimes, and refilling of leaks throughout the lifetime of extinguishers was modeled (EPA 2023d).

Together, these updates increased ODS substitute emissions on average by 0.06 MMT CO_2 Eq. (0.6 percent) between 1990 and 2021, compared to the previous (i.e., 2023) *Inventory* submission.

Planned Improvements

Future improvements to the Vintaging Model are planned for the Refrigeration and Air-conditioning, Fire Suppression, and Aerosols sectors. Specifically, refrigerated storage space estimates published biannually from the United States Department of Agriculture (USDA) are being compared to cold storage warehouse space currently estimated in the Vintaging Model. Flooding agent fire suppression market transitions are under review to align more closely with real world activities. In addition, further refinement of HFC consumption in MDIs is expected from review of data collected on HFC use for MDI production, imports, and exports in response to requests pursuant to AIM Act regulations for application-specific allowances for MDIs. EPA expects these revisions to be prepared for the 2025 *Inventory* submission.

As discussed above, future reporting under the AIM Act may provide useful information for verification purposes and possible improvements to the Vintaging Model, such as information on HFC stockpiling behaviors. EPA expects this reporting by late 2023 and incorporation into the 2025 or 2026 report. Should the data suggest structural changes to the model, such as the handling of stockpiles before use, EPA expects to introduce the revised model for the 2025 or 2026 *Inventory* submission.

Several potential improvements to the *Inventory* were identified in the 2022 *Inventory* submission based on the comparisons mentioned above and discussed in Annex 3.9—net supply values from the GHGRP and emission estimates derived from atmospheric measurements—and remain valid. To estimate HFC emissions for just the contiguous United States, matching the coverage by the atmospheric measurements, EPA will investigate the availability of data from Alaska, Hawaii, and U.S. territories. This is planned by the next (i.e., 2025) *Inventory* submission. To improve estimates of HFC-125 and HFC-143a, further research into the refrigeration market can be made. Research in this industry on the shift away from blends such as R-404A or success in lowering emission rates could be used to improve the *Inventory* estimate. This is planned for the 2025 *Inventory*. That said, for the years where both the atmospheric measurements and the model display a roughly constant emission of HFC-143a at similar levels, the new results suggest robust estimates for the refrigeration market. Uncertainty estimates by species would aid in comparisons to atmospheric data. EPA continues to explore the possibility of revising the Monte Carlo analysis to differentiate between species, starting with the higher-emitted HFCs identified above, in a future (i.e., 2025) *Inventory* submission. Reclamation reports and, when available, information gathered under the AIM Act, could be used to improve the understanding of how chemical moves through the economy and could resolve some of the temporal effects discussed in Annex 3.9. This would likely require revisions to the basic model

structure and could be introduced for the 2026 or 2027 *Inventory* submission. The additional data from the atmospheric measurements suggests additional items to investigate. The faster uptick in HFC-32 and HFC-125 emissions suggests additional emissions of R-410A compared to the model's estimation. Further investigation into the average emission rate, the variability over time of the emission rate, stocks, lifetimes, and other factors will be investigated for the next (i.e., 2025) *Inventory* submission.

4.26 Electrical Equipment (CRT Source Category 2G1)

The largest use of sulfur hexafluoride (SF_6), both in the United States and internationally, is as an electrical insulator and interrupter in equipment that transmits and distributes electricity (RAND 2004). The gas has been employed by the electric power industry in the United States since the 1950s because of its dielectric strength and arc-quenching characteristics. It is used in gas-insulated substations, circuit breakers, and other switchgear. SF_6 has replaced flammable insulating oils in many applications and allows for more compact substations in dense urban areas. Another greenhouse gas emitted in much smaller amounts by the electric power industry is tetrafluoromethane (CF_4), which is mixed with SF_6 to avoid liquefaction at low temperatures (Middleton 2000). While mixed gas circuit breakers are more common in extremely cold climates in geographies outside of the United States, some U.S. manufacturers of electrical equipment are emitting CF_4 during the manufacturing of equipment designed to hold the SF_6/CF_4 gas mixture. However, no electrical equipment facilities in the United States have reported emissions of or equipment using CF_4. SF_6 emissions exceed PFC emissions from electric power systems on both a GWP-unweighted and GWP-weighted basis. This reporting category (2G1) includes emissions from electrical equipment.

Fugitive emissions of SF_6 and CF_4 can escape from gas-insulated substations and switchgear through seals, especially from older equipment. The gas can also be released during equipment manufacturing, installation, servicing, and disposal. Emissions of SF_6 and CF_4 from equipment manufacturing and from electrical equipment systems were estimated to be 5.1 MMT CO_2 Eq. (0.3 kt) in 2022. This quantity represents a 79 percent decrease from the estimate for 1990 (see Table 4-129 and Table 4-130). There are a few potential causes for this decrease: a sharp increase in the price of SF_6 during the 1990s and a growing awareness of the environmental impact of SF_6 emissions through programs such as EPA's voluntary SF_6 Emission Reduction Partnership for Electric Power Systems (Partnership) and EPA's GHGRP, regulatory drivers at the state and local levels, and research and development of alternative gases to SF_6 that can be used in gas-insulated substations. Utilities participating in the Partnership have lowered their emission factor from 13 percent in 1999 (kg SF_6 emitted per kg of nameplate capacity) to 0.9 percent in 2022. SF_6 emissions reported by electric power systems to EPA's GHGRP have decreased by 56 percent from 2011 to 2022,[123] with much of the reduction seen from utilities that are not participants in the Partnership. These utilities may be making relatively large reductions in emissions as they take advantage of relatively large and/or inexpensive emission reduction opportunities (i.e., "low hanging fruit," such as replacing major leaking circuit breakers) that Partners have already taken advantage of under the voluntary program

[123] Analysis of emission trends from facilities reporting to EPA's GHGRP is imperfect due to an inconsistent group of reporters year to year. A facility that has reported total non-biogenic greenhouse gas emissions below 15,000 metric tons of carbon dioxide equivalent (MT CO_2 Eq.) for three consecutive years or below 25,000 MT CO_2 Eq. for five consecutive years to EPA's GHGRP can discontinue reporting for all direct emitter subparts. For this sector, most of the variability in the group of reporters is due to facilities exiting the GHGRP due to being below one of these thresholds; however, facilities must re-enter the program if their emissions at a later date are above 25,000 MT CO_2 Eq., which may occur for a variety of reasons, including changes in facility size and changes in emission rates.

(Ottinger et al. 2014). Total emissions from electrical equipment in 2022 were lower than 2021 emissions, decreasing by 15.3 percent.

Table 4-129: SF_6 and CF_4 Emissions from Electric Power Systems and Electrical Equipment Manufacturers (MMT CO_2 Eq.)

	1990	2005	2018	2019	2020	2021	2022
Electric Power Systems	24.3	11.2	4.7	5.7	5.3	5.6	4.8
Electrical Equipment Manufacturers	0.3	0.7	0.3	0.4	0.5	0.4	0.3
Total	24.7	11.9	5.0	6.1	5.9	6.0	5.1

Note: Totals may not sum due to independent rounding.

Table 4-130: SF_6 and CF_4 Emissions from Electric Power Systems and Electrical Equipment Manufacturers (kt)

	1990	2005	2018	2019	2020	2021	2022
SF_6 Emissions	1.0	0.5	0.2	0.3	0.3	0.3	0.2
CF_4 Emissions	+	+	NO	+	+	+	+

+ Does not exceed 0.5 kt.
NO (Not Occurring)

Methodology and Time-Series Consistency

The estimates of emissions from electrical equipment are comprised of emissions from electric power systems and emissions from the manufacture of electrical equipment. The methodologies for estimating both sets of emissions are described below.

1990 through 1998 Emissions from Electric Power Systems

Emissions from electric power systems from 1990 through 1998 were estimated based on (1) the emissions estimated for this source category in 1999, which, as discussed in the next section, were based on the emissions reported during the first year of EPA's SF_6 Emission Reduction Partnership for Electric Power Systems (Partnership), and (2) the RAND survey of global SF_6 emissions. Because most utilities participating in the Partnership reported emissions only for 1999 through 2011, modeling was used to estimate SF_6 emissions from electric power systems for the years 1990 through 1998. To perform this modeling, U.S. emissions were assumed to follow the same trajectory as global emissions from this source during the 1990 through 1999 period. To estimate global emissions, the RAND survey of global SF_6 sales was used, together with the following equation for estimating emissions, which is derived from the mass-balance equation for chemical emissions (Volume 3, Equation 7.3) in the *2006 IPCC Guidelines*.[124] (Although Equation 7.3 of the *2006 IPCC Guidelines* appears in the discussion of substitutes for ozone-depleting substances, it is applicable to emissions from any long-lived pressurized equipment that is periodically serviced during its lifetime.)

[124] Ideally, sales to utilities in the United States between 1990 and 1999 would be used as a model. However, this information was not available. There were only two U.S. manufacturers of SF_6 during this time period, so it would not have been possible to conceal sensitive sales information by aggregation.

Equation 4-24: Estimation for SF_6 Emissions from Electric Power Systems

Emissions (kilograms SF_6) = SF_6 purchased to refill existing equipment (kilograms) + nameplate capacity of retiring equipment (kilograms) [125]

Note that the above equation holds whether the gas from retiring equipment is released or recaptured; if the gas is recaptured, it is used to refill existing equipment, thereby lowering the amount of SF_6 purchased by utilities for this purpose.

Gas purchases by utilities and equipment manufacturers from 1961 through 2003 are available from the RAND (2004) survey. To estimate the quantity of SF_6 released or recovered from retiring equipment, the nameplate capacity of retiring equipment in a given year was assumed to equal 81.2 percent of the amount of gas purchased by electrical equipment manufacturers 40 years previous (e.g., in 2000, the nameplate capacity of retiring equipment was assumed to equal 81.2 percent of the gas purchased in 1960). The remaining 18.8 percent was assumed to have been emitted at the time of manufacture. The 18.8 percent emission factor is an average of IPCC default SF_6 emission rates for Europe and Japan for 1995 (IPCC 2006). The 40-year lifetime for electrical equipment is also based on IPCC (2006). The results of the two components of the above equation were then summed to yield estimates of global SF_6 emissions from 1990 through 1999.

U.S. emissions between 1990 and 1999 are assumed to follow the same trajectory as global emissions during this period. To estimate U.S. emissions, global emissions for each year from 1990 through 1998 were divided by the estimated global emissions from 1999. The result was a time series of factors that express each year's global emissions as a multiple of 1999 global emissions. Historical U.S. emissions were estimated by multiplying the factor for each respective year by the estimated U.S. emissions of SF_6 from electric power systems in 1999 (estimated to be MMT CO_2 Eq.).

Two factors may affect the relationship between the RAND sales trends and actual global emission trends. One is utilities' inventories of SF_6 in storage containers. When SF_6 prices rise, utilities are likely to deplete internal inventories before purchasing new SF_6 at the higher price, in which case SF_6 sales will fall more quickly than emissions. On the other hand, when SF_6 prices fall, utilities are likely to purchase more SF_6 to rebuild inventories, in which case sales will rise more quickly than emissions. This effect was accounted for by applying 3-year smoothing to utility SF_6 sales data. The other factor that may affect the relationship between the RAND sales trends and actual global emissions is the level of imports from and exports to Russia and China. SF_6 production in these countries is not included in the RAND survey and is not accounted for in any another manner by RAND. However, atmospheric studies confirm that the downward trend in estimated global emissions between 1995 and 1998 was real (see the Uncertainty discussion below).

1999 through 2022 Emissions from Electric Power Systems

Emissions from electric power systems from 1999 to 2022 were estimated based on: (1) reporting from utilities participating in EPA's SF_6 Emission Reduction Partnership for Electric Power Systems (Partners), which began in 1999; (2) reporting from utilities covered by EPA's GHGRP, which began in 2012 for emissions occurring in 2011 (GHGRP-Only Reporters); (3) SF_6 emissions from California estimated by the California Air Resources Board (CARB) and (4) the relationship between utilities' reported emissions and their transmission miles as reported in the 2001, 2004, 2007, 2010, 2013, and 2016 Utility Data Institute (UDI) Directories of Electric Power Producers and Distributors (UDI 2001, 2004, 2007, 2010, 2013, and 2017), and 2019, 2020, and 2021 Homeland Infrastructure Foundation-Level Data (HIFLD) (HIFLD 2019, 2020, and 2021), which was applied to the electric power systems that do not report to EPA (Non-Reporters). Total U.S. transmission mileage was interpolated between 2016 and 2019 to estimate transmission mileage of electric power systems in 2017 and 2018. (Transmission miles are defined as the miles of lines carrying voltages above 34.5 kV).

[125] Nameplate capacity is defined as the amount of SF_6 within fully charged electrical equipment.

Partners

Over the period from 1999 to 2022, Partner utilities, which for inventory purposes are defined as utilities that either currently are or previously have been part of the Partnership,[126] represented 49 percent, on average, of total U.S. transmission miles. Partner utilities estimated their emissions using a Tier 3 utility-level mass balance approach (IPCC 2006). If a Partner utility did not provide data for a particular year, emissions were interpolated between years for which data were available or extrapolated based on Partner-specific transmission mile growth rates. In 2012, many Partners began reporting their emissions (for 2011 and later years) through EPA's GHGRP (discussed further below) rather than through the Partnership. In 2022, less than 1 percent of the total emissions attributed to Partner utilities were reported through Partnership reports. Approximately 99.6 percent of the total emissions attributed to Partner utilities were reported and verified through EPA's GHGRP.[127] Overall, the emission rates reported by Partners have decreased significantly throughout the time series.

Non-Partners

Non-Partners consist of two groups: Utilities that have reported to the GHGRP beginning in 2012 (reporting 2011 emissions) or later years (GHGRP-only Reporters) and utilities that have never reported to the GHGRP (Non-Reporters). EPA's GHGRP requires users of SF_6 in electric power systems to report emissions if the facility has a total SF_6 nameplate capacity that exceeds 17,820 pounds. (This quantity is the nameplate capacity that would result in annual SF_6 emissions equal to 25,000 metric tons of CO_2 equivalent at the historical emission rate reported under the Partnership). As under the Partnership, electric power systems that report their SF_6 emissions under EPA's GHGRP are required to use the Tier 3 utility-level mass-balance approach. GHGRP-Only Reporters accounted for 16 percent of U.S. transmission miles and 14 percent of estimated U.S. emissions from electric power system in 2022.[128]

From 1999 through 2018, emissions from both GHGRP-only Reporters and Non-Reporters were estimated in the same way. From 1999 through 2008, emissions were estimated using the results of a regression analysis that correlated the 1999 emissions from Partner utilities with their 1999 transmission miles.[129] The 1999 regression coefficient (emission factor) was held constant through 2008 and multiplied by the transmission miles estimated for the non-Partners for each year.

The 1999 regression equation for Non-Partners was developed based on the emissions reported by a subset of Partner utilities who reported non-zero emissions and non-zero transmission miles (representing approximately 50 percent of total U.S. transmission miles). The regression equation for 1999 is displayed in the equation below.

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[126] Starting in the 1990 to 2015 *Inventory*, partners who had reported three years or less of data prior to 2006 were removed. Most of these Partners had been removed from the list of current Partners but remained in the Inventory due to the extrapolation methodology for non-reporting partners.

[127] Only data reported as of August 21, 2023 are used in the emission estimates for the prior year of reporting. Emissions for Partners that did not report to the Partnership or GHGRP are extrapolated for three years using a utility-specific transmission mile growth rate. After four consecutive years of non-reporting they are included in the 'non-reporting Partners' category. It should be noted that data reported through EPA's GHGRP must go through a verification process. For electric power systems, verification involved a series of electronic range, completeness, and algorithm checks for each report submitted.

[128] GHGRP-reported and Partner transmission miles from a number of facilities were equal to zero with non-zero emissions. These facilities emissions were added to the emissions totals for their respective parent companies when identifiable and not included in the regression equation when not identifiable or applicable. Other facilities reported non-zero transmission miles with zero emissions, or zero transmission miles and zero emissions. These facilities were not included in the development of the regression equations (discussed further below). These emissions are already implicitly accounted for in the relationship between transmission miles and emissions.

[129] In the United States, SF_6 is contained primarily in transmission equipment rated above 34.5 kV.

Equation 4-25: Regression Equation for Estimating SF_6 Emissions of Non-Reporting Facilities in 1999

$$\text{Emissions (kg)} = 0.771 \times \text{Transmission Miles}$$

The 1999 emission factor (0.77 SF_6 emissions/Transmission Miles) for the non-Partners was held constant to estimate non-Partner emissions from 2000-2008. Non-partner emissions were assumed to decrease beginning in 2009, trending toward the regression coefficient (emission factor) calculated for the GHGRP-only reporters based on their reported 2011 emissions and transmission miles. Emission factors for 2009 and 2010 were linearly interpolated between the 1999 and 2011 emission factors. For 2009, the emissions of non-Partners were estimated by multiplying their transmission miles by the interpolated 2009 emission factor (0.65 kg/transmission mile).

The 2011 regression equation was developed based on the emissions reported by GHGRP-Only Reporters who reported non-zero emissions and non-zero transmission miles (representing approximately 23 percent of total U.S. transmission miles). The regression equation for 2011 is displayed below.

Equation 4-26: Regression Equation for Estimating SF_6 Emissions of GHGRP-Only Reporters in 2011

$$\text{Emissions (kg)} = 0.397 \times \text{Transmission Miles}$$

For 2011 and later years, the emissions of GHGRP-only reporters were generally equated to their reported emissions, unless they did not report. The emissions of GHGRP-only reporters that have years of non-reporting between reporting years are gap filled by interpolating between reported values.

For 2010 and later years, the emissions of non-Reporters were estimated by multiplying their transmission miles by the estimated 2010 emission factor (0.52 kg/transmission mile), which was held constant from 2010 through 2022.

Off-ramping GHGRP Facilities

The GHGRP program has an "off-ramp" provision (40 CFR Part 98.2(i)) that exempts facilities from reporting under certain conditions. If reported total greenhouse gas emissions are below 15,000 metric tons of carbon dioxide equivalent (MT CO_2 Eq.) for three consecutive years or below 25,000 MT CO_2 Eq. for five consecutive years, the facility may elect to discontinue reporting. Emissions of GHGRP reporters that have off-ramped are extrapolated for three years of non-reporting using a utility-specific transmission mile growth rate, unless the utility has transmission mileage in California. After three consecutive years of non-reporting, emissions for facilities (except those in California) that off-ramped from GHGRP were estimated using an emissions rate derived from the reported emissions and transmission miles of GHGRP-only reporters in the respective year. For facilities in California, a California-specific emissions rate is used as described in the following section.

Table 4-131: GHGRP-only Average Emission Rate (kg per mile)

Year	2011	2018	2019	2020	2021	2022
Average emission rate	0.43	0.22	0.29	0.27	0.25	0.22

Table 4-132: Categorization of Utilities and Timeseries for Application of Corresponding Emission Estimation Methodologies

Categorization of Utilities	Timeseries
Partners	1999 - 2021
Non-Partners (GHGRP-Only)	2011 – 2021
Non-Partners (Remaining Non-Reporting Utilities)	1999 – 2021
Off-ramping GHGRP Facilities	2017 – 2021

California

CARB reports the total SF_6 emissions from electrical equipment within the state of California (CARB 2023). Because California utilities are required to report their SF_6 emissions to CARB even when they are not required to report to the GHGRP, CARB's estimates of California SF_6 emissions are expected to be more accurate for the California utilities that do not report to GHGRP than the methodology described above. As a result, the CARB SF_6 emissions estimates are used as California's contribution to the national total for 2011-2022, except in years where CARB's estimate is smaller than the California estimates reported to EPA or years for which CARB has not published estimates. Since CARB's emissions estimates include emissions from facilities that do not report to GHGRP, emissions for California GHGRP reporters that have off-ramped are not extrapolated. Specifically, CARB estimates are used for 2011, 2012, 2013, 2014, 2017, 2018, 2019, 2020, and 2021.

For each utility with transmission mileage in California, the GHGRP or voluntarily reported emissions attributed to California for that utility were determined using the percentage of that utility's transmission mileage within California based on data from HIFLD. These emissions across all California utilities were summed to find the California emissions that were reported through GHGRP or voluntarily to the EPA. Then, if CARB's emissions estimates for the reporting year were larger than the those from GHGRP and voluntary reporting, CARB's emissions replaced the California emissions from GHGRP and voluntary reporting.

If CARB's emissions estimates were lower than the California emissions from GHGRP and voluntary reporting, it is assumed there is likely an error, as this would imply negative emissions by GHGRP non-reporters. This was the case in 2015 and 2016. For these years, the GHGRP and voluntarily reported emissions from California are retained, and emissions from non-reporting utilities are estimated using a California-specific SF_6 emissions rate, which is based on CARB emission data. The California SF_6 emissions rate of 0.41 lbs SF_6 per transmission mile is found by taking the average of CARB emissions divided by the total California transmission mileage in years where CARB estimates are larger. Emissions from California non-reporting utilities are then found by multiplying the California SF_6 emissions rate by the California transmission mileage from non-reporting utilities. This methodology is also used if CARB has not published emissions estimates for a particular year. CARB has not yet published estimates for 2022.

Table 4-133: California GHGRP and Voluntarily Reported SF_6 Emissions Compared to CARB's SF_6 Emissions (MMT CO_2 Eq.)

	2011	2015	2016	2017	2018	2019	2020	2021	2022
CA GHGRP and Voluntary	0.19	0.16	0.24	0.12	0.11	0.14	0.20	0.14	0.15
CARB (CARB 2023)	0.24	0.14	0.10	0.18	0.14	0.17	0.24	0.24	NE
Final CA	0.24	0.21	0.29	0.18	0.14	0.17	0.24	0.24	0.20

NE (Not Estimated)

Total Industry Emissions

Total electric power system emissions from 1999 through 2022 were determined for each year by summing the Partner reported and estimated emissions (reported data was available through the EPA's SF_6 Emission Reduction Partnership for Electric Power Systems), the GHGRP-only reported emissions, off-ramping GHGRP Facilities (non-reporters), non-reporters who eventually report to GHGRP, and the non-reporting utilities' emissions (except California). Then, the California GHGRP and voluntarily reported emissions are subtracted from the total and replaced with CARB's emissions (or GHGRP and voluntarily reported emissions plus California non-reporting utilities' emissions).

Non-Partner Transmission Miles

Data on transmission miles for each Non-Reporter for the years 2000, 2003, 2006, and 2009, 2012, and 2016 were obtained from the 2001, 2004, 2007, 2010, 2013, and 2017 UDI Directories of Electric Power Producers and Distributors, respectively (UDI 2001, 2004, 2007, 2010, 2013, and 2017). For 2019 to 2022 non-reporter transmission mileage was derived by subtracting reported transmission mileage data from the total U.S.

transmission mileage from 2019 to 2022 HIFLD Data (HIFLD 2019, 2020, 2021, and 2022). The following trends in transmission miles have been observed over the time series:

- The U.S. transmission system grew by over 22,000 miles between 2000 and 2003 yet declined by almost 4,000 miles between 2003 and 2006. Given these fluctuations, periodic increases are assumed to occur gradually. Therefore, transmission mileage was assumed to increase at an annual rate of 1.2 percent between 2000 and 2003 and decrease by 0.20 percent between 2003 and 2006.
- The U.S. transmission system's annual growth rate grew to 1.7 percent from 2006 to 2009 as transmission miles increased by more than 33,000 miles.
- The annual growth rate for 2009 through 2012 was calculated to be 1.4 percent as transmission miles grew yet again by over 29,000 miles during this time period.
- The annual transmission mile growth rate for 2012 through 2016 was calculated to be 0.2 percent, as transmission miles increased by approximately 5,500 miles.
- The annual transmission mile growth rate for 2016 through 2020 was calculated to be 0.9 percent, as transmission miles increased by approximately 26,000 miles.
- The annual transmission mile growth rate for 2020 through 2021 was calculated to be 2.2 percent, as transmission miles increased by approximately 16,000 miles.
- The annual transmission mile growth rate for 2021 through 2022 was calculated to be 0.7 percent, as transmission miles increased by approximately 5,500 miles.

Transmission miles for each year for non-reporters were calculated by interpolating between UDI reported values obtained from the 2001, 2004, 2007, 2010, 2013 and 2017 UDI directories and HIFLD data for 2019 and subsequent years. In cases where a non-reporter previously reported the GHGRP or the Partnership, transmission miles were interpolated between the most recently reported value and the next available UDI value.

1990 through 2022 Emissions from Manufacture of Electrical Equipment

Three different methods were used to estimate 1990 to 2022 emissions from original electrical equipment manufacturers (OEMs).

- OEM SF_6 emissions from 1990 through 2000 were derived by assuming that manufacturing emissions equaled 10 percent of the quantity of SF_6 provided with new equipment. The 10 percent emission rate is the average of the "ideal" and "realistic" manufacturing emission rates (4 percent and 17 percent, respectively) identified in a paper prepared under the auspices of the International Council on Large Electric Systems (CIGRE) in February 2002 (O'Connell et al. 2002). The quantity of SF_6 provided with new equipment was estimated based on statistics compiled by the National Electrical Manufacturers Association (NEMA). These statistics were provided for 1990 to 2000.
- OEM SF_6 emissions from 2000 through 2010 were estimated by (1) interpolating between the emission rate estimated for 2000 (10 percent) and an emission rate estimated for 2011 based on reporting by OEMs through the GHGRP (5.7 percent), and (2) estimating the quantities of SF_6 provided with new equipment for 2001 to 2010. The quantities of SF_6 provided with new equipment were estimated using Partner reported data and the total industry SF_6 nameplate capacity estimate (156.5 MMT CO_2 Eq. in 2010). Specifically, the ratio of new nameplate capacity to total nameplate capacity of a subset of Partners for which new nameplate capacity data was available from 1999 to 2010 was calculated. These ratios were then multiplied by the total industry nameplate capacity estimate for each year to derive the amount of SF_6 provided with new equipment for the entire industry. Additionally, to obtain the 2011 emission rate (necessary for estimating 2001 through 2010 emissions), the estimated 2011 emissions (estimated using the third methodology listed below) were divided by the estimated total quantity of SF_6

provided with new equipment in 2011. The 2011 quantity of SF_6 provided with new equipment was estimated in the same way as the 2001 through 2010 quantities.

- OEM CF_4 emissions from 1991 through 2010 were estimated by using an average ratio of reported SF_6 and CF_4 emissions from 2011 through 2013. This ratio was applied to the estimated SF_6 emissions for 1991 through 2010 to arrive at CF_4 emissions. CF_4 emissions are estimated starting in 1991 and assumed zero prior to 1991 based on the entry of the CF_4/SF_6 gas mixture into the market (Middleton 2000).
- OEM emissions from 2011 through 2022 were estimated using the SF_6 and CF_4 emissions from OEMs reporting to the GHGRP, and an assumption that these reported emissions account for a conservatively low estimate of 50 percent of the total emissions from all U.S. OEMs (those that report and those that do not).
- OEM SF_6 emissions from facilities off-ramping from the GHGRP were determined by extrapolation. First, emission growth rates were calculated for each reporting year for each OEM reporting facility as well as an average emissions growth rate (2011 through 2022). Averages of reported emissions from last three consecutive reporting years were multiplied by the average growth rate for each off-ramping OEM to estimate emissions for the non-reporting year(s).

Methodological approaches were applied to the entire time series to ensure time-series consistency from 1990 through 2022.

Uncertainty

To estimate the uncertainty associated with emissions of SF_6 and CF_4 from electrical equipment, uncertainties associated with four quantities were estimated: (1) emissions from Partners, (2) emissions from GHGRP-Only Reporters, (3) emissions from Non-Reporters, and (4) emissions from manufacturers of electrical equipment. A Monte Carlo analysis was then applied to estimate the overall uncertainty of the emissions estimate.

Total emissions from the SF_6 Emission Reduction Partnership include emissions from both reporting (through the Partnership or EPA's GHGRP) and non-reporting Partners. For reporting Partners, individual Partner-reported SF_6 data was assumed to have an uncertainty of +/- 10 percent. Based on a Monte Carlo analysis, the cumulative uncertainty of all Partner-reported data was estimated to be 4.5 percent. The uncertainty associated with extrapolated or interpolated emissions from non-reporting Partners was assumed to be 20 percent.

For GHGRP-Only Reporters, reported SF_6 data was assumed to have an uncertainty of 10 percent. Based on a Monte Carlo analysis, the cumulative uncertainty of all GHGRP-Only reported data was estimated to be 7.4 percent.

As discussed below, EPA has substantially revised its method for estimating emissions from non-Reporters, assuming that the average emission rate of non-Reporters has declined much more slowly than the average emission rate of reporting facilities rather than declining at the same rate. This assumption brings the U.S. SF_6 emissions estimated in this *Inventory* into better agreement with the U.S. SF_6 emissions inferred from atmospheric observations. However, it must be emphasized that the actual emission rates of non-Reporters remain unknown. It is possible that they are lower or even higher than estimated here. One possibility is that SF_6 sources other than electric power systems are contributing to the emissions inferred from atmospheric observations, implying that the emissions from non-Reporters are lower than estimated here. Another is that the emissions inferred from atmospheric measurements are over- (or under-) estimated, implying that emissions from non-Reporters could be either lower or higher than estimated here. These uncertainties are difficult to quantify and are not reflected in the estimated uncertainty below. The estimated uncertainty below accounts only for the two sources of uncertainty associated with the regression equations used to estimate emissions in 2019 from Non-Reporters: (1) uncertainty in the coefficients (as defined by the regression standard error estimate), and (2) the uncertainty in total transmission miles for Non-Reporters. Uncertainties were also estimated regarding (1) estimates of SF_6 and CF_4 emissions from OEMs reporting to EPA's GHGRP, and (2) the assumption on the percent share of OEM emissions from OEMs reporting to EPA's GHGRP.

The results of the Approach 2 quantitative uncertainty analysis are summarized in Table 1-57. electrical equipment emissions were estimated to be between 3.8 and 6.4 MMT CO_2 Eq. at the 95 percent confidence level, a range of approximately 25 percent below and 25 percent above the emission estimate of 5.1 MMT CO_2 Eq. CF_4 emissions were estimated to be between 0.000006 and 0.000009 MMT CO_2 Eq. at the 95 percent confidence level, a range of approximately 20 percent below and 20 percent above the emission estimate of 0.0000074 MMT CO_2 Eq.

Table 4-134: Approach 2 Quantitative Uncertainty Estimates for SF_6 and CF_4 Emissions from Electrical Equipment (MMT CO_2 Eq. and Percent)

Source	Gas	2022 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to 2022 Emission Estimate[a] (MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Electrical Equipment	SF_6	5.1	3.8	6.4	-25%	+25%
Electrical Equipment	CF_4	0.0000074	0.000006	0.000009	-20%	+20%

[a] Range of emission estimates predicted by Monte Carlo stochastic simulation for a 95 percent confidence interval.

In addition to the uncertainty quantified above for the 2022 estimate, there is uncertainty associated with the emission rates of GHGRP-only facilities before 2011 and of non-Reporters throughout the time series. As noted above in the discussion of the uncertainty of non-Reporters for 2022, these uncertainties are difficult to quantify.

There is also uncertainty associated with using global SF_6 sales data to estimate U.S. emission trends from 1990 through 1999. However, the trend in global emissions implied by sales of SF_6 appears to reflect the trend in global emissions implied by changing SF_6 concentrations in the atmosphere. That is, emissions based on global sales declined by 29 percent between 1995 and 1998 (RAND 2004), and emissions based on atmospheric measurements declined by 17 percent over the same period (Levin et al. 2010).

Several pieces of evidence indicate that U.S. SF_6 emissions were reduced as global emissions were reduced. First, the decreases in sales and emissions coincided with a sharp increase in the price of SF_6 that occurred in the mid-1990s and that affected the United States as well as the rest of the world. A representative from DILO, a major manufacturer of SF_6 recycling equipment, stated that most U.S. utilities began recycling rather than venting SF_6 within two years of the price rise. Finally, the emissions reported by the one U.S. utility that reported its emissions for all the years from 1990 through 1999 under the Partnership showed a downward trend beginning in the mid-1990s.

QA/QC and Verification

For more information on the general QA/QC process applied to this source category, consistent with Volume 1, Chapter 6 of the *2006 IPCC Guidelines*, see the QA/QC and Verification Procedures section in the introduction of the IPPU chapter and Annex 8 for more details. Category specific QC findings are described below.

For the GHGRP data, EPA verifies annual facility-level reports through a multi-step process (e.g., including a combination of pre-and post-submittal electronic checks and manual reviews by staff) to identify potential errors and ensure that data submitted to EPA are accurate, complete, and consistent (EPA 2015).[130] Based on the results of the verification process, EPA follows up with facilities to resolve mistakes that may have occurred. The post-submittals checks are consistent with a number of general and category-specific QC procedures including: range checks, statistical checks, algorithm checks, and year-to-year checks of reported data and emissions.

[130] GHGRP Report Verification Factsheet. See https://www.epa.gov/sites/production/files/2015-07/documents/ghgrp_verification_factsheet.pdf.

Additionally, EPA provides additional quality control for the SF_6 emissions estimates using atmospheric derived estimates for comparison. The *2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories* (IPCC 2019) Volume 1: General Guidance and Reporting, Chapter 6: Quality Assurance, Quality Control and Verification notes that atmospheric concentration measurements can provide independent data sets as a basis for comparison with inventory estimates. Further, it identifies fluorinated gases as particularly suited for such comparisons. The *2019 Refinement* makes this conclusion for fluorinated gases based on their lack of significant natural sources,[131] their generally long atmospheric lifetimes, their well-known loss mechanisms, and the potential uncertainties in bottom-up inventory methods for some of their sources. Unlike non-fluorinated greenhouse gases (CO_2, CH_4, and N_2O), SF_6 has no significant natural sources; therefore, the SF_6 estimates derived from atmospheric measurements are driven overwhelmingly by anthropogenic emissions. The *2019 Refinement* provides guidance on conducting such comparisons (as summarized in Table 6.2 of IPCC (2019) Volume 1, Chapter 6) and provides guidance on using such comparisons to identify areas of improvement in national inventories (as summarized in Box 6.5 of IPCC (2019) Volume 1, Chapter 6). Emission estimates derived from atmospheric measurements of SF_6 made at NOAA and described in Hu et al. (2022) were used to perform a comparison to the inventory estimates. This comparison resulted in changes to historical emission estimates, as more thoroughly described in the previous *Inventory* cycle (EPA 2022). No further changes were made to the electrical equipment estimates for the current (i.e., 1990 through 2022) *Inventory* based on this comparison.

Recalculations Discussion

Several updates to activity data led to recalculations of previous *Inventory* results. The major updates are as follows:

- As discussed in the methodology above, CARB estimates of SF_6 emissions from electrical equipment in California were used as California's contribution to the national total starting in 2011, except in cases where CARB emissions were lower than GHGRP and voluntarily reported emissions from California, or in years where CARB has not published SF_6 emissions estimates.
- Updates were made to reporter emissions where facilities had resubmitted data.
- A correction was made to estimate 2021 nameplate capacities for two off-ramping utilities, which off-ramped in 2021; these estimations were inadvertently omitted in the previous *Inventory*.
- SF_6 emissions from electrical equipment manufacturing was corrected due to an erroneous data pull in the previous *Inventory*. This caused emissions to increase in years 2011 through 2019.
- Partner transmission mileage used for calculating average share of Partner utilities across the time series and for estimating nameplate capacity for non-reporting utilities was corrected. The calculation was previously referencing partner transmission mileage for the prior year for 2013 through 2021.

Planned Improvements

EPA plans to revisit the methodology for determining emissions from the manufacture of electrical equipment, in particular, the assumption that emissions reported by OEMs account for a conservatively low estimate of 50 percent of the total emissions from all U.S. OEMs. Additional market research will be required to confirm or modify the assumptions regarding the portion of industry not reporting to the GHGRP program.

[131] See Harnisch and Eisenhauer (1998).

4.27 SF_6 and PFCs from Other Product Use (CRT Source Category 2G.2)

There are a variety of other products and processes that use fluorinated greenhouse gases. This section estimates emissions of sulphur hexafluoride (SF_6) and perfluorocarbons (PFCs) from other product use (CRT Source Category 2G.2), including military and scientific applications. Many of these applications utilize SF_6 or PFCs to exploit their unique chemical properties, such as the high dielectric strength of SF_6 and the stability of PFCs. Emission profiles from these processes may vary greatly, ranging from immediate and unavoidable release of all of the chemical to largely avoidable, delayed release from leak-tight products after decades of use.

Military applications employ SF_6 and PFCs in many processes, such as the use of SF_6 in the radar systems of military reconnaissance planes of the Boeing E-3A type, commonly known as Airborne Warning and Control Systems (AWACS). These systems use SF_6 to prevent electric flashovers in the hollow conductors of the antenna, where voltages can reach up to 135 kilovolts (kV). During ascent of the planes, SF_6 is automatically released from the AWACS to maintain appropriate pressure difference between the system and the outside air. During descent, the system is automatically charged with SF_6 from an SF_6 container on board. Most emissions occur during ascent but may also occur from system leakage during other phases of flight or during time on the ground. Emissions from AWACS are largely dependent on the number of active planes and sorties (take-offs) per year.

Other uses of SF_6 in military applications include the oxidation of lithium in navel torpedoes and infrared decoys. SF_6 has also been documented for use in the quieting of torpedo propellers, as well as a by-product of the processing of nuclear material for the production of fuel and nuclear warheads.

Military electronics are believed to be a key application for PFC heat transfer fluids, particularly in areas such as ground and airborne radar avionics, missile guidance systems, and sonar. PFCs may also be used to cool electric motors, especially for equipment where noise reduction is a priority (e.g., submarines). The specific PFCs used in military applications are similar to heat transfer fluids identified in the electronics industry (see Section 4.24). PFCs are typically contained in a closed system, so the emissions are most likely to occur during the manufacture, maintenance, and disposal of equipment.

SF_6 and PFCs are also employed in several scientific applications, such as for use in particle accelerators. Particle accelerators can be found in university and research settings, as well as in industrial and medical applications. SF_6 is typically used as an insulating gas and is operated in a vessel exceeding atmospheric pressure. The amount of SF_6 used in particle accelerators is largely dependent on the terminal voltage of the unit. Emissions of SF_6 typically occur when SF_6 is transferred to storage tanks while maintenance is occurring, when pressure relief valves are actuated, and through slow leaks. The emission and charge assumptions for industrial and medical particle accelerators differ from those of university and research accelerators, as discussed in the methodology below. PFCs (particularly PFC-14) may also be used in particle accelerators as particle detectors or counters (Workman 2022).

SF_6 may also be employed in other high-voltage scientific equipment, including lasers, x-rays, and electron microscopes. SF_6 emission estimates for this equipment were not disaggregated from particle accelerators for this *Inventory*.

There is a range of unidentified processes that also use SF_6 and PFCs, such as R&D activities. PFCs are likely used primarily as heat transfer fluids (HTFs). Emissions reported for these unknown activities group under “Other Scientific Applications”.

Emissions of SF_6 and PFCs from the applications outlined above are presented in Table 4-135.

Table 4-135: SF_6 and PFC Emissions from Other Product Use (MMT CO_2 Eq.)

Year	1990	2005	2018	2019	2020	2021	2022
SF_6	0.6	0.6	0.4	0.4	0.3	+	0.3
Total AWACs	**0.6**	**0.6**	**0.4**	**0.4**	**0.3**	**+**	**0.3**
SF_6	0.3	0.3	0.0	0.0	0.0	0.0	0.0
PFCs	0.1	0.1	0.2	0.2	0.2	0.1	0.2
Total Other Military Applications	**0.4**	**0.4**	**0.2**	**0.2**	**0.2**	**0.1**	**0.2**
SF_6	0.4	0.5	0.4	0.2	0.1	0.2	0.2
PFC-14	+	+	+	+	+	+	+
Total Particle Accelerators	**0.4**	**0.5**	**0.4**	**0.2**	**0.1**	**0.2**	**0.2**
SF_6	+	+	+	+	0.1	0.2	0.1
PFCs	+	+	+	+	+	+	+
Total Other Scientific Applications	**+**	**+**	**+**	**+**	**0.1**	**0.2**	**0.1**
Total Other Product Use	**1.4**	**1.5**	**0.9**	**0.8**	**0.7**	**0.5**	**0.8**

+ Does not exceed 0.05 MMT CO_2 Eq.

Note: PFC subtotals include estimates for HFEs. Totals may not sum due to independent rounding.

Methodology and Time-Series Consistency

Emissions are based primarily on data reported through the Federal Energy Management Program (FEMP). However, the availability of data from FEMP differs across the 1990 through 2022 time series. Consequently, additional emission estimates were made through utilizing methodologies from the IPCC. Emissions from military applications and scientific applications were estimated separately, and the approaches are described immediately below.

Military Applications

1990 through 2007

FEMP data was not readily available for the 1990 to 2007 period as the first reporting year was in 2008. Thus for this period, estimated SF_6 emissions from AWACS were calculated based using the IPCC Tier 1 methodology (IPCC 2006). IPCC provided a default emissions factor of 740kg of SF_6 per plane per year. It was assumed that the U.S. AWAC fleet between 1990 through 2022 remained constant at 33 planes. The IPCC methodology was utilized for all years from 1990 to 2007.

Emissions for other military applications were estimated by taking the average of the emissions estimated for other applications as described in the next section for first five FEMP reporting years (i.e., 2008 through 2012) and held constant between 1990 through 2007. Emissions from AWACS were not specifically reported by FEMP; the estimates developed for AWACS using the IPCC methodology above were employed to determine emissions from remaining unidentified military applications.

2008 through 2021

For the period 2008 through 2021, the Department of Defense (DOD) reported emission data through FEMP which were used to develop estimates for SF_6 and PFCs from other military applications. SF_6 emission estimates developed for AWACS using the IPPC Tier 1 methodology (see 1990 through 2007) were compared against SF_6 emissions reported by DOD between 2008 and 2021. In years where SF_6 emissions reported by DOD was smaller than those estimated using the IPCC Tier 1 methodology, DOD-reported emissions were assumed to account for total AWAC emissions; in years where DOD emissions were greater than the calculated AWAC emissions, the remainder is assumed to be from other SF_6 applications.

Emissions from PFCs, HFEs, and other perfluoro compounds are directly reported by DOD. In years where there are data gaps from FEMP between two reporting years, expected emissions were interpolated.

2022

Estimates for emissions from AWACS and other military uses for 2022 were determined by taking an average of the previous five reporting years (i.e., 2017 through 2021).

Scientific Applications

1990 through 2007

For the period 1990 through 2007, where no reported data is available from the Department of Energy (DOE), estimates for emissions of SF_6 and PFCs from other product use at Department of Energy Laboratories were determined by taking an average of the first five reporting years (i.e., 2008 through 2012) and held constant from 1990 to 2007.

SF_6 emissions from other (non-DOE) research and industrial particle accelerators in the United States was calculated based on the IPCC Tier 1 methodology for estimating emissions from industrial and university/research particle accelerators. Default emission factors, charge sizes, and usage rates are provided by size and type of accelerator in the IPCC methodology. These default assumptions were multiplied against the number of particle accelerators estimated to be active in the United States by year. This methodology remained the same from 1990 to 2007.

2008 through 2021

For the period 2008 through 2021, SF_6 and PFC emissions from government particle accelerators and other scientific equipment were developed using DOE-reported emissions. SF_6 and PFC emissions from particle accelerators were directly reported by DOE. Other fugitive emissions reported by DOE for SF_6 were assumed to represent emissions from particle accelerators and other scientific equipment, as well as two DOE-managed power facilities (WAPA and BPA).[132] Emissions from these two facilities were subtracted out to present only SF_6 emissions from scientific equipment. Reported fugitive emissions for PFC-14 were assumed to wholly represent particle accelerator applications. SF_6 emissions from non-government particle accelerators were estimated using the IPPC Tier 1 methodology used for 1990 through 2007.

Process emissions from other applications for SF_6 and PFCs were reported by DOE for activities such as R&D, and these emissions were summed by gas. However, the estimates presented here do not include emissions reported for semiconductor research and manufacture, or from refrigeration and air conditioning. Emissions from additional PFCs, HFEs, and other perfluoro compounds are directly reported by DOE and are reported as "Other Applications." Emissions reported to FEMP were generally calculated based on consumption data. In a number of years, negative values for emissions were reported due to more gas being returned to supply than purchased in a given year. When negative values were reported, EPA took the average of that year and the proceeding and following year and applied that value to all three years. This 3-year average was assumed to be more representative of actual emissions.

In years where there are data gaps between two reporting years, emissions were interpolated.

2022

For emission estimates developed using DOE-reported emissions, estimates for 2022 were determined by taking an average of the previous five reporting years (i.e., 2017 through 2021). SF_6 emissions from non-government

[132] DOE-reported fugitive emissions for SF_6 and PFCs includes emissions from high-voltage scientific equipment such as lasers, x-rays, and electron microscopes. Emissions from this equipment is included in the particle accelerators total.

particle accelerators were estimated using the same IPPC Tier 1 methodology used for 2008 through 2021.

Uncertainty

A quantitative uncertainty analysis of this source category was performed using the IPCC-recommended Approach 2 uncertainty estimation methodology, the Monte Carlo stochastic simulation technique. The Monte Carlo stochastic simulation was performed on the total emissions estimate from other product use, represented in equation form as:

Equation 4-27: Total Emissions from Other Product Use

$$\begin{aligned}&\text{Total Emissions } (E_T)\\ &\quad = \text{ Military Applications } SF_6 \text{ and PFC Emissions } \left(E_{Military}\right)\\ &\quad + \text{ Scientific Applications of } SF_6 \text{ and PFC Emissions } \left(E_{Scientific}\right)\end{aligned}$$

The uncertainty in the total emissions for other product use, presented in Table 4-124 below, results from the convolution of two distributions of emissions, namely from military applications and scientific applications. The approaches for estimating uncertainty in each of the sources are described below:

Military Applications Emission Uncertainty

The Monte Carlo stochastic simulation was performed on the emissions estimate from military applications, represented in equation form as:

Equation 4-28: Total Emissions from Military Applications

$$\begin{aligned}&\text{Military Applications } SF_6 \text{ and PFC Emissions } \left(E_{Military}\right)\\ &\quad = \text{ Military AWACS } SF_6 \text{ Emissions } \left(E_{AWACS,SF_6,Military}\right)\\ &\quad + \text{ Other Military Applications } SF_6 \text{ Emissions } \left(E_{Other,SF_6,Military}\right)\\ &\quad + \text{ Other Military Applications PFC Emissions } \left(E_{Other,PFC,Military}\right)\end{aligned}$$

The uncertainty in $E_{Military}$ results from the convolution of three distributions of emissions, $E_{AWACS,SF6,Military}$, $E_{Other,SF6,Military}$, and $E_{Other,PFC,Military}$. The approaches for estimating each distribution and combining them to arrive at the reported 95 percent confidence interval (CI) for $E_{Military}$ are described in the remainder of this section.

The uncertainty estimate of $E_{AWACS,SF6,Military}$, or SF_6 emissions from AWACS, is developed based on the number of AWACS in commission in the United States and the per-plane emission factor. The estimated number of active planes installed with AWACS is 33, although estimates range between 31 and 35. The IPCC provides a per-plane emission factor of 740 kg of SF_6 per plane annually and estimates the uncertainty to have bounds of ±14 percent.

The uncertainty in $E_{Other,SF6,Military}$ and $E_{Other,PFC,Military}$, or SF_6 and PFC emissions from other military applications, was obtained by determining the accuracy of government-reported emissions data and reviewing the methodology the Department of Defense uses for developing inventory estimates.

The next step in estimating the uncertainty in emissions from military AWACS and other military applications is convolving the distribution of reported emissions, emission factors, and number of AWACS using Monte Carlo simulation. For this Monte Carlo simulation, the distributions of the reported emissions and emission factors are assumed to be normally distributed, and the number of AWACS is assumed to have a uniform distribution since this is a discrete number of planes. The uncertainty bounds are assigned at 1.96 standard deviations around the estimated mean.

Scientific Applications Emission Uncertainty

The Monte Carlo stochastic simulation was performed on the emissions estimate from scientific applications,

represented in equation form as:

Equation 4-29: Total Emissions from Scientific Applications

$$\begin{aligned}&\text{Scientific Applications } SF_6 \text{ and PFC Emissions } \left(E_{Scientific}\right)\\&= \text{ Particle Accelerators } SF_6 \text{ Emissions } \left(E_{Accelerators,SF_6,Scientific}\right)\\&+ \text{ Particle Accelerators PFC Emissions } \left(E_{Accelerators,PFC,Military}\right)\\&+ \text{ Other Scientific Applications } SF_6 \text{ Emissions } \left(E_{Other,SF_6,Scientific}\right)\\&+ \text{Other Scientific Applications PFC Emissions } \left(E_{Other,PFC,Scientific}\right)\end{aligned}$$

The uncertainty in $E_{Scientific}$ results from the convolution of four distributions of emissions, $E_{Accelerators,SF6,Scientific}$, $E_{Accelerators,PFC,Military}$, $E_{Other,SF6,Scientific}$, and $E_{Other,PFC,Scientific}$. The approaches for estimating each distribution and combining them to arrive at the reported 95 percent confidence interval (CI) for $E_{Scientific}$ are described in the remainder of this section.

The uncertainty estimate of $E_{Accelerators,SF6,Scientific}$ and $E_{Accelerators,PFC,Scientific}$, or SF_6 and PFC emissions from particle accelerators, is developed based on fugitive and process emissions reported by the Department of Energy and emission estimates from the number active university and industrial particle accelerators in the United States. The number of active particle accelerators in the United States for the time series 1990 through 2022 was determined using expert judgment; default emission factors and charge sizes for particle accelerators of various sizes were provided by IPCC guidelines. Emissions of SF_6 from electrical transmission and distribution equipment were removed from total emissions estimates for this source category, as they are reported elsewhere in the *Inventory.*

The uncertainty in $E_{Other,SF6,Scientific}$ and $E_{Other,PFC,Scientific}$, or SF_6 and PFC emissions from other scientific applications, was obtained by determining the accuracy of government-reported emissions data and reviewing the methodology the Department of Energy uses for developing inventory estimates.

The next step in estimating the uncertainty in emissions from particle accelerators and other scientific applications is convolving the distribution of calculated emissions, emission factors, number of accelerators using Monte Carlo simulation. Similarly, the distributions of the reported emissions and emission factors for this Monte Carlo simulation are assumed to be normally distributed, and the number of particle accelerators and other scientific applications is assumed to have a uniform distribution since this is a discrete number of accelerators. The uncertainty bounds are assigned at 1.96 standard deviations around the estimated mean.

The emissions estimate for total U.S. SF_6 and PFC emissions from other product use were estimated to be between 0.5 and 1.1 MMT CO_2 Eq. at a 95 percent CI level. This range represents 36 percent below and 38 percent above the 2022 emission estimate of 0.8 MMT CO_2 Eq. for all emissions from others product use. This range and the associated percentages apply to the estimate of total emissions rather than those of individual gases. Uncertainties associated with individual gases will be somewhat higher than the aggregate but were not explicitly modeled.

Table 4-136: Approach 2 Quantitative Uncertainty Estimates for SF_6 and PFC Emissions from Other Product Use (MMT CO_2 Eq. and Percent)

Source	Gas	2022 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (MMT CO_2 Eq.)		(%)	
			Lower Bound[b]	Upper Bound[b]	Lower Bound	Upper Bound
Other Product Use	SF_6 and PFC	0.8	0.5	1.1	-36%	+38%

[a] Range of emission estimates predicted by Monte Carlo stochastic simulation for a 95 percent confidence interval.

[b] Absolute lower and upper bounds were calculated using the corresponding lower and upper bounds in percentages.

QA/QC and Verification

For more information on the general QA/QC process applied to this source category, consistent with Volume 1, Chapter 6 of the *2006 IPCC Guidelines*, see the QA/QC and Verification Procedures section in the introduction of the IPPU chapter and Annex 8 for more details.

Recalculations Discussion

This is a new category included for the current (i.e., 1990 to 2022) *Inventory*, thus, no recalculations were performed.

4.28 Nitrous Oxide from Product Uses (CRT Source Category 2G3)

Nitrous oxide (N_2O) is a clear, colorless, oxidizing liquefied gas with a slightly sweet odor which is used in a wide variety of specialized product uses and applications. This reporting category (2G3) includes exhalation emissions of N_2O that arise from medical applications and evaporative emissions of N_2O from use as a propellant in aerosol products primarily in food industry. The amount of N_2O that is actually emitted depends upon the specific product use or application.

There are a total of three N_2O production facilities currently operating in the United States (Ottinger 2021). Nitrous oxide is primarily used in carrier gases with oxygen to administer more potent inhalation anesthetics for general anesthesia, and as an anesthetic in various dental and veterinary applications. The second main use of N_2O is as a propellant in pressure and aerosol products, the largest application being pressure-packaged whipped cream. Small quantities of N_2O also are used in the following applications:

- Oxidizing agent and etchant used in semiconductor manufacturing;
- Oxidizing agent used, with acetylene, in atomic absorption spectrometry;
- Production of sodium azide, which is used to inflate airbags;
- Fuel oxidant in auto racing; and
- Oxidizing agent in blowtorches used by jewelers and others (Heydorn 1997).

Production of N_2O in 2022 was approximately 15 kt (see Table 4-137).

Table 4-137: N_2O Production (kt)

Year	1990	2005	2018	2019	2020	2021	2022
Production (kt)	16	15	15	15	15	15	15

Nitrous oxide emissions were 3.8 MMT CO_2 Eq. (14 kt N_2O) in 2022 (see Table 4-138). Production of N_2O stabilized during the 1990s because medical markets had found other substitutes for anesthetics, and more medical procedures were being performed on an outpatient basis using local anesthetics that do not require N_2O. The use of N_2O as a propellant for whipped cream has also stabilized due to the increased popularity of cream products packaged in reusable plastic tubs (Heydorn 1997).

Table 4-138: N_2O Emissions from N_2O Product Usage (MMT CO_2 Eq.)

Year	1990	2005	2018	2019	2020	2021	2022
N_2O Product Usage	3.8	3.8	3.8	3.8	3.8	3.8	3.8

Table 4-139: N_2O Emissions from N_2O Product Usage (kt N_2O)

Year	1990	2005	2018	2019	2020	2021	2022
N_2O Product Usage	14	14	14	14	14	14	14

Methodology and Time-Series Consistency

Emissions from N_2O product uses are calculated using a country-specific methodology that is consistent with *2006 IPCC Guidelines* and based on available data. The *2006 IPCC Guidelines* do not define tier methodologies for this source category. Emissions of N_2O are estimated using the national N_2O production by subcategory use or application, the share of the subcategory, and the appropriate emission rate for each category. The following equation is adapted from Equation 8.24 of the *2006 IPCC Guidelines*:

Equation 4-30: N_2O Emissions from Product Use

$$E_{pu} = \sum_{a} (P \times S_a \times ER_a)$$

where,

E_{pu} = N_2O emissions from product uses, metric tons

P = Total U.S. production of N_2O, metric tons

a = specific application

S_a = Share of N_2O usage by application *a*

ER_a = Emission rate for application *a*, percent

The share of total quantity of N_2O usage by end-use represents the share of national N_2O produced that is used by the specific subcategory (e.g., anesthesia, food processing). In 2020, the medical/dental industry used an estimated 89.5 percent of total N_2O produced, followed by food processing propellants at 6.5 percent. All other subcategories, including semiconductor manufacturing, atomic absorption spectrometry, sodium azide production, auto racing, and blowtorches, used the remainder of the N_2O produced. This subcategory breakdown changed slightly in the mid-1990s. For instance, the small share of N_2O usage in the production of sodium azide declined significantly during the 1990s. Due to the lack of information on the specific time period of the phase-out in this market subcategory, most of the N_2O usage for sodium azide production is assumed to have ceased after 1996, with the majority of its small share of the market assigned to the larger medical/dental consumption subcategory (Heydorn 1997). For 1990 through 1996, N_2O usage was allocated across the following subcategories: medical applications, food processing propellant, and sodium azide production. A usage emissions rate was then applied for each subcategory to estimate the amount of N_2O emitted.

Only the medical/dental and food propellant subcategories were assumed to release emissions into the atmosphere that are not captured under another source category, and therefore these subcategories were the only usage subcategories with emission rates. Emissions of N_2O from semiconductor manufacturing are described in Section 4.24 and reported under CRT Source Category 2H3. For the medical/dental subcategory, due to the poor solubility of N_2O in blood and other tissues, none of the N_2O is assumed to be metabolized during anesthesia and quickly leaves the body in exhaled breath. Therefore, an emission factor of 100 percent was used for this subcategory (IPCC 2006). For N_2O used as a propellant in pressurized and aerosol food products, none of the N_2O is reacted during the process and all of the N_2O is emitted to the atmosphere, resulting in an emission factor of 100 percent for this subcategory (IPCC 2006). For the remaining subcategories, all of the N_2O is consumed or reacted during the process, and therefore the emission rate was considered to be zero percent (Tupman 2002).

The 1990 through 1992 N_2O production data were obtained from SRI Consulting's *Nitrous Oxide, North America* (Heydorn 1997). Nitrous oxide production data for 1993 through 1995 were not available. Production data for

1996 was specified as a range in two data sources (Heydorn 1997; Tupman 2002). In particular, for 1996, Heydorn (1997) estimates N_2O production to range between 13.6 and 18.1 thousand metric tons. Tupman (2002) provided a narrower range (15.9 to 18.1 thousand metric tons) for 1996 that falls within the production bounds described by Heydorn (1997). Tupman (2002) data are considered more industry-specific and current; therefore, the midpoint of the narrower production range was used to estimate N_2O emissions for years 1993 through 2001 (Tupman 2002). The 2002 and 2003 N_2O production data were obtained from the Compressed Gas Association Nitrous Oxide Fact Sheet and Nitrous Oxide Abuse Hotline (CGA 2002, 2003). These data were also provided as a range. For example, in 2003, CGA (2003) estimates N_2O production to range between 13.6 and 15.9 thousand metric tons. Due to the lack of publicly available data, production estimates for years 2004 through 2022 were held constant at the 2003 value.

The 1996 share of the total quantity of N_2O used by each subcategory was obtained from SRI Consulting's *Nitrous Oxide, North America* (Heydorn 1997). The 1990 through 1995 share of total quantity of N_2O used by each subcategory was kept the same as the 1996 number provided by SRI Consulting. The 1997 through 2001 share of total quantity of N_2O usage by sector was obtained from communication with a N_2O industry expert (Tupman 2002). The 2002 and 2003 share of total quantity of N_2O usage by sector was obtained from CGA (2002, 2003). Due to the lack of publicly available data, the share of total quantity of N_2O usage data for years 2004 through 2021 was assumed to equal the 2003 value. The emission factor for the food processing propellant industry was obtained from SRI Consulting's *Nitrous Oxide, North America* (Heydorn 1997) and confirmed by a N_2O industry expert (Tupman 2002). The emission factor for all other subcategories was obtained from communication with a N_2O industry expert (Tupman 2002). The emission factor for the medical/dental subcategory was obtained from the *2006 IPCC Guidelines*.

Methodological approaches were applied to the entire time series to ensure consistency in emissions from 1990 through 2022.

Uncertainty

The overall uncertainty associated with the 2022 N_2O emission estimate from N_2O product usage was calculated using the *2006 IPCC Guidelines* Approach 2 methodology. Uncertainty associated with the parameters used to estimate N_2O emissions include production data, total market share of each end use, and the emission factors applied to each end use, respectively. The uncertainty associated with N_2O production data is ±25 percent, and a uniform probability density function is assigned, based on expert judgment (RTI 2023). The uncertainty associated with the market share for the medical/dental subcategory is ±0.56 percent, and uncertainty for the market share of food propellant subcategory is ±25 percent, both based on expert judgment (RTI 2023). Uncertainty for emission factors was assumed to be zero, and using this suggested uncertainty provided in the *2006 IPCC Guidelines* is appropriate based on expert judgment (RTI 2023).

The results of this Approach 2 quantitative uncertainty analysis are summarized in Table 4-140. Nitrous oxide emissions from N_2O product usage were estimated to be between 2.9 and 4.6 MMT CO_2 Eq. at the 95 percent confidence level. This indicates a range of approximately 24 percent below to 24 percent above the emission estimate of 3.8 MMT CO_2 Eq.

Table 4-140: Approach 2 Quantitative Uncertainty Estimates for N_2O Emissions from N_2O Product Usage (MMT CO_2 Eq. and Percent)

Source	Gas	2022 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
N_2O from Product Uses	N_2O	3.8	2.9	4.6	-24%	+24%

[a] Range of emission estimates predicted by Monte Carlo stochastic simulation for a 95 percent confidence interval.

QA/QC and Verification

General quality assurance/quality control (QA/QC) procedures were applied consistent with the U.S. Inventory QA/QC plan, which is in accordance with Volume 1, Chapter 6 of *2006 IPCC Guidelines* as described in the introduction of the IPPU chapter (see Annex 8 for more details).

Recalculations Discussion

No recalculations were performed for the 1990 to 2021 portion of the time series.

Planned Improvements

EPA recently initiated an evaluation of alternative production statistics for cross-verification and updating time-series activity data, emission factors, assumptions, etc., and a reassessment of N_2O product use subcategories that accurately represent trends. This evaluation includes conducting a literature review of publications and research that may provide additional details on the industry. This work remains ongoing, and thus far no additional sources of data have been found to update this category.

Pending additional resources and planned improvement prioritization, EPA may also evaluate production and use cycles, and the potential need to incorporate a time lag between production and ultimate product use and resulting release of N_2O. Additionally, planned improvements include considering imports and exports of N_2O for product uses.

Finally, for future Inventories, EPA will examine data from EPA's GHGRP to improve the emission estimates for the N_2O product use subcategory. Particular attention will be made to ensure aggregated information can be published without disclosing CBI and time-series consistency, as the facility-level reporting data from EPA's GHGRP are not available for all inventory years as required in this *Inventory*. This is a lower priority improvement, and EPA is still assessing the possibility of incorporating aggregated GHGRP CBI data to estimate emissions; therefore, this planned improvement is still in development and not incorporated in the current *Inventory* report.

4.29 Industrial Processes and Product Use Sources of Precursor Gases

In addition to the main greenhouse gases addressed above, many industrial processes can result in emissions of various greenhouse gas precursors. The reporting requirements of the Paris Agreement and the UNFCCC[133] request that information should be provided on precursor emissions, which include carbon monoxide (CO), nitrogen oxides (NO_x), non-methane volatile organic compounds (NMVOCs), and sulfur dioxide (SO_2). These gases are not direct greenhouse gases, but indirectly impact Earth's radiative balance by altering the concentrations of greenhouse gases (e.g., ozone) and atmospheric aerosol (e.g., particulate sulfate). Combustion byproducts such as CO and NO_x are emitted from industrial applications that employ thermal incineration as a control technology. NMVOCs, commonly referred to as "hydrocarbons," are the primary gases emitted from most processes employing organic or petroleum-based products, and can also result from the product storage and handling.

[133] See paragraph 51 of Annex to 18/CMA.1 available online at: https://unfccc.int/sites/default/files/resource/CMA2018_03a02E.pdf.

Accidental releases of precursors associated with product use and handling can constitute major emissions in this category. In the United States, emissions from product use are primarily the result of solvent evaporation, whereby the lighter hydrocarbon molecules in the solvents escape into the atmosphere. The major categories of product uses include: degreasing, graphic arts, surface coating, other industrial uses of solvents (e.g., electronics), dry cleaning, and non-industrial uses (e.g., uses of paint thinner). Product usage in the United States also results in the emission of hydrofluorocarbons (HFCs) and small amounts of hydrofluoroethers (HFEs), which are included under Substitution of Ozone Depleting Substances and the Electronics Industry in this chapter.

Total emissions of NO_x, CO, NMVOCs, and SO_2 from non-energy industrial processes and product use from 1990 to 2022 are reported in Table 4-141.

Table 4-141: NO_x, CO, NMVOC, and SO_2 Emissions from Industrial Processes and Product Use (kt)

Gas/Source	1990	2005	2018	2019	2020	2021	2022
NO_x	**774**	**672**	**461**	**440**	**393**	**403**	**389**
Mineral Industry	160	200	118	114	101	99	95
Other Industrial Processes[a]	326	355	218	206	187	189	184
Metal Industry	96	58	63	60	52	60	56
Chemical Industry	192	80	61	59	54	55	53
CO	**4,099**	**1,701**	**1,022**	**1,011**	**855**	**902**	**897**
Metal Industry	2,261	707	447	448	340	355	335
Other Industrial Processes[a]	564	662	332	331	294	309	329
Mineral Industry	182	120	111	106	96	95	95
Chemical Industry	1,093	211	132	126	125	142	138
NMVOCs	**6,982**	**3,668**	**3,119**	**2,996**	**3,366**	**3,508**	**3,505**
Other Industrial Processes[a]	6,270	3,396	3,003	2,883	3,261	3,398	3,401
Chemical Industry	601	221	88	86	81	84	79
Mineral Industry	9	10	7	7	6	6	6
Metal Industry	102	40	21	20	17	19	19
SO_2	**1,488**	**776**	**335**	**309**	**266**	**274**	**261**
Other Industrial Processes[a]	474	256	145	134	120	126	119
Chemical Industry	283	242	106	97	83	83	75
Mineral Industry	166	138	25	25	26	28	28
Metal Industry	566	140	58	53	37	38	39

[a] Other Industrial Processes includes storage and transport, other industrial processes (manufacturing of agriculture, food, and kindred products; wood, pulp, paper, and publishing products; rubber and miscellaneous plastic products; machinery products; construction; transportation equipment; and textiles, leather, and apparel products), and miscellaneous sources (catastrophic/accidental release, other combustion (structural fires), health services, repair shops, and fugitive dust). It does not include agricultural fires or slash/prescribed burning, which are accounted for under the Field Burning of Agricultural Residues source.

Note: Totals by gas may not sum due to independent rounding.

Source: (EPA 2023a). Emission categories from EPA (2023a) are aggregated into sectors and categories reported under the Paris Agreement and the UNFCCC as shown in Table ES-3.

Methodology and Time-Series Consistency

Emission estimates for 1990 through 2020 were obtained from data published on the National Emissions Inventory (NEI) Air Pollutant Emissions Trends Data website (EPA 2023a). For Table 4-141, NEI reported emissions of CO, NO_x, SO_2, and NMVOCs were recategorized from NEI Emissions Inventory System (EIS) sectors to source categories more closely aligned with reporting sectors and categories under the Paris Agreement and the UNFCCC based on

discussions between the EPA GHG Inventory and NEI staff (see crosswalk documented in Annex 6.3).[134] EIS sectors mapped to the IPPU sector categories in this report include: chemical and allied product manufacturing, metals processing, storage and transport, solvent utilization, other industrial processes, and miscellaneous sources. As described in the NEI Technical Support Documentation (TSD) (EPA 2023c), NEI emissions are estimated through a combination of emissions data submitted directly to the EPA by state, local, and tribal air agencies, as well as additional information added by the Agency from EPA emissions programs, such as the emission trading program, Toxics Release Inventory (TRI), and data collected during rule development or compliance testing.

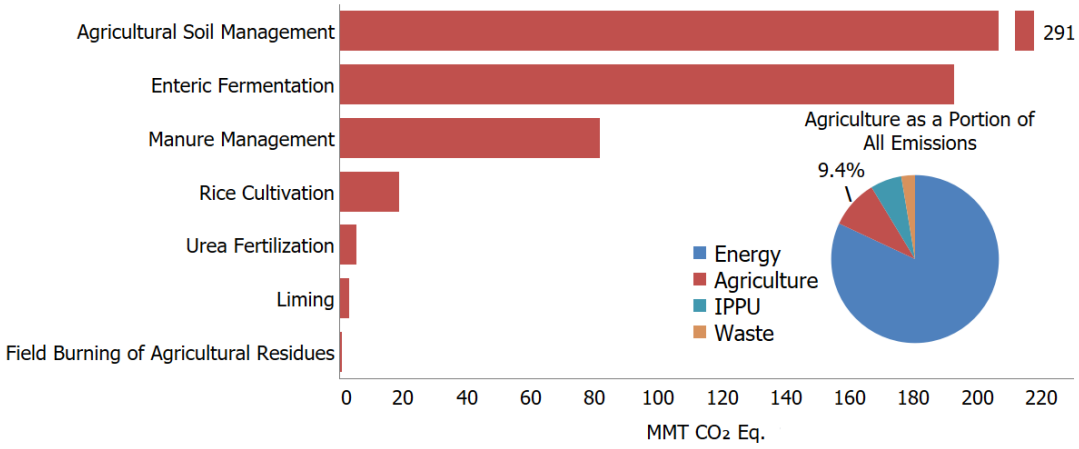
Methodological approaches were applied to the entire time series to ensure time-series consistency from 1990 through 2021, which are described in detail in the NEI's TSD and on EPA's Air Pollutant Emission Trends web site (EPA 2023a; EPA 2023c). A quantitative uncertainty analysis was not performed.

[134] The NEI estimates and reports emissions from six criteria air pollutants (CAPs) and 187 hazardous air pollutants (HAPs) in support of National Ambient Air Quality Standards. EPA reported CAP emission trends are grouped into 60 sectors and 15 Tier 1 source categories, which broadly cover similar source categories to those presented in this chapter. For reporting precursor emissions in the common reporting tables (CRTs), EPA has mapped and regrouped emissions of greenhouse gas precursors (CO, NO_x, SO_2, and NMVOCs) from NEI's EIS sectors to better align with NIR source categories, and to ensure consistency and completeness to the extent possible. See Annex 6.3 for more information on this mapping.

5. Agriculture

Agricultural activities contribute directly to emissions of greenhouse gases through a variety of processes. This chapter provides an assessment of methane (CH_4) from enteric fermentation, livestock manure management, rice cultivation and field burning of agricultural residues; nitrous oxide (N_2O) emissions from agricultural soil management, livestock manure management, and field burning of agricultural residues; as well as carbon dioxide (CO_2) emissions from liming and urea fertilization (see Figure 5-1). Additional CO_2, CH_4 and N_2O fluxes from agriculture-related land-use and land-use conversion activities, such as cultivation of cropland, management on grasslands, grassland fires, aquaculture, and conversion of forest land to cropland, are presented in the Land Use, Land-Use Change, and Forestry (LULUCF) chapter. Carbon dioxide emissions from stationary and mobile on-farm energy use and CH_4 and N_2O emissions from stationary on-farm energy use are reported in the Energy chapter under the Industrial sector emissions. Methane and N_2O emissions from mobile on-farm energy use are reported in the Energy chapter under mobile fossil fuel combustion emissions.

Figure 5-1: 2022 Agriculture Sector Greenhouse Gas Emission Sources



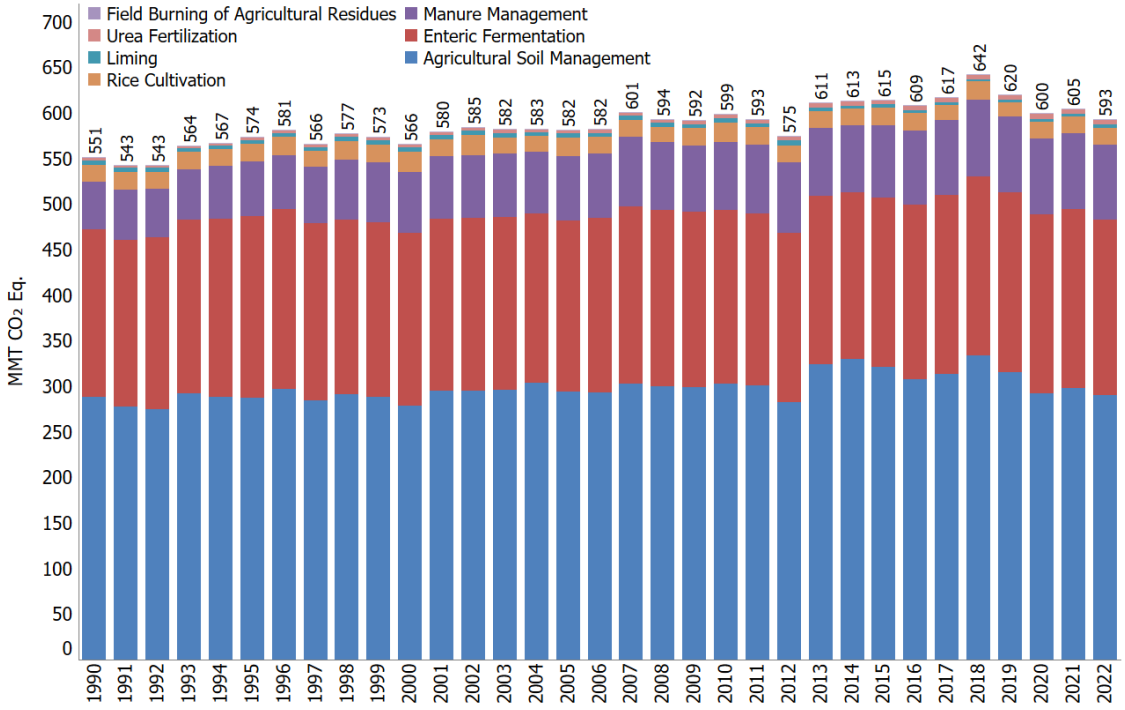
In 2022, the Agriculture sector was responsible for emissions of 593.4 MMT CO_2 Eq.,[1] or 9.4 percent of total U.S. greenhouse gas emissions. Emissions of N_2O by agricultural soil management through activities such as fertilizer

[1] Following the current reporting requirements under the Paris Agreement and the United Nations Framework Convention on Climate Change (UNFCCC), this Inventory report presents CO_2 equivalent values based on the IPCC *Fifth Assessment Report* (AR5) GWP values. See the Introduction chapter as well as Chapter 9 for more information.

application and other agricultural practices that increased nitrogen availability in the soil was the largest source of U.S. N_2O emissions, accounting for 74.6 percent, and the largest source of emissions from the Agriculture sector, accounting for 49.0 percent of total sector emissions. Methane emissions from enteric fermentation and manure management represented 27.4 percent and 9.2 percent of total CH_4 emissions from anthropogenic activities, respectively, and 32.5 and 10.9 percent of Agriculture sector emissions, respectively. Of all domestic animal types, beef and dairy cattle were the largest emitters of CH_4. Rice cultivation and field burning of agricultural residues were minor sources of CH_4. Manure management and field burning of agricultural residues were also small sources of N_2O emissions. Urea fertilization and liming each accounted for 0.1 percent of total CO_2 emissions from anthropogenic activities.

Table 5-1 and Table 5-2 present emission estimates for the Agriculture sector. Between 1990 and 2022, CO_2 and CH_4 emissions from agricultural activities increased by 21 percent and 14.5 percent, respectively, while N_2O emissions from agricultural activities fluctuated from year to year but increased by 1.9 percent overall. Trends in sources of agricultural emissions over the 1990 to 2022 time series are shown in Figure 5-2.

Figure 5-2: Trends in Agriculture Sector Greenhouse Gas Emission Sources



Each year, some emission estimates in the Agriculture sector of the *Inventory* are recalculated and revised with improved methods and/or data. In general, recalculations are made to the U.S. greenhouse gas emission estimates either to incorporate new methodologies or, most commonly, to update recent historical data. These improvements are implemented consistently across the previous *Inventory's* time series (i.e., 1990 through 2021) to ensure that the trend is accurate. This year's key improvements include: manure management: updates to beef feedlot and poultry waste management system (WMS) data; field burning of agricultural residues: addition of residue burning from sugarcane. For more information on specific methodological updates, please see the Recalculations Discussions within the respective source category sections of this chapter. In total, the methodological and historic data improvements made to the Agriculture sector in this *Inventory* increased greenhouse gas emission estimates by an average of 5.3 MMT CO_2 Eq. (0.9 percent) across the time series.

Emissions reported in the Agriculture chapter include those from all states; however, for Hawaii and Alaska some agricultural practices that can increase nitrogen availability in the soil, and thus cause N_2O emissions, are not

included (see chapter sections on Uncertainty and Time-Series Consistency and Planned Improvements for more details). Emissions from the Agriculture sector occurring in U.S. Territories and the District of Columbia are not estimated due to incomplete data, with the exception of urea fertilization in Puerto Rico. EPA continues to identify and review available data on an ongoing basis to include agriculture emissions from U.S. Territories, to the extent they are occurring, in future *Inventories*. Other minor outlying U.S. Territories in the Pacific Islands have no permanent populations (e.g., Baker Island) and therefore EPA assumes no agricultural activities are occurring. See Annex 5 for more information on EPA's assessment of the sources not included in this *Inventory*.

Table 5-1: Emissions from Agriculture (MMT CO_2 Eq.)

Gas/Source	1990	2005	2018	2019	2020	2021	2022
CO_2	**7.1**	**7.9**	**7.2**	**7.2**	**8.0**	**7.6**	**8.6**
Urea Fertilization	2.4	3.5	4.9	5.0	5.1	5.2	5.3
Liming	4.7	4.4	2.2	2.2	2.9	2.4	3.3
CH_4	**241.7**	**264.4**	**285.0**	**280.2**	**282.4**	**281.8**	**276.8**
Enteric Fermentation	183.1	188.2	196.8	197.3	196.3	196.5	192.6
Manure Management	39.1	55.0	67.7	66.7	66.9	66.4	64.7
Rice Cultivation	18.9	20.6	19.9	15.6	18.6	18.3	18.9
Field Burning of Agricultural Residues	0.5	0.6	0.6	0.7	0.6	0.6	0.6
N_2O	**302.3**	**309.5**	**350.2**	**332.6**	**309.2**	**315.3**	**308.0**
Agricultural Soil Management	288.8	294.1	333.4	315.6	292.1	298.0	290.8
Manure Management	13.4	15.2	16.6	16.8	16.9	17.1	17.0
Field Burning of Agricultural Residues	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Total	**551.1**	**581.8**	**642.4**	**620.1**	**599.7**	**604.8**	**593.4**

Note: Totals may not sum due to independent rounding.

Table 5-2: Emissions from Agriculture (kt)

Gas/Source	1990	2005	2018	2019	2020	2021	2022
CO_2	**7,106**	**7,856**	**7,176**	**7,237**	**8,019**	**7,616**	**8,595**
Urea Fertilization	2,417	3,504	4,936	5,034	5,132	5,229	5,327
Liming	4,690	4,351	2,240	2,203	2,887	2,387	3,268
CH_4	**8,633**	**9,444**	**10,179**	**10,008**	**10,087**	**10,066**	**9,885**
Enteric Fermentation	6,539	6,722	7,028	7,045	7,010	7,017	6,878
Manure Management	1,398	1,964	2,418	2,382	2,390	2,373	2,312
Rice Cultivation	677	735	711	558	664	653	674
Field Burning of Agricultural Residues	19	23	22	23	22	22	22
N_2O	**1,141**	**1,168**	**1,322**	**1,255**	**1,167**	**1,190**	**1,162**
Agricultural Soil Management	1,090	1,110	1,258	1,191	1,102	1,124	1,097
Manure Management	50	57	63	63	64	65	64
Field Burning of Agricultural Residues	1	1	1	1	1	1	1

Note: Totals by gas may not sum due to independent rounding.

Box 5-1: Methodological Approach for Estimating and Reporting U.S. Emissions and Removals

Consistent with Article 13.7(a) of the Paris Agreement and Article 4.1(a) of the UNFCCC as well as relevant decisions under those agreements, the emissions and removals presented in this report and this chapter are organized by source and sink categories and calculated using internationally-accepted methods provided by the Intergovernmental Panel on Climate Change (IPCC) in the *2006 IPCC Guidelines for National Greenhouse Gas Inventories* (*2006 IPCC Guidelines*). Additionally, the calculated emissions and removals in a given year for the United States are presented in a common format in line with the reporting guidelines for the reporting of inventories under the Paris Agreement and the UNFCCC. The Parties' use of consistent methods to calculate emissions and removals for their inventories helps to ensure that these reports are comparable. The

presentation of emissions provided in the Agriculture chapter does not preclude alternative examinations (e.g., economic sectors). Rather, this chapter presents emissions in a common format consistent with how Parties are to report their national inventories under the Paris Agreement and the UNFCCC. The report itself, and this chapter, follow this common format and provide an explanation of the application of methods used to calculate emissions from agricultural activities.

5.1 Enteric Fermentation (CRT Source Category 3A)

Methane is produced as part of normal digestive processes in animals. During digestion, microbes resident in an animal's digestive system ferment food consumed by the animal. This microbial fermentation process, referred to as enteric fermentation, produces CH_4 as a byproduct, which can be exhaled or eructated by the animal. The amount of CH_4 produced and emitted by an individual animal depends primarily upon the animal's digestive system, and the amount and type of feed it consumes.[2]

Ruminant animals (e.g., cattle, buffalo, sheep, goats, and camels) are the major emitters of CH_4 because of their unique digestive system. Ruminants possess a rumen, or large "fore-stomach," in which microbial fermentation breaks down the feed they consume into products that can be absorbed and metabolized. The microbial fermentation that occurs in the rumen enables them to digest coarse plant material that non-ruminant animals cannot. Ruminant animals, consequently, have the highest CH_4 emissions per unit of body mass among all animal types.

Non-ruminant animals (e.g., swine, horses, and mules and asses) also produce CH_4 emissions through enteric fermentation, although this microbial fermentation occurs in the large intestine. These non-ruminants emit significantly less CH_4 on a per-animal-mass basis than ruminants because the capacity of the large intestine to produce CH_4 is lower.

In addition to the type of digestive system, an animal's feed quality and feed intake also affect CH_4 emissions. In general, lower feed quality and/or higher feed intake leads to higher CH_4 emissions. Feed intake is positively correlated to animal size, growth rate, level of activity and production (e.g., milk production, wool growth, pregnancy, or work). Therefore, feed intake varies among animal types as well as among different management practices for individual animal types (e.g., animals in feedlots or grazing on pasture).

Methane emission estimates from enteric fermentation are provided in Table 5-3 and Table 5-4. Total livestock CH_4 emissions in 2022 were 192.6 MMT CO_2 Eq. (6,878 kt). Beef cattle remain the largest contributor of CH_4 emissions from enteric fermentation, accounting for 71 percent in 2022. Emissions from dairy cattle in 2022 accounted for 25 percent, and the remaining methane emissions were from swine, horses, sheep, goats, American bison, mules and asses.[3]

[2] CO_2 emissions from livestock are not estimated because annual net CO_2 emissions are assumed to be zero – the CO_2 photosynthesized by plants is returned to the atmosphere as respired CO_2 (IPCC 2006).

[3] Enteric fermentation emissions from poultry are not estimated because no IPCC method has been developed for determining enteric fermentation CH_4 emissions from poultry; at this time, developing a country-specific method would require a disproportionate amount of resources given the small magnitude of this source category. Enteric fermentation emissions from camels are not estimated because there is no significant population of camels in the United States. Given the insignificance of estimated camel emissions in terms of the overall level and trend in national emissions, there are no immediate improvement

Table 5-3: CH_4 Emissions from Enteric Fermentation (MMT CO_2 Eq.)

Livestock Type	1990	2005	2018	2019	2020	2021	2022
Beef Cattle	132.8	139.6	141.2	141.7	140.5	140.3	137.0
Dairy Cattle	43.3	41.3	48.6	48.5	48.8	49.4	48.9
Swine	2.3	2.6	3.1	3.2	3.2	3.1	3.1
Horses	1.1	2.0	1.4	1.3	1.2	1.1	1.0
Sheep	2.9	1.5	1.3	1.3	1.3	1.3	1.3
Goats	0.6	0.7	0.7	0.7	0.7	0.7	0.7
American Bison	0.1	0.5	0.4	0.4	0.5	0.5	0.5
Mules and Asses	+	0.1	0.1	0.1	0.1	0.1	0.1
Total	**183.1**	**188.2**	**196.8**	**197.3**	**196.3**	**196.5**	**192.6**

+ Does not exceed 0.05 MMT CO_2 Eq.

Note: Totals may not sum due to independent rounding.

Table 5-4: CH_4 Emissions from Enteric Fermentation (kt CH_4)

Livestock Type	1990	2005	2018	2019	2020	2021	2022
Beef Cattle	4,742	4,986	5,042	5,062	5,018	5,010	4,891
Dairy Cattle	1,547	1,473	1,737	1,732	1,743	1,764	1,748
Swine	81	92	110	115	115	111	110
Horses	40	70	48	46	43	40	37
Sheep	102	55	47	47	47	47	46
Goats	23	26	24	25	25	25	25
American Bison	4	17	15	16	16	17	17
Mules and Asses	1	2	3	3	3	3	3
Total	**6,539**	**6,722**	**7,028**	**7,045**	**7,010**	**7,017**	**6,878**

Note: Totals may not sum due to independent rounding.

From 1990 to 2022, emissions from enteric fermentation have increased by 5.2 percent. From 2021 to 2022, emissions decreased by 2 percent, largely driven by a decrease in beef cattle populations. While emissions generally follow trends in cattle populations, there are exceptions across the time series. For example, while dairy cattle emissions increased 13 percent over the entire time series, the population has declined by 4.5 percent, and milk production increased 45.9 percent (USDA 2021; USDA 2022). These trends indicate that while emissions per head are increasing, emissions per unit of product (i.e., meat, milk) are decreasing.

Generally, from 1990 to 1995 emissions from beef cattle increased and then decreased from 1996 to 2004. These trends were mainly due to fluctuations in beef cattle populations and increased digestibility of feed for feedlot cattle. Beef cattle emissions generally increased from 2004 to 2007, as beef cattle populations increased, and an extensive literature review indicated a trend toward a decrease in feed digestibility for those years. Beef cattle emissions decreased again from 2007 to 2014, as populations again decreased, but increased from 2015 to 2018, consistent with another increase in population over those same years. Emissions and populations generally declined from 2018 to 2022, with a slight post-pandemic rebound in 2021.

Emissions from dairy cattle generally trended downward from 1990 to 2004, along with an overall dairy cattle population decline during the same period. Similar to beef cattle, dairy cattle emissions rose from 2004 to 2007 due to population increases and a decrease in feed digestibility (based on an analysis of more than 350 dairy cow diets used by producers across the United States). Dairy cattle emissions continued to trend upward from 2007 to 2018, generally in line with dairy cattle population changes.

plans to include this emissions category in the *Inventory*. See Annex 5 for more information on significance of estimated camel emissions.

Regarding trends in other animals, populations of sheep have steadily declined, with an overall decrease of 55 percent since 1990. Horse populations peaked in 2007 and have been declining by an average of 4 percent annually since 2007, with their current population 6 percent lower than it was in 1990. Goat populations increased by about 20 percent through 2007 followed by a steady decrease through 2012. Since 2012, goat populations continue to increase by 1 percent annually. Swine populations have trended upward through most of the time series, increasing 43 percent from 1990 to 2020. However, swine populations decreased by around 5 percent from 2020 to 2022. The population of American bison more than quadrupled over the 1990 to 2022 time period, while the population of mules and asses increased by a factor of five.

Methodology and Time-Series Consistency

Livestock enteric fermentation emission estimate methodologies fall into two categories: cattle and other domesticated animals. Cattle, due to their large population, large size, and particular digestive characteristics, account for the majority of enteric fermentation CH_4 emissions from livestock in the United States. A more detailed methodology (i.e., IPCC Tier 2) was therefore applied to estimate emissions for all cattle. Emission estimates for other domesticated animals (horses, sheep, swine, goats, American bison, and mules and asses) were estimated using the IPCC Tier 1 approach, as suggested by the *2006 IPCC Guidelines* (see the Planned Improvements section).

While the large diversity of animal management practices cannot be precisely characterized and evaluated, significant scientific literature exists that provides the necessary data to estimate cattle emissions using the IPCC Tier 2 approach. The Cattle Enteric Fermentation Model (CEFM), developed by EPA and used to estimate cattle CH_4 emissions from enteric fermentation using IPCC's Tier 2 method, incorporates this information and other analyses of livestock population, feeding practices, and production characteristics.

Methodological approaches, changes to historic data, and other parameters were applied to the entire time series to ensure consistency in emissions estimates from 1990 through 2022. See Annex 3.10 for more detailed information on the methodology and data used to calculate CH_4 emissions from enteric fermentation. In addition, variables and the resulting emissions are also available at the state level in Annex 3.10.

Inventory Methodology for Cattle

National cattle population statistics were disaggregated into the following cattle sub-populations:

- Dairy Cattle
  - Calves
  - Heifer Replacements
  - Cows
- Beef Cattle
  - Calves
  - Heifer Replacements
  - Heifer and Steer Stockers
  - Animals in Feedlots (Heifers and Steer)
  - Cows
  - Bulls

Calf birth rates, end-of-year population statistics, detailed feedlot placement information, and slaughter weight data were used to create a transition matrix that models cohorts of individual animal types and their specific emission profiles. The key variables tracked for each of the cattle population categories are described in Annex 3.10. These variables include performance factors such as pregnancy and lactation as well as average weights and weight gain. Annual cattle population data were obtained from the U.S. Department of Agriculture's (USDA) National Agricultural Statistics Service (NASS) *QuickStats* database (USDA 2023).

Diet characteristics were estimated by region for dairy, grazing beef, and feedlot beef cattle. These diet characteristics were used to calculate digestible energy (DE) values (expressed as the percent of gross energy intake digested by the animal) and CH_4 conversion rates (Y_m) (expressed as the fraction of gross energy converted to CH_4) for each regional population category. The IPCC recommends Y_m ranges of 3.0±1.0 percent for feedlot cattle and 6.5±1.0 percent for other well-fed cattle consuming temperate-climate feed types (IPCC 2006). Given the availability of detailed diet information for different regions and animal types in the United States, DE and Y_m values unique to the United States were developed. The diet characterizations and estimation of DE and Y_m values were based on information from state agricultural extension specialists, a review of published forage quality studies and scientific literature, expert opinion, and modeling of animal physiology.

The diet characteristics for dairy cattle were based on Donovan (1999) and an extensive review of nearly 20 years of literature from 1990 through 2009. Estimates of DE were national averages based on the feed components of the diets observed in the literature for the following year groupings: 1990 through 1993, 1994 through 1998, 1999 through 2003, 2004 through 2006, 2007, and 2008 onward.[4] Base year Y_m values by region were estimated using Donovan (1999). As described in ERG (2016), a ruminant digestion model (COWPOLL, as selected in Kebreab et al. 2008) was used to evaluate Y_m for each diet evaluated from the literature, and a function was developed to adjust regional values over time based on the national trend. Dairy replacement heifer diet assumptions were based on the observed relationship in the literature between dairy cow and dairy heifer diet characteristics.

For feedlot animals, the DE and Y_m values used for 1990 were recommended by Johnson (1999). Values for DE and Y_m for 1991 through 1999 were linearly extrapolated based on the 1990 and 2000 data. DE and Y_m values for 2000 onwards were based on survey data in Galyean and Gleghorn (2001) and Vasconcelos and Galyean (2007).

For grazing beef cattle, Y_m values were based on Johnson (2002), DE values for 1990 through 2006 were based on specific diet components estimated from Donovan (1999), and DE values from 2007 onwards were developed from an analysis by Archibeque (2011), based on diet information in Preston (2010) and USDA-APHIS:VS (2010). Weight and weight gains for cattle were estimated from Holstein (2010), Doren et al. (1989), Enns (2008), Lippke et al. (2000), Pinchack et al. (2004), Platter et al. (2003), Skogerboe et al. (2000), and expert opinion. See Annex 3.10 for more details on the method used to characterize cattle diets and weights in the United States.

Calves younger than 4 months are not included in emission estimates because calves consume mainly milk and the IPCC recommends the use of a Y_m of zero for all juveniles consuming only milk. Diets for calves aged 4 to 6 months are assumed to go through a gradual weaning from milk decreasing to 75 percent at 4 months, 50 percent at age 5 months, and 25 percent at age 6 months. The portion of the diet made up with milk still results in zero emissions. For the remainder of the diet, beef calf DE and Y_m are set equivalent to those of beef replacement heifers, while dairy calf DE is set equal to that of dairy replacement heifers and dairy calf Y_m is provided at 4 and 7 months of age by Soliva (2006). Estimates of Y_m for 5- and 6-month-old dairy calves are linearly interpolated from the values provided for 4 and 7 months.

To estimate CH_4 emissions, the population was divided into state, age, sub-type (i.e., dairy cows and replacements, beef cows and replacements, heifer and steer stockers, heifers and steers in feedlots, bulls, beef calves 4 to 6 months, and dairy calves 4 to 6 months), and production (i.e., pregnant, lactating) groupings to more fully capture differences in CH_4 emissions from these animal types. The transition matrix was used to simulate the age and weight structure of each sub-type on a monthly basis in order to more accurately reflect the fluctuations that occur throughout the year. Cattle diet characteristics were then used in conjunction with Tier 2 equations from IPCC (2006) to produce CH_4 emission factors for the following cattle types: dairy cows, beef cows, dairy replacements, beef replacements, steer stockers, heifer stockers, steer feedlot animals, heifer feedlot animals, bulls, and calves. To estimate emissions from cattle, monthly population data from the transition matrix were multiplied by the calculated emission factor for each cattle type in each state. More details are provided in Annex 3.10.

[4] Due to inconsistencies in the 2003 literature values, the 2002 values were used for 2003 as well.

Non-Cattle Livestock

Emission estimates for other animal types were based on average emission factors (Tier 1 default IPCC emission factors) representative of entire populations of each animal type. The methodology is in accordance with the methodological decision tree for methane emissions from enteric fermentation (IPCC 2019). Methane emissions from these animals accounted for a minor portion of total CH_4 emissions from livestock in the United States from 1990 through 2022. Additionally, the variability in emission factors for each of these other animal types (e.g., variability by age, production system, and feeding practice within each animal type) is less than that for cattle.

Annual livestock population data for 1990 to 2022 for sheep, swine, goats, horses, mules and asses, and American bison were obtained for available years from USDA-NASS (USDA 2023; USDA 2019). Horse, goat, and mule and ass population data were available for 1987, 1992, 1997, 2002, 2007, 2012, and 2017 (USDA 2019); the remaining years between 1990 and 2022 were interpolated and extrapolated from the available estimates (with the exception of goat populations being held constant between 1990 and 1992). American bison population estimates were available from USDA for 2002, 2007, 2012, and 2017 (USDA 2019) and from the National Bison Association (1999) for 1990 through 1999. Additional years were based on observed trends from the National Bison Association (1999), interpolation between known data points, and extrapolation beyond 2012, as described in more detail in Annex 3.10.

Methane emissions from sheep, goats, swine, horses, American bison, and mules and asses were estimated by using emission factors utilized in Crutzen et al. (1986, cited in IPCC 2006; IPCC 2019). These emission factors are representative of typical animal sizes, feed intakes, and feed characteristics in developed countries. For American bison, the emission factor for buffalo was used and adjusted based on the ratio of live weights to the 0.75 power. The methodology is the same as that recommended by IPCC (2006).

Uncertainty

A quantitative uncertainty analysis for this source category was performed using the IPCC-recommended Approach 2 uncertainty estimation methodology based on a Monte Carlo stochastic simulation technique as described in ICF (2003). These uncertainty estimates were developed for the 1990 through 2001 *Inventory* (i.e., 2003 submission to the UNFCCC). While there are plans to update the uncertainty to reflect recent methodological updates and forthcoming changes (see Planned Improvements, below), at this time the uncertainty estimates were directly applied to the 2022 emission estimates in this *Inventory*.

A total of 185 primary input variables (177 for cattle and 8 for non-cattle) were identified as key input variables for the uncertainty analysis. A normal distribution was assumed for almost all activity- and emission factor-related input variables. Triangular distributions were assigned to three input variables (specifically, cow-birth ratios for the three most recent years included in the 2001 model run) to ensure only positive values would be simulated. For some key input variables, the uncertainty ranges around their estimates (used for *Inventory* estimation) were collected from published documents and other public sources; others were based on expert opinion and best estimates. In addition, both endogenous and exogenous correlations between selected primary input variables were modeled. The exogenous correlation coefficients between the probability distributions of selected activity-related variables were developed through expert judgment.

Among the individual cattle sub-source categories, beef cattle account for the largest amount of CH_4 emissions, as well as the largest degree of uncertainty in the emission estimates—due mainly to the difficulty in estimating the diet characteristics for grazing members of this animal group. Among non-cattle, horses represent the largest percent of uncertainty in the uncertainty analysis last conducted in 2001 because the Food and Agricultural Organization (FAO) of the United Nations population estimates used for horses at that time had a higher degree of uncertainty than for the USDA population estimates used for swine, goats, and sheep. The horse populations are

drawn from the same USDA source as the other animal types[5], and therefore the uncertainty range around horses is likely overestimated. Cattle calves, American bison, mules and asses were excluded from the initial uncertainty estimate because they were not included in emission estimates at that time.

The uncertainty ranges associated with the activity data-related input variables were ±10 percent or lower. However, for many emission factor-related input variables, the lower- and/or the upper-bound uncertainty estimates were over 20 percent. The results of the quantitative uncertainty analysis are summarized in Table 5-5. Based on this analysis, enteric fermentation CH_4 emissions in 2022 were estimated to be between 171.4 and 227.2 MMT CO_2 Eq. at a 95 percent confidence level, which indicates a range of 11 percent below to 18 percent above the 2022 emission estimate of 192.6 MMT CO_2 Eq.

As a comparison to the Approach 2, a quantitative uncertainty analysis for this source category was performed using the IPCC (2006) recommended Approach 1 based on simple error propagation. Enteric fermentation CH_4 emissions in 2022 were estimated to be between 132.6 and 252.6 MMT CO_2 Eq., which indicates a range of ±31 percent above and below the 2022 emission estimate of 192.6 MMT CO_2 Eq. A ±10 percent uncertainty factor is applied to the activity data (e.g., animal populations), and a ±40 percent default uncertainty factor is applied to the emission factors (IPCC 2019).

Table 5-5: Approach 2 Quantitative Uncertainty Estimates for CH_4 Emissions from Enteric Fermentation (MMT CO_2 Eq. and Percent)

Source	Gas	2022 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a, b, c] (MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Enteric Fermentation	CH_4	192.6	171.4	227.2	-11%	+18%

[a] Range of emissions estimates predicted by Monte Carlo stochastic simulation for a 95 percent confidence interval.
[b] Note that the relative uncertainty range was estimated with respect to the 2001 emission estimates from the 2003 submission and applied to the 2022 estimates.
[c] The overall uncertainty calculated in 2003, and applied to the 2022 emission estimate, did not include uncertainty estimates for calves, American bison, and mules and asses. Additionally, for bulls the emissions estimate was based on the Tier 1 methodology. Since bull emissions are now estimated using the Tier 2 method, the uncertainty surrounding their estimates is likely lower than indicated by the previous uncertainty analysis.

QA/QC and Verification

In order to ensure the quality of the emission estimates from enteric fermentation, the General (IPCC Tier 1) and category-specific (Tier 2) Quality Assurance/Quality Control (QA/QC) procedures were implemented consistent with the *U.S. Inventory QA/QC Plan* outlined in Annex 8. Category-specific or Tier 2 QA procedures included independent review of emission estimate methodologies from previous *Inventories*.

As part of the quality assurance process, average implied emissions factors for U.S. dairy and beef cattle were developed based on CEFM output and compared to emission factors for other countries provided by IPCC (2006). This comparison is discussed in further detail in Annex 3.10.

Over the past few years, particular importance has been placed on harmonizing the data exchange between the enteric fermentation and manure management source categories. The current *Inventory* utilizes the same transition matrix from the CEFM for estimating cattle populations and weights for both source categories, and the CEFM is used to output volatile solids and nitrogen excretion estimates using the diet assumptions in the model in

[5] The change from using FAO data to USDA data for horse populations took place during the development of the 1990 through 2011 *Inventory*, published in 2013.

conjunction with the energy balance equations from the IPCC (2006). This approach facilitates the QA/QC process for both of these source categories.

Recalculations Discussion

In the previous *Inventory*, 1990 to 2020 estimates were retained from the 1990 through 2020 *Inventory*, and 2021 estimates were based on a simplified approach that used emission factors and extrapolated population estimates for all animals. For the current *Inventory*, the CEFM was used for cattle for all years, resulting in different estimates for 2021 than the prior *Inventory*.

For cattle, there were also changes to emissions resulting from activity data changes, including:

- The USDA published minor data revisions that EPA incorporated into the CEFM:
    - Calf birth data were revised for 2020;
    - Dairy cow milk production values were updated for several states for 2020;
    - Slaughter data were revised for 2020.
- EPA revised annual milk fat values in the CEFM from 2000 through 2021 with updated annual values from USDA's Economic Research Services (ERS) dairy data (USDA 2022). In the previous *Inventory*, EPA derived annual averages from monthly ERS milk fat values, which is no longer available beyond 2010 (USDA 2021).
- EPA discovered and corrected an error within the CEFM related to the urinary energy input used for feedlot cattle, which affected VS results for this animal group. The urinary energy default was updated from 0.04 to 0.02 for feedlot cattle. These updates will affect values in Section 5.2 Manure Management.

Planned Improvements

Regular annual data reviews and updates are necessary to maintain an emissions inventory that reflects the current base of knowledge. In addition to the documented approaches currently used to address data availability, EPA conducts the following annual assessments to identify and determine the applicability of newer data when updating the estimates to extend time series each year:

- Further research to improve the estimation of dry matter intake (as gross energy intake) using data from appropriate production systems;
- Updating input variables that are from older data sources, such as beef births by month, beef and dairy annual calving rates, and beef cow lactation rates;
- Investigating the availability of data for dairy births by month, to replace the current assumption that births are evenly distributed throughout the year;
- Investigating the availability of annual data for the DE, Y_m, and crude protein values of specific diet and feed components for grazing and feedlot animals (including investigating the availability of existing models to estimate diet characteristics, as well as the use and impact of feed additives on emissions);
- Further investigation on additional sources or methodologies for estimating DE for dairy cattle, given the many challenges in characterizing dairy cattle diets;
- Further evaluation of the assumptions about weights and weight gains for beef cows, such that trends beyond 2007 are updated, rather than held constant; and
- Further evaluation of the estimated weight for dairy cows (i.e., 1,500 lbs) that is based solely on Holstein cows as mature dairy cow weight is likely slightly overestimated, based on knowledge of the breeds of dairy cows in the United States.

Depending upon the outcome of ongoing investigations, future improvement efforts for enteric fermentation could include some of the following options which are additional to the regular updates, and may or may not have implications for regular updates once addressed:

- Potentially updating to a Tier 2 methodology for other animal types (i.e., sheep, swine, goats, horses). Efforts to move to Tier 2 will consider the emissions significance of livestock types;
- Investigation of methodologies and emission factors for including enteric fermentation emission estimates from poultry;
- Comparison of the current CEFM with other models that estimate enteric fermentation emissions for quality assurance and verification;
- Investigation of recent research implications suggesting that certain parameters in enteric models may be simplified without significantly diminishing model accuracy; and
- Recent changes that have been implemented to the CEFM warrant an assessment of the current uncertainty analysis; therefore, a revision of the quantitative uncertainty surrounding emission estimates from this source category will be initiated. EPA plans to perform this uncertainty analysis following the completed updates to the CEFM.

EPA is continuously investigating these recommendations and potential improvements and working with USDA and other experts to utilize the best available data and methods for estimating emissions. Many of these improvements are major updates and may take multiple years to implement in full.

5.2 Manure Management (CRT Source Category 3B)

The treatment, storage, and transportation of livestock manure can produce anthropogenic CH_4 and N_2O emissions.[6] Methane is produced by the anaerobic decomposition of manure and nitrous oxide is produced from direct and indirect pathways through the processes of nitrification and denitrification; in addition, there are many underlying factors that can affect these resulting emissions from manure management, as described below.

When livestock manure is stored or treated in systems that promote anaerobic conditions (e.g., as a liquid/slurry in lagoons, ponds, tanks, or pits), the decomposition of the volatile solids component in the manure tends to produce CH_4. When manure is handled as a solid (e.g., in stacks or drylots) or deposited on pasture, range, or paddock lands, it tends to decompose aerobically and produce CO_2 and little or no CH_4. Ambient temperature, moisture, and manure storage or residency time affect the amount of CH_4 produced because they influence the growth of the bacteria responsible for CH_4 formation. For non-liquid-based manure systems, moist conditions (which are a function of rainfall and humidity) can promote CH_4 production. Manure composition, which varies by animal diet, growth rate, and animal type (particularly the different animal digestive systems), also affects the amount of CH_4 produced. In general, the greater the energy content of the feed, the greater the potential for CH_4 emissions. However, some higher-energy feeds also are more digestible than lower quality forages, which can result in less overall waste excreted from the animal.

As previously stated, N_2O emissions are produced through both direct and indirect pathways. Direct N_2O emissions are produced as part of the nitrogen (N) cycle through the nitrification and denitrification of the N in livestock dung

[6] CO_2 emissions from livestock are not estimated because annual net CO_2 emissions are assumed to be zero – the CO_2 photosynthesized by plants is returned to the atmosphere as respired CO_2 (IPCC 2006).

and urine.[7] There are two pathways for indirect N_2O emissions. The first is the result of the volatilization of N in manure (as NH_3 and NO_x) and the subsequent deposition of these gases and their products (NH_4^+ and NO_3^-) onto soils and the surface of lakes and other waters. The second pathway is the runoff and leaching of N from manure into the groundwater below, into riparian zones receiving drain or runoff water, or into the ditches, streams, rivers, and estuaries into which the land drainage water eventually flows.

The production of direct N_2O emissions from livestock manure depends on the composition of the manure (manure includes both feces and urine), the type of bacteria involved in the process, and the amount of oxygen and liquid in the manure system. For direct N_2O emissions to occur, the manure must first be handled aerobically where organic N is mineralized or decomposed to NH_4 which is then nitrified to NO_3 (producing some N_2O as a byproduct) (nitrification). Next, the manure must be handled anaerobically where the nitrate is then denitrified to N_2O and N_2 (denitrification). NO_x can also be produced during denitrification (Groffman et al. 2000; Robertson and Groffman 2015). These emissions are most likely to occur in dry manure handling systems that have aerobic conditions, but that also contain pockets of anaerobic conditions due to saturation. A very small portion of the total N excreted is expected to convert to N_2O in the waste management system (WMS).

Indirect N_2O emissions are produced when nitrogen is lost from the system through volatilization (as NH_3 or NO_x) or through runoff and leaching. The vast majority of volatilization losses from these operations are NH_3. Although there are also some small losses of NO_x, there are no quantified estimates available for use, so losses due to volatilization are only based on NH_3 loss factors. Runoff losses would be expected from operations that house animals or store manure in a manner that is exposed to weather. Runoff losses are also specific to the type of animal housed on the operation due to differences in manure characteristics. Little information is known about leaching from manure management systems as most research focuses on leaching from land application systems. However, storage systems are often designed to minimize leaching (e.g., clay soil or synthetic liners in lagoons). Since leaching losses are expected to be minimal, leaching losses are coupled with runoff losses and the runoff/leaching estimate provided in this chapter does not account for any leaching losses.

Estimates of CH_4 emissions from manure management in 2022 were 64.7 MMT CO_2 Eq. (2,312 kt); in 1990, emissions were 39.1 MMT CO_2 Eq. (1,398 kt). This represents a 65 percent increase in emissions from 1990. Emissions increased on average by 0.8 MMT CO_2 Eq. (2 percent) annually over this period. The majority of this increase is due to dairy cattle and beef cattle manure, where emissions increased 109 and 146 percent, respectively. From 2021 to 2022, there was a 3 percent decrease in total CH_4 emissions from manure management, mainly due to a decrease in swine, dairy, and beef cattle populations.

Although a large quantity of managed manure in the United States is handled as a solid, producing little CH_4, the general trend in manure management, particularly for dairy cattle and swine (which are both shifting towards larger facilities), is one of increasing use of liquid systems. Also, new regulations controlling the application of manure nutrients to land have shifted manure management practices at smaller dairies from daily spread systems to storage and management of the manure on site. In many cases, manure management systems with the most substantial methane emissions are those associated with confined animal management operations where manure is handled in liquid-based systems. Nitrous oxide emissions from manure management vary significantly between the types of management system used and can also result in indirect emissions due to other forms of nitrogen loss from the system (IPCC 2006).

While national dairy animal populations have decreased since 1990, some states have seen increases in their dairy cattle populations as the industry becomes more concentrated in certain areas of the country and the number of animals contained on each facility increases. These areas of concentration, such as California, New Mexico, and Idaho, tend to utilize more liquid-based systems to manage (flush or scrape) and store manure. Thus, the shift

[7] Direct and indirect N_2O emissions from dung and urine spread onto fields either directly as daily spread or after it is removed from manure management systems (i.e., lagoon, pit, etc.) and from livestock dung and urine deposited on pasture, range, or paddock lands are accounted for and discussed in the agricultural soil management source category within the Agriculture sector.

toward larger dairy cattle and swine facilities since 1990 has translated into an increasing use of liquid manure management systems, which have higher potential CH_4 emissions than dry systems. This significant shift in both the dairy cattle and swine industries was accounted for by incorporating state and WMS-specific CH_4 conversion factor (MCF) values in combination with the 1992, 1997, 2002, 2007, 2012, and 2017 farm-size distribution data reported in the U.S. Department of Agriculture (USDA) *Census of Agriculture* (USDA 2019d).

In 2022, total N_2O emissions from manure management were estimated to be 17.0 MMT CO_2 Eq. (64 kt); in 1990, emissions were 13.4 MMT CO_2 Eq. (50 kt). These values include both direct and indirect N_2O emissions from manure management. Nitrous oxide emissions have increased since 1990. Multiple drivers increase N_2O emissions, such as increasing nitrogen excretion rates for some animal types (see Annex, Table A-163) and increasing numbers of animals on feedlots versus other dry systems (e.g., pasture). Across the entire time series, the overall net effect is that N_2O emissions showed a 27 percent increase from 1990 to 2022, but recent declines in a few animal populations (e.g., swine and dairy cattle) resulted in a 0.9 percent decrease from 2021 to 2022.

Table 5-6 and Table 5-7 provide estimates of CH_4 and N_2O emissions from manure management by animal category.[8]

Table 5-6: CH_4 and N_2O Emissions from Manure Management (MMT CO_2 Eq.)

Gas/Animal Type	1990	2005	2018	2019	2020	2021	2022
CH_4[a]	**39.1**	**55.0**	**67.7**	**66.7**	**66.9**	**66.4**	**64.7**
Dairy Cattle	16.0	26.4	35.7	34.4	34.7	34.3	33.4
Swine	17.4	22.7	24.7	24.9	24.9	24.6	23.8
Poultry	3.8	3.4	3.0	3.1	3.0	3.0	3.0
Beef Cattle	1.8	2.2	4.2	4.1	4.2	4.4	4.3
Horses	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Sheep	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Goats	+	+	+	+	+	+	+
American Bison	+	+	+	+	+	+	+
Mules and Asses	+	+	+	+	+	+	+
N_2O[b]	**13.4**	**15.2**	**16.6**	**16.8**	**16.9**	**17.1**	**17.0**
Beef Cattle	5.2	6.0	5.9	6.0	6.1	6.4	6.4
Dairy Cattle	5.5	5.5	6.2	6.2	6.2	6.3	6.2
Swine	1.1	1.5	1.8	1.8	1.9	1.8	1.8
Poultry	1.3	1.8	2.3	2.3	2.3	2.3	2.3
Sheep	0.1	0.3	0.3	0.3	0.3	0.3	0.3
Horses	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Goats	+	+	+	+	+	+	+
Mules and Asses	+	+	+	+	+	+	+
American Bison[c]	NA	NA	NA	NA	NA	NA	NA
Total	**52.5**	**70.2**	**84.3**	**83.5**	**83.8**	**83.6**	**81.7**

+ Does not exceed 0.05 MMT CO_2 Eq.

NA (Not Available)

[a] Accounts for CH_4 reductions due to capture and destruction of CH_4 at facilities using anaerobic digesters.

[b] Includes both direct and indirect N_2O emissions.

[c] There are no American bison N_2O emissions from managed systems; American bison are maintained entirely on pasture, range, and paddock.

[8] Manure management emissions from camels are not estimated because there is no significant population of camels in the United States. Given the insignificance of estimated camel emissions in terms of the overall level and trend in national emissions, there are no immediate improvement plans to include this emissions category in the Inventory. See Annex 5 for more information on significance of estimated camel emissions.

Notes: N_2O emissions from manure deposited on pasture, range and paddock are included in the agricultural soils management category. Totals may not sum due to independent rounding.

Table 5-7: CH_4 and N_2O Emissions from Manure Management (kt)

Gas/Animal Type	1990	2005	2018	2019	2020	2021	2022
CH_4[a]	**1,398**	**1,964**	**2,418**	**2,382**	**2,390**	**2,373**	**2,312**
Dairy Cattle	572	943	1,274	1,227	1,238	1,226	1,193
Swine	621	812	882	890	888	877	851
Poultry	135	123	108	111	109	108	108
Beef Cattle	63	78	149	148	150	157	154
Horses	4	5	3	3	3	3	2
Sheep	3	2	2	2	2	2	2
Goats	+	+	+	+	+	+	+
American Bison	+	+	+	+	+	+	+
Mules and Asses	+	+	+	+	+	+	+
N_2O[b]	**50**	**57**	**63**	**63**	**64**	**65**	**64**
Beef Cattle	20	23	22	23	23	24	24
Dairy Cattle	21	21	23	23	24	24	23
Swine	4	6	7	7	7	7	7
Poultry	5	7	9	9	9	9	9
Sheep	+	1	1	1	1	1	1
Horses	+	+	+	+	+	+	+
Goats	+	+	+	+	+	+	+
Mules and Asses	+	+	+	+	+	+	+
American Bison[c]	NA	NA	NA	NA	NA	NA	NA

+ Does not exceed 0.5 kt.

NA (Not Available)

[a] Accounts for CH_4 reductions due to capture and destruction of CH_4 at facilities using anaerobic digesters.

[b] Includes both direct and indirect N_2O emissions.

[c] There are no American bison N_2O emissions from managed systems; American bison are maintained entirely on pasture, range, and paddock.

Notes: N_2O emissions from manure deposited on pasture, range and paddock are included in the agricultural soils management category. Totals by gas may not sum due to independent rounding.

Methodology and Time-Series Consistency

The methodologies presented in IPCC (2006) form the basis of the CH_4 and N_2O emission estimates for each animal type, including Tier 1, Tier 2, and use of the CEFM previously described for enteric fermentation. These methodologies use:

- IPCC (2019) Tier 1 default N_2O emission factors and MCFs for dry systems
- U.S. specific MCFs for liquid systems (ERG 2001)
- U.S. specific values for volatile solids (VS) production rate and nitrogen excretion rate for some animal types, including cattle values from the CEFM

This combination of Tier 1 and Tier 2 methods was applied to all livestock animal types and follows guidance for methodological choice presented in decision trees from the IPCC (2006). This section presents a summary of the methodologies used to estimate CH_4 and N_2O emissions from manure management.

See Annex 3.11 for more detailed information on the methodologies (including detailed formulas and emission factors), data used to calculate CH_4 and N_2O emissions, and emission results (including input variables and results at the state-level) from manure management.

Methane Calculation Methods

The following inputs were used in the calculation of manure management CH_4 emissions for 1990 through 2022:

- Animal population data (by animal type and state);
- Typical animal mass (TAM) data (by animal type);
- Portion of manure managed in each WMS, by state and animal type;
- VS production rate (by animal type and state or United States);
- Methane producing potential (B0) of the volatile solids (by animal type); and
- Methane conversion factors (MCF), the extent to which the CH_4 producing potential is realized for each type of WMS (by state and manure management system, including the impacts of any biogas collection efforts).

Methane emissions were estimated by first determining activity data, including animal population, TAM, WMS usage, and waste characteristics. The activity data sources are described below:

- Annual animal population data for 1990 through 2022 for all livestock types, except goats, horses, mules and asses, and American bison were obtained from the USDA-NASS. For cattle, the USDA populations were utilized in conjunction with birth rates, detailed feedlot placement information, and slaughter weight data to create the transition matrix in the Cattle Enteric Fermentation Model (CEFM) that models cohorts of individual animal types and their specific emission profiles. The key variables tracked for each of the cattle population categories are described in Section 5.1 and in more detail in Annex 3.10. Goat population data for 1992, 1997, 2002, 2007, 2012, and 2017; horse and mule and ass population data for 1987, 1992, 1997, 2002, 2007, 2012, and 2017; and American bison population for 2002, 2007, 2012, and 2017 were obtained from the *Census of Agriculture* (USDA 2019d). American bison population data for 1990 through 1999 were obtained from the National Bison Association (1999).
- The TAM is an annual average weight that was obtained for animal types other than cattle from information in USDA's *Agricultural Waste Management Field Handbook* (USDA 1996), the American Society of Agricultural Engineers, Standard D384.1 (ASAE 1998) and others (Meagher 1986; EPA 1992; Safley 2000; ERG 2003b; IPCC 2006; ERG 2010a). For a description of the TAM data used for cattle, see Annex 3.10.
- WMS usage was estimated for swine and dairy cattle for different farm size categories using state and regional data from USDA (USDA APHIS 1996; Bush 1998; Ott 2000; USDA 2016c) and EPA (ERG 2000a; EPA 2002a and 2002b; ERG 2018, ERG 2019). For beef cattle and poultry, manure management system usage data were not tied to farm size but were based on other data sources (ERG 2000a; USDA APHIS 2000; UEP 1999, ERG 2023). For other animal types, manure management system usage was based on previous estimates (EPA 1992). American bison WMS usage was assumed to be the same as not on feed (NOF) cattle, while mules and asses were assumed to be the same as horses.
- VS production rates for all cattle except for calves were calculated by head for each state and animal type in the CEFM. VS production rates by animal mass for all other animals were determined using data from USDA's *Agricultural Waste Management Field Handbook* (USDA 1996 and 2008; ERG 2010b and 2010c) and data that was not available in the most recent *Handbook* were obtained from the American Society of Agricultural Engineers, Standard D384.1 (ASAE 1998) or the *2006 IPCC Guidelines* (IPCC 2006). American bison VS production was assumed to be the same as NOF bulls.
- B_0 was determined for each animal type based on literature values (Morris 1976; Bryant et al. 1976; Hashimoto 1981; Hashimoto 1984; EPA 1992; Hill 1982; Hill 1984).
- MCFs for dry systems were set equal to default IPCC factors based on state climate for each year (IPCC 2019). The IPCC 2019 factors are more representative of U.S. systems and reflect the latest science. MCFs for liquid/slurry, anaerobic lagoon, and deep pit systems were calculated based on the forecast performance of biological systems relative to temperature changes as predicted in the van't Hoff-Arrhenius equation which is consistent with IPCC (2006) Tier 2 methodology.

- Data from anaerobic digestion systems with CH_4 capture and combustion were obtained from the EPA AgSTAR Program, including information available in the AgSTAR project database (EPA 2023). Anaerobic digester emissions were calculated based on estimated methane production and collection and destruction efficiency assumptions (ERG 2008).
- For all cattle except for calves, the estimated amount of VS (kg per animal-year) managed in each WMS for each animal type, state, and year were taken from the CEFM, assuming American bison VS production to be the same as NOF bulls. For animals other than cattle, the annual amount of VS (kg per year) from manure excreted in each WMS was calculated for each animal type, state, and year. This calculation multiplied the animal population (head) by the VS excretion rate (kg VS per 1,000 kg animal mass per day), the TAM (kg animal mass per head) divided by 1,000, the WMS distribution (percent), and the number of days per year (365.25).

The estimated amount of VS managed in each WMS was used to estimate the CH_4 emissions (kg CH_4 per year) from each WMS. The amount of VS (kg per year) was multiplied by the B_0 (m^3 CH_4 per kg VS), the MCF for that WMS (percent), and the density of CH_4 (kg CH_4 per m^3 CH_4). The CH_4 emissions for each WMS, state, and animal type were summed to determine the total U.S. CH_4 emissions. See details in Step 5 of Annex 3.11.

Nitrous Oxide Calculation Methods

The following inputs were used in the calculation of direct and indirect manure management N_2O emissions for 1990 through 2022:

- Animal population data (by animal type and state);
- TAM data (by animal type);
- Portion of manure managed in each WMS (by state and animal type);
- Total Kjeldahl N excretion rate (Nex);
- Direct N_2O emission factor (EF_{WMS});
- Indirect N_2O emission factor for volatilization ($EF_{volatilization}$);
- Indirect N_2O emission factor for runoff and leaching ($EF_{runoff/leach}$);
- Fraction of N loss from volatilization of NH_3 and NO_x ($Frac_{gas}$); and
- Fraction of N loss from runoff and leaching ($Frac_{runoff/leach}$).

Nitrous oxide emissions were estimated by first determining activity data, including animal population, TAM, WMS usage, and waste characteristics. The activity data sources (except for population, TAM, and WMS, which were described above) are described below:

- Nex for all cattle except for calves were calculated by head for each state and animal type in the CEFM. Nex rates by animal mass for all other animals were determined using data from USDA's *Agricultural Waste Management Field Handbook* (USDA 1996 and 2008; ERG 2010b and 2010c) and data from the American Society of Agricultural Engineers, Standard D384.1 (ASAE 1998) and IPCC (2006). American bison Nex were assumed to be the same as NOF bulls.[9]
- All N_2O emission factors (direct and indirect) were taken from IPCC (2006).
- Country-specific estimates for the fraction of N loss from volatilization ($Frac_{gas}$) and runoff and leaching ($Frac_{runoff/leach}$) were developed. $Frac_{gas}$ values were based on WMS-specific volatilization values as estimated from EPA's *National Emission Inventory - Ammonia Emissions from Animal Agriculture*

[9] Nex of American bison on grazing lands are accounted for and discussed in the agricultural soil management source category and included under pasture, range and paddock (PRP) emissions. Because American bison are maintained entirely on unmanaged WMS and N_2O emissions from unmanaged WMS are not included in the manure management source category, there are no N_2O emissions from American bison included in the manure management source category.

Operations (EPA 2005). $Frac_{runoff/leaching}$ values were based on regional cattle runoff data from EPA's Office of Water (EPA 2002b; see Annex 3.11).

To estimate N_2O emissions for cattle (except for calves), the estimated amount of N excreted (kg per animal-year) that is managed in each WMS for each animal type, state, and year were taken from the CEFM. For calves and other animals, the amount of N excreted (kg per year) in manure in each WMS for each animal type, state, and year was calculated. The population (head) for each state and animal was multiplied by TAM (kg animal mass per head) divided by 1,000, the nitrogen excretion rate (Nex, in kg N per 1,000 kg animal mass per day), WMS distribution (percent), and the number of days per year.

Direct N_2O emissions were calculated by multiplying the amount of N excreted (kg per year) in each WMS by the N_2O direct emission factor for that WMS (EF_{WMS}, in kg N_2O-N per kg N) and the conversion factor of N_2O-N to N_2O. These emissions were summed over state, animal, and WMS to determine the total direct N_2O emissions (kg of N_2O per year). See details in Step 6 of Annex 3.11.

Indirect N_2O emissions from volatilization (kg N_2O per year) were then calculated by multiplying the amount of N excreted (kg per year) in each WMS by the fraction of N lost through volatilization ($Frac_{gas}$) divided by 100, the emission factor for volatilization ($EF_{volatilization}$, in kg N_2O per kg N), and the conversion factor of N_2O-N to N_2O. Indirect N_2O emissions from runoff and leaching (kg N_2O per year) were then calculated by multiplying the amount of N excreted (kg per year) in each WMS by the fraction of N lost through runoff and leaching ($Frac_{runoff/leach}$) divided by 100, the emission factor for runoff and leaching ($EF_{runoff/leach}$, in kg N_2O per kg N), and the conversion factor of N_2O-N to N_2O. The indirect N_2O emissions from volatilization and runoff and leaching were summed to determine the total indirect N_2O emissions. See details in Step 6 of Annex 3.11.

Following these steps, direct and indirect N_2O emissions were summed to determine total N_2O emissions (kg N_2O per year) for the years 1990 to 2022.

Methodological approaches, changes to historic data, and other parameters were applied to the entire time series to ensure consistency in emissions estimates from 1990 through 2022. In some cases, the activity data source changed over the time series. For example, updated WMS distribution data were applied to 2016 for dairy cows and 2009 for swine. While previous WMS distribution data were from another data source, EPA integrated the more recent data source to reflect the best available current WMS distribution data for these animals. EPA assumed a linear interpolation distribution for years between the two data sources. Refer to Annex 3.11 for more details on data sources and methodology.

Uncertainty

An analysis (ERG 2003a) was conducted for the manure management emission estimates presented in the 1990 through 2001 *Inventory* (i.e., 2003 submission to the UNFCCC) to determine the uncertainty associated with estimating CH_4 and N_2O emissions from livestock manure management. The quantitative uncertainty analysis for this source category was performed in 2002 through the IPCC-recommended Approach 2 uncertainty estimation methodology, the Monte Carlo stochastic simulation technique. The uncertainty analysis was developed based on the methods used to estimate CH_4 and N_2O emissions from manure management systems. The series of equations used were condensed into a single equation for each animal type and state. The equations for each animal group contained four to five variables around which the uncertainty analysis was performed for each state. A normal probability distribution was assumed for all variables in the estimation equations. While there are plans to update the uncertainty to reflect recent manure management updates and forthcoming changes (see Planned Improvements, below), at this time the uncertainty estimates were directly applied to the 2022 emission estimates.

The results of the Approach 2 quantitative uncertainty analysis are summarized in Table 5-8. Manure management CH_4 emissions in 2022 were estimated to be between 53.1 and 77.7 MMT CO_2 Eq. at a 95 percent confidence level, which indicates a range of 18 percent below to 20 percent above the actual 2022 emission estimate of 64.7 MMT CO_2 Eq. At the 95 percent confidence level, N_2O emissions were estimated to be between 14.3 and 21.1 MMT CO_2

Eq. (or approximately 16 percent below and 24 percent above the actual 2022 emission estimate of 17.0 MMT CO_2 Eq.).

A quantitative uncertainty analysis for this source category was also performed using the IPCC (2006) recommended Approach 1 based on simple error propagation as well. Based on this analysis, manure management:

- CH_4 emissions in 2022 were estimated to be between 50.4 and 79.0 MMT CO_2 Eq., which indicates a range of ±21 percent above and below the 2022 emission estimate of 64.7 MMT CO_2 Eq. A ±25 percent uncertainty factor is applied to the activity data (e.g., animal populations), and a ±30 percent default uncertainty factor for Tier 1 and ±20 percent default uncertainty factor for Tier 2 is applied to the emission factors (IPCC 2006).
- N_2O emissions in 2022 were estimated to be between 11.8 and 22.2 MMT CO_2 Eq., which indicates a range of ±31 percent above and below the 2022 emission estimate of 17.0 MMT CO_2 Eq. A ±25 percent uncertainty factor is applied to the activity data (e.g., animal populations), and a ±50 percent default uncertainty factor is applied to the emission factors (IPCC 2006).
- CH_4 and N_2O emissions in 2022 were estimated to be between 66.5 and 96.9 MMT CO_2 Eq., which indicates a range of ±19 percent above and below the 2022 emission estimate of 81.7 MMT CO_2 Eq. A ±25 percent uncertainty factor is applied to the activity data (e.g., animal populations), and a ±20-50 percent default uncertainty factor is applied to the emission factors (IPCC 2006).

Table 5-8: Approach 2 Quantitative Uncertainty Estimates for CH_4 and N_2O (Direct and Indirect) Emissions from Manure Management (MMT CO_2 Eq. and Percent)

Source	Gas	2022 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Manure Management	CH_4	64.7	53.1	77.7	-18%	+20%
Manure Management	N_2O	17.0	14.3	21.1	-16%	+24%

[a] Range of emission estimates predicted by Monte Carlo stochastic simulation for a 95 percent confidence interval.

QA/QC and Verification

General (Tier 1) and category-specific (Tier 2) QA/QC activities were conducted consistent with the U.S. Inventory QA/QC plan outlined in Annex 8. Tier 2 activities focused on comparing estimates for the previous and current Inventories for N_2O emissions from managed systems and CH_4 emissions from livestock manure. All errors identified were corrected. Order of magnitude checks were also conducted, and corrections made where needed. In addition, manure N data were checked by comparing state-level data with bottom-up estimates derived at the county level and summed to the state level. Similarly, a comparison was made by animal and WMS type for the full time series, between national level estimates for N excreted, both for pasture and managed systems, and the sum of county estimates for the full time series. This was done to ensure consistency between excreted N within the manure management sector and those data provided to the managed soils sector. All errors identified were corrected.

Time-series data, including population, are validated by experts to ensure they are representative of the best available U.S.-specific data. The U.S.-specific values for TAM, Nex, VS, B_0, and MCF were also compared to the IPCC default values and validated by experts. Although significant differences exist in some instances, these differences are due to the use of U.S.-specific data and the differences in U.S. agriculture as compared to other countries. The

U.S. manure management emission estimates use the most reliable country-specific data, which are more representative of U.S. animals and systems than the IPCC (2006) default values.

For additional verification of the 1990 to 2022 estimates, the implied CH_4 emission factors for manure management (kg of CH_4 per head per year) were compared against the default IPCC (2006) values. Table 5-9 presents the implied emission factors of kg of CH_4 per head per year used for the manure management emission estimates as well as the IPCC (2006) default emission factors. The U.S. implied emission factors fall within the range of the IPCC (2006) default values, except in the case of sheep, goats, and some years for horses and dairy cattle. The U.S. implied emission factors are less than the IPCC (2006) default value for those animals due to the use of U.S.-specific data for typical animal mass and VS excretion. There is an increase in implied emission factors for dairy cattle and swine across the time series. This increase reflects the dairy cattle and swine industry trend towards larger farm sizes; large farms are more likely to manage manure as a liquid and therefore produce more CH_4 emissions. See the Recalculations for explanations for changes that affect emissions which impact these implied emission factors.

Table 5-9: IPCC (2006) Implied Emission Factor Default Values Compared with Calculated Values for CH_4 from Manure Management (kg/head/year)

Animal Type	IPCC Default CH_4 Emission Factors (kg/head/year)[a]	1990	2005	2018	2019	2020	2021	2022
Dairy Cattle	48-112	29.3	53.0	67.0	65.0	65.9	65.0	64.1
Beef Cattle	1-2	0.8	0.9	1.8	1.8	1.8	1.9	1.9
Swine	10-45	11.5	13.3	12.0	11.6	11.5	11.8	11.6
Sheep	0.19-0.37	0.3	0.4	0.4	0.4	0.4	0.4	0.4
Goats	0.13-0.26	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Poultry	0.02-1.4	0.1	0.1	0.05	0.05	0.05	0.05	0.05
Horses	1.56-3.13	1.9	1.4	1.2	1.2	1.2	1.2	1.2
American Bison	NA	0.8	0.9	0.9	0.9	0.9	0.9	0.9
Mules and Asses	0.76-1.14	0.4	0.4	0.4	0.4	0.4	0.4	0.4

NA (Not Applicable)

[a] Ranges reflect *2006 IPCC Guidelines* (Volume 4, Table 10.14) default emission factors for North America across different climate zones.

In addition, default IPCC (2006) emission factors for N_2O were compared to the U.S. *Inventory* implied N_2O emission factors. Default N_2O emission factors from the *2006 IPCC Guidelines* were used to estimate N_2O emission from each WMS in conjunction with U.S.-specific Nex values. The implied emission factors differed from the U.S. *Inventory* values due to the use of U.S.-specific Nex values and differences in populations present in each WMS throughout the time series.

Recalculations Discussion

In the previous *Inventory*, 1990 to 2020 estimates were retained from the 1990 through 2020 *Inventory*, and 2021 estimates were based on a simplified approach that used emission factors and extrapolated population estimates for all animals. For the current *Inventory*, the calculations were rerun for all years, resulting in different estimates for 2021 than the prior *Inventory*.

There were also changes to emissions resulting from activity data changes, including:

- EPA updated the WMS distributions for broilers, layers, and beef feedlot animal types. For broilers, this affected 1993 through 2021, for layers 2000 through 2021, and for beef feedlots all years of the time series (ERG 2023).

- EPA updated the calf TAM values to coincide with values used within the CEFM. This affected all years of the time series.
- EPA updated the solid storage direct N_2O emission factor to the updated guidance provided in IPCC (2019).
- EPA updated how poultry digesters were applied, splitting other poultry and caged layers (previously done for broilers) as well as the year for which select swine anaerobic digesters were shutdown per notes provided in AgSTAR.
- EPA discovered and corrected an error within the CEFM (see NIR section 5.1 and annex 3.10) related to the urinary energy input used for feedlot cattle, which affected VS results for this animal group. The urinary energy default was updated from 0.04 to 0.02 for feedlot cattle.

The cumulative effect of all these recalculations had a minor impact on the overall manure management emissions estimates:

- CH_4 emissions increased an average 0.6 percent over the time series, with the largest decrease of 0.2 percent (0.1 MMT CO_2 Eq) in 2002 to the largest increase of 1.8 percent (1.2 MMT CO_2 Eq.) in 2017.
- N_2O emissions increased an average 3.4 percent over the time series, with the largest decrease of 3.6 percent (0.6 MMT CO_2 Eq.) in 2020 and the largest increase of 7.8 percent (1.0 MMT CO_2 Eq.) in 1990.
- Over the time series the average total emissions increased by 1.2 percent from the previous *Inventory*. The changes ranged from the largest decrease 0.5 percent (0.4 MMT CO_2 Eq.) in 2020, to the largest increase 2.1 percent (1.1 MMT CO_2 Eq.) in 1990.

Planned Improvements

Regular annual data reviews and updates are necessary to maintain an emissions inventory that reflects the current base of knowledge. In addition to the documented approaches currently used to address data availability, EPA conducts data assessments to pursue a number of potential improvements.

Potential improvements (long-term improvements) for future *Inventory* years include:

- Providing supplemental details on CH_4 emissions reductions due to the use of anaerobic digesters (the *Inventory* currently estimates only emissions from anaerobic digestion systems).
- Investigating the updated IPCC *2019 Refinement* default N_2O emissions factor for anaerobic digesters. Historically, EPA has not estimated N_2O emissions from digesters as the default guidance was no emissions. Incorporating AgSTAR data for N_2O emissions, like CH_4 emissions, is a longer-term goal for EPA.
- Investigating updates to the current anaerobic digester MCFs based on IPCC (2019).

EPA is aware of the following potential updates or improvements but notes that implementation will be based on available resources and data availability:

- Updating the B_0 data used in the *Inventory*, as data become available. EPA is conducting outreach with counterparts from USDA as to available data and research on B_0.
- Comparing CH_4 and N_2O emission estimates with estimates from other models and more recent studies and compare the results to the *Inventory*.
- Comparing manure management emission estimates with on-farm measurement data to identify opportunities for improved estimates.
- Comparing VS and Nex data to literature data to identify opportunities for improved estimates.

- Determining if there are revisions to the U.S.-specific method for calculating liquid systems for MCFs based on updated guidance from the IPCC *2019 Refinement*. EPA previously began this investigation to determine the potential differences between the methods.
- Investigating improved emissions estimate methodologies for swine pit systems with less than one month of storage (the updated swine WMS data included this WMS category).
- Improving the linkages with the Enteric Fermentation source category estimates. For future Inventories, it may be beneficial to have the CEFM and Manure Management calculations in the same model, as they rely on much of the same activity data and on each other's outputs to properly calculate emissions. EPA has begun this investigation and plans to develop a model to calculate emissions for these two categories.
- Continuing to investigate new sources of WMS data. EPA is collaborating with the USDA to collect or use existing survey data for potential improvements to the *Inventory*.
- Revising the uncertainty analysis to address changes that have been implemented to the CH_4 and N_2O estimates. The plan is to align the timing of the updated Manure Management uncertainty analysis with the uncertainty analysis for Enteric Fermentation.

5.3 Rice Cultivation (CRT Source Category 3C)

Most of the world's rice is grown on flooded fields (Baicich 2013) that create anaerobic conditions leading to CH_4 production through a process known as methanogenesis. Approximately 60 to 90 percent of the CH_4 produced by methanogenic bacteria in flooded rice fields is oxidized in the soil and converted to CO_2 by methanotrophic bacteria. The remainder is emitted to the atmosphere (Holzapfel-Pschorn et al. 1985; Sass et al. 1990) or transported as dissolved CH_4 into groundwater and waterways (Neue et al. 1997). Methane is transported to the atmosphere primarily through the rice plants, but some CH_4 also escapes via ebullition (i.e., bubbling through the water) and to a much lesser extent by diffusion through the water (van Bodegom et al. 2001).

Water management is arguably the most important factor affecting CH_4 emissions in rice cultivation, and improved water management has the largest potential to mitigate emissions (Yan et al. 2009). Upland rice fields are not flooded, and therefore do not produce CH_4, but large amounts of CH_4 can be emitted in continuously irrigated fields, which is the most common practice in the United States (USDA 2012). Single or multiple aeration events with drainage of a field during the growing season can significantly reduce these emissions (Wassmann et al. 2000a), but drainage may also increase N_2O emissions. Deepwater rice fields (i.e., fields with flooding depths greater than one meter, such as natural wetlands) tend to have fewer living stems reaching the soil, thus reducing the amount of CH_4 transport to the atmosphere through the plant compared to shallow-flooded systems (Sass 2001).

Other management practices also influence CH_4 emissions from flooded rice fields including rice residue straw management and application of organic amendments, in addition to cultivar selection due to differences in the amount of root exudates[10] among rice varieties (Neue et al. 1997). These practices influence the amount of organic matter available for methanogenesis, and some practices, such as mulching rice straw or composting organic amendments, can reduce the amount of labile carbon and limit CH_4 emissions (Wassmann et al. 2000b).

[10] The roots of rice plants add organic material to the soil through a process called "root exudation." Root exudation is thought to enhance decomposition of the soil organic matter and release nutrients that the plant can absorb for production. The amount of root exudate produced by a rice plant over a growing season varies among rice varieties.

Fertilization practices also influence CH_4 emissions, particularly the use of fertilizers with sulfate, which can reduce CH_4 emissions (Wassmann et al. 2000b; Linquist et al. 2012). Other environmental variables also impact the methanogenesis process such as soil temperature and soil type. Soil temperature regulates the activity of methanogenic bacteria, which in turn affects the rate of CH_4 production. Soil texture influences decomposition of soil organic matter but is also thought to have an impact on oxidation of CH_4 in the soil (Sass et al. 1994).

Rice is currently cultivated in 12 states, including Arkansas, California, Florida, Illinois, Kentucky, Louisiana, Minnesota, Mississippi, Missouri, New York, Tennessee, and Texas. Soil types, rice varieties, and cultivation practices vary across the United States, but most farmers apply fertilizers and do not harvest crop residues. In addition, a second, ratoon rice crop is sometimes grown in the Southeastern region of the country. Ratoon crops are produced from regrowth of the stubble remaining after the harvest of the first rice crop. Methane emissions from ratoon crops are higher than those from the primary crops due to the increased amount of labile organic matter available for anaerobic decomposition in the form of relatively fresh crop residue straw. Emissions tend to be higher in rice fields if the residues have been in the field for less than 30 days before planting the next rice crop (Lindau and Bollich 1993; IPCC 2006; Wang et al. 2013).

A combination of Tier 1 and 3 methods are used to estimate CH_4 emissions from rice cultivation across most of the time series, while a surrogate data method has been applied to estimate national emissions for 2021 to 2022 in this *Inventory* due to lack of data in these years of the time series. National emission estimates based on surrogate data will be recalculated in a future *Inventory* with the Tier 1 and 3 methods as data becomes available.

Overall, rice cultivation is a minor source of CH_4 emissions in the United States relative to other source categories (see Table 5-10, Table 5-11, and Figure 5-3). Most emissions occur in Arkansas, California, Louisiana, Mississippi, Missouri, and Texas. In 2022, CH_4 emissions from rice cultivation were 18.9 MMT CO_2 Eq. (674 kt CH_4). Annual emissions fluctuated between 1990 and 2022, which is largely due to differences in the amount of rice harvested areas over time. There has been a marginal decrease in emissions since 1990. Interestingly, the estimated emissions in 2022 are roughly the same as emissions in 1990.

Table 5-10: CH_4 Emissions from Rice Cultivation (MMT CO_2 Eq.)

State	1990	2005	2018	2019	2020	2021	2022
Arkansas	6.3	8.8	8.0	5.6	6.8	NE	NE
California	3.2	3.4	3.7	3.5	3.6	NE	NE
Florida	+	+	+	+	+	NE	NE
Illinois	+	+	+	+	+	NE	NE
Kentucky	+	+	+	+	+	NE	NE
Louisiana	3.5	3.8	3.7	3.2	3.7	NE	NE
Minnesota	+	+	+	+	+	NE	NE
Mississippi	1.1	1.3	0.7	0.6	0.6	NE	NE
Missouri	0.5	1.2	1.2	0.9	1.0	NE	NE
New York	+	+	+	+	+	NE	NE
Tennessee	+	+	+	+	+	NE	NE
Texas	4.3	1.9	2.6	1.9	2.9	NE	NE
Total	**18.9**	**20.6**	**19.9**	**15.6**	**18.6**	**18.3**	**18.9**

+ Does not exceed 0.05 MMT CO_2 Eq.

NE (Not Estimated). State-level emissions are not estimated for 2021 through 2022 in this *Inventory*. A surrogate method is used to estimate emissions for these years only at the national scale.

Note: Totals may not sum due to independent rounding.

Table 5-11: CH_4 Emissions from Rice Cultivation (kt CH_4)

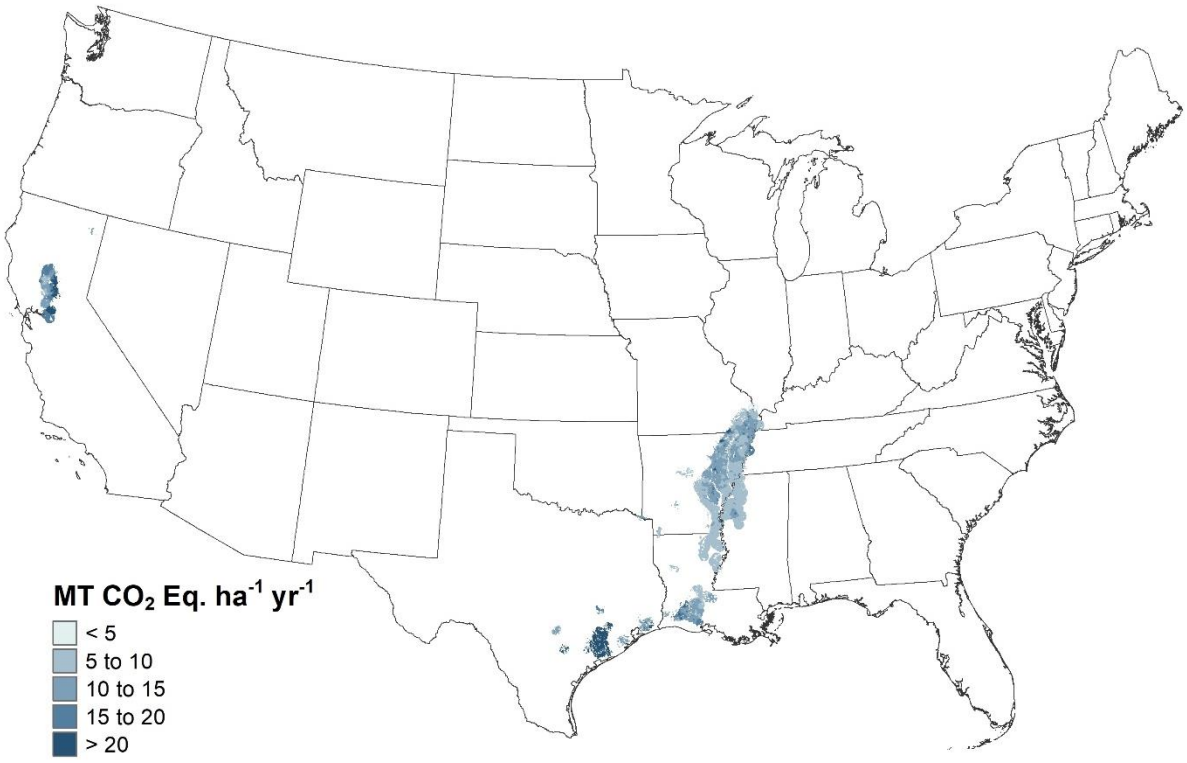
State	1990	2005	2018	2019	2020	2021	2022
Arkansas	224.2	315.5	287.1	200.5	243.4	NE	NE
California	114.5	122.8	131.5	123.9	129.1	NE	NE
Florida	+	1.2	+	+	+	NE	NE
Illinois	+	0.4	0.1	+	0.1	NE	NE
Kentucky	+	+	+	+	+	NE	NE
Louisiana	124.9	135.0	131.4	113.7	130.4	NE	NE
Minnesota	1.0	1.7	+	0.8	+	NE	NE
Mississippi	39.0	46.5	24.3	20.3	21.5	NE	NE
Missouri	19.5	42.7	43.0	31.8	34.4	NE	NE
New York	0.2	+	+	+	+	NE	NE
Tennessee	+	0.1	+	+	+	NE	NE
Texas	153.5	69.5	93.6	67.0	104.7	NE	NE
Total	**677**	**735**	**711**	**558**	**664**	**653**	**674**

+ Does not exceed 0.5 kt.

NE (Not Estimated). State-level emissions are not estimated for 2021 through 2022 in this *Inventory*. A surrogate method is used to estimate emissions for these years only at the national scale.

Note: Totals may not sum due to independent rounding.

Figure 5-3: Annual CH_4 Emissions from Rice Cultivation, 2020, Using the Tier 3 DayCent Model



Note: Only national-scale emissions are estimated for 2021 and 2022 in this *Inventory* using a surrogate data method described in the Methodology section; therefore, the fine-scale emission patterns in this map are based on the estimates for 2020.

Methodology and Time-Series Consistency

The methodology used to estimate CH_4 emissions from rice cultivation is based on a combination of IPCC Tier 1 and 3 approaches. The Tier 3 method utilizes the DayCent process-based model to estimate CH_4 emissions from rice cultivation (Cheng et al. 2013) and has been tested in the United States (see Annex 3.12) and Asia (Cheng et al. 2013, 2014). The model simulates hydrological conditions and thermal regimes, organic matter decomposition, root exudation, rice plant growth and its influence on oxidation of CH_4, as well as CH_4 transport through the plant and via ebullition (Cheng et al. 2013). The method captures the influence of organic amendments and rice straw management on methanogenesis in the flooded soils, and ratooning of rice crops with a second harvest during the growing season. In addition to CH_4 emissions, DayCent simulates soil carbon stock changes and N_2O emissions (Parton et al. 1987 and 1998; Del Grosso et al. 2010) and allows for a seamless set of simulations for crop rotations that include both rice and non-rice crops.

The Tier 1 method is applied to estimate CH_4 emissions from rice when grown in rotation with crops that are not simulated by DayCent, such as vegetable crops. The Tier 1 method is also used for areas converted between agriculture (i.e., cropland and grassland) and other land uses, such as forest land, wetland, and settlements. In addition, the Tier 1 method is used to estimate CH_4 emissions from organic soils (i.e., Histosols) and from areas with very gravelly, cobbly, or shaley soils (greater than 35 percent by volume). The Tier 3 method using DayCent has not been fully tested for estimating emissions associated with these conditions.

The Tier 1 method for estimating CH_4 emissions from rice production utilizes a default base emission rate and scaling factors (IPCC 2006). The base emission rate represents emissions for continuously flooded fields with no organic amendments. Scaling factors are used to adjust the base emission rate for water management and organic amendments that differ from continuous flooding with no organic amendments. The method accounts for pre-season and growing season flooding; types and amounts of organic amendments; and the number of rice production seasons within a single year (i.e., single cropping and double-cropping with ratooning). The Tier 1 analysis is implemented in the Agriculture and Land Use National Greenhouse Gas Inventory (ALU) software (Ogle et al. 2016).[11]

Rice cultivation areas are based on crop and land use histories recorded in the USDA National Resources Inventory (NRI) survey (USDA-NRCS 2020) and extended through 2020 using the USDA-NASS Crop Data Layer Product (USDA-NASS 2021, Johnson and Mueller 2010). The areas have been modified in the original NRI survey through a process in which the Forest Inventory and Analysis (FIA) survey data and the National Land Cover Dataset (Yang et al. 2018) are harmonized with the NRI data (Nelson et al. 2020). This process ensures that the land use areas are consistent across all land use categories (See Section 6.1, Representation of the U.S. Land Base for more information).

The NRI is a statistically based sample of all non-federal land and includes approximately 604,000 survey locations in agricultural cropland and grassland for the conterminous United States and Hawaii of which 7,888 include one or more years of rice cultivation. The Tier 3 method is used to estimate CH_4 emissions from 5,998 of the NRI survey locations, and the remaining 1,890 survey locations are estimated with the Tier 1 method. Each NRI survey location is associated with a survey weight that allows scaling of CH_4 emission to the entire land base with rice cultivation (i.e., each weight approximates the amount of area with the same land-use/management history as the survey location). Land-use and some management information in the NRI (e.g., crop type, soil attributes, and irrigation) were collected on a 5-year cycle beginning in 1982, along with cropping rotation data in four out of five years for each five-year time period (i.e., 1979 to 1982, 1984 to 1987, 1989 to 1992, and 1994 to 1997). The NRI program began collecting annual data in 1998, with data through 2017 (USDA-NRCS 2020). For 2018-2020, the time series is extended with the crop data provided in USDA-NASS CDL (USDA-NASS 2021). CDL data have a 30 to 58 m spatial resolution, depending on the year. NRI survey locations are overlaid on the CDL in a geographic information

[11] See http://www.nrel.colostate.edu/projects/ALUsoftware/.

system, and the crop types are extracted to extend the cropping histories. The harvested rice areas in each state are presented in Table 5-12.

Table 5-12: Rice Area Harvested (1,000 Hectares)

State/Crop	1990	2005	2018	2019	2020	2021	2022
Arkansas	611	782	659	512	663	NE	NE
California	251	237	226	218	224	NE	NE
Florida	0	3	0	0	0	NE	NE
Illinois	0	1	0	0	1	NE	NE
Kentucky	0	0	0	0	0	NE	NE
Louisiana	399	400	356	313	383	NE	NE
Minnesota	3	6	0	3	0	NE	NE
Mississippi	177	191	98	96	109	NE	NE
Missouri	48	96	99	74	85	NE	NE
New York	1	0	0	0	0	NE	NE
Tennessee	0	1	0	0	0	NE	NE
Texas	294	104	164	119	167	NE	NE
Total	**1,784**	**1,823**	**1,603**	**1,335**	**1,633**	**NE**	**NE**

NE (Not Estimated). Area data will be updated in the next *Inventory*.
Note: Totals may not sum due to independent rounding.

The Southeastern states have sufficient growing periods for a ratoon crop in some years (Table 5-13). For example, the growing season length is occasionally sufficient for ratoon crops to be grown on about two percent of the rice fields in Arkansas. No data are available about ratoon crops in Missouri or Mississippi, so the average amount of ratooning in Arkansas was assigned to these states. Ratoon cropping occurs much more frequently in Louisiana (LSU 2015 for years 2000 through 2013, 2015) and Texas (TAMU 2015 for years 1993 through 2015), averaging 32 percent and 45 percent of rice acres planted, respectively. Florida also has a large fraction of area with a ratoon crop (49 percent). Ratoon rice crops are not grown in California. Ratooning practices are assigned to individual NRI locations using a hot-deck imputation method with six complete imputations for each NRI location to address uncertainty. The method is based on random assignment of ratooning to approximate the percentages of fields managed with ratooning provided in Table 5-14.

Table 5-13: Average Ratooned Area as Percent of Primary Growth Area (Percent)

State	1990-2015
Arkansas[a]	1.9%
California	0%
Florida[b]	45.2%
Louisiana[c]	39.5%
Mississippi[a]	37.8%
Missouri[a]	2.4%
Texas[d]	49.5%

[a] Arkansas: *1990–2000* (Slaton 1999 through 2001); *2001–2011* (Wilson 2002 through 2007, 2009 through 2012); *2012–2013* (Hardke 2013, 2014). Estimates of ratooning for Missouri and Mississippi are based on the data from Arkansas.
[b] Florida - Ratoon: *1990–2000* (Schueneman 1997, 1999 through 2001); *2001* (Deren 2002); *2002–2003* (Kirstein 2003 through 2004, 2006); *2004* (Cantens 2004 through 2005); *2005–2013* (Gonzalez 2007 through 2014).
[c] Louisiana: *1990–2013* (Linscombe 1999, 2001 through 2014).
[d] Texas: *1990–2002* (Klosterboer 1997, 1999 through 2003); *2003–2004* (Stansel 2004 through 2005); *2005* (Texas Agricultural Experiment Station 2006); *2006–2013* (Texas Agricultural Experiment Station 2007 through 2014).

While rice crop production in the United States includes a minor amount of land with mid-season drainage or alternate wet-dry periods, the majority of rice growers use continuously flooded water management systems (Hardke 2015; UCCE 2015; Hollier 1999; Way et al. 2014). Therefore, continuous flooding was assumed in the DayCent simulations and the Tier 1 analysis. Variation in flooding can be incorporated in future inventories if updated water management data are available.

Winter flooding is another key practice associated with water management in rice fields, and the impact of winter flooding on CH_4 emissions is addressed in the Tier 3 and Tier 1 analyses. Flooding is used to prepare fields for the next growing season, and to create waterfowl habitat (Young 2013; Miller et al. 2010; Fleskes et al. 2005). Fitzgerald et al. (2000) suggests that as much as 50 percent of the annual emissions may occur during winter flooding. Winter flooding is a common practice with an average of 34 percent of fields managed with winter flooding in California (Miller et al. 2010; Fleskes et al. 2005), and approximately 21 percent of the fields managed with winter flooding in Arkansas (Wilson and Branson 2005 and 2006; Wilson and Runsick 2007 and 2008; Wilson et al. 2009 and 2010; Hardke and Wilson 2013 and 2014; Hardke 2015). No data are available on winter flooding for Texas, Louisiana, Florida, Missouri, or Mississippi. For these states, the average amount of flooding is assumed to be similar to Arkansas. In addition, the amount of flooding is assumed to be relatively constant over the *Inventory* time series. Similar to ratooning practices, winter flooding is assigned to individual NRI locations using a hot-deck imputation method with six complete imputations for each NRI location to address uncertainty. The method is based on random assignment of winter flooding to approximate the percentages of fields managed with winter flooding as discussed above.

A data splicing method is used to estimate emissions from 2021 to 2022 associated with the rice CH_4 emissions for Tier 1 and 3 methods. Specifically, a linear regression model with autoregressive moving average (ARMA) errors was used to estimate the relationship between the surrogate data and emissions data from 1990 through 2020, which were derived using the Tier 3 methods (Brockwell and Davis 2016). Surrogate data are based on rice commodity statistics from USDA-NASS.[12] See Box 5-2 for more information about the surrogate data method. For the Tier 1 method, a linear-time series model is used to estimate emissions for 2021 to 2022 without surrogate data.

Box 5-2: Surrogate Data Method

An approach to extend the time series is needed to estimate emissions from rice cultivation because there are gaps in activity data at the end of the time series. This is mainly because the National Resources Inventory (NRI) does not release data every year, and the NRI is a key data source for estimating greenhouse gas emissions.

A surrogate data method has been selected to impute missing emissions at the end of the time series. A linear regression model with autoregressive moving average (ARMA) errors (Brockwell and Davis 2016) is used to estimate the relationship between the surrogate data and the observed 1990 to 2020 emissions data that has been compiled using the inventory methods described in this section. The model to extend the time series is given by

$$Y = X\beta + \varepsilon,$$

where Y is the response variable (e.g., CH_4 emissions), $X\beta$ is the surrogate data that is used to predict the missing emissions data, and ε is the remaining unexplained error. Models with a variety of surrogate data were tested, including commodity statistics, weather data, or other relevant information. Parameters are estimated from the observed data for 1990 to 2020 using standard statistical techniques, and these estimates are used to predict the missing emissions data for 2021 to 2022.

A critical issue in using splicing methods is to adequately account for the additional uncertainty introduced by predicting emissions with related information without compiling the full inventory. For example, predicting CH_4 emissions will increase the total variation in the emission estimates for these specific years, compared to those years in which the full inventory is compiled. This added uncertainty is quantified within the model framework using a Monte Carlo approach. The approach requires estimating parameters for results in each Monte Carlo simulation for the full inventory (i.e., the surrogate data model is refit with the emissions estimated in each Monte Carlo iteration from the full inventory analysis with data from 1990 to 2020).

[12] See https://quickstats.nass.usda.gov/.

In order to ensure time-series consistency, the same methods are applied from 1990 to 2020, and data splicing methods are used to approximate emissions for the remainder of the 2021 to 2022 time series based on the emissions data from 1990 to 2020. The surrogate data method and linear time series approach, used for the Tier 3 and 1 methods, respectively, are consistent with data splicing methods in IPCC (2006).

Uncertainty

Sources of uncertainty in the Tier 3 method include management practices, uncertainties in model structure (i.e., algorithms and parameterization), and variance associated with the NRI sample. Sources of uncertainty in the IPCC (2006) Tier 1 method include the emission factors, management practices, and variance associated with the NRI sample. The total uncertainty was quantified with two variance components (Ogle et al. 2010) that are combined using simple error propagation methods provided by the IPCC (2006), i.e., by taking the square root of the sum of the squares of the standard deviations of the uncertain quantities. For the first variance component, a Monte Carlo analysis was used to propagate uncertainties in the Tier 1 and 3 methods for the management data, as well as emission factors and model structure/parameterization, respectively. The second variance component is quantifying uncertainty in scaling from the NRI survey to the entire area of rice cultivation, and is computed using a standard variance estimator for a two-stage sample design (Särndal et al. 1992). For 2021 to 2022, there is additional uncertainty propagated through the Monte Carlo analysis associated with the surrogate data method (See Box 5-2 for information about propagating uncertainty with the surrogate data method). The uncertainties from the Tier 1 and 3 approaches are combined to produce the final CH_4 emissions estimate using simple error propagation (IPCC 2006). Additional details on the uncertainty methods are provided in Annex 3.12.

Rice cultivation CH_4 emissions in 2022 were estimated to be between 5.1 and 32.6 MMT CO_2 Eq. at a 95 percent confidence level, which indicates a range of 73 percent below to 73 percent above the 2022 emission estimate of 18.9 MMT CO_2 Eq. (see Table 5-14).

Table 5-14: Approach 2 Quantitative Uncertainty Estimates for CH_4 Emissions from Rice Cultivation (MMT CO_2 Eq. and Percent)

Source	Inventory Method	Gas	2022 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (MMT CO_2 Eq.)		(%)	
				Lower Bound	Upper Bound	Lower Bound	Upper Bound
Rice Cultivation	Tier 3	CH_4	15.9	2.2	29.6	-86%	+86%
Rice Cultivation	Tier 1	CH_4	3.0	2.0	4.0	-34%	+34%
Rice Cultivation	**Total**	**CH_4**	**18.9**	**5.1**	**32.6**	**-73%**	**+73%**

[a] Range of emission estimates is the 95 percent confidence interval.

QA/QC and Verification

General (Tier 1) and category-specific (Tier 2) QA/QC activities were conducted consistent with the U.S. Inventory QA/QC plan outlined in Annex 8. Quality control measures include checking input data, model scripts, and results to ensure data are properly handled throughout the inventory process. Inventory reporting forms and text are reviewed and revised as needed to correct transcription errors.

Model results are compared to field measurements to verify that results adequately represent CH_4 emissions. The comparisons included over 17 long-term experiments, representing about 238 combinations of management treatments across all the sites. A statistical relationship was developed to assess uncertainties in the model structure and parameterization, adjusting the estimates for model bias and assessing precision in the resulting estimates (methods are described in Ogle et al. 2007). See Annex 3.12 for more information.

Recalculations Discussion

Several improvements have been implemented in this *Inventory* leading to recalculations, including a) updated time series of land representation data that identifies which points and years were sown with rice (Nelson et al 2020), b) extending the time-series of crop history with CDL data, c) imputing ratooning and winter flooding onto individual NRI survey points, d) updated fertilizer and organic amendment additions, and e) revisions to the approach for assigning organic matter amendments and crop residue inputs. As a result of these changes, CO_2-equivalent emissions changed annually with an average annual increase of 0.97 MMT CO_2 Eq., or 5.5 percent, over the time series from 1990 to 2021 compared to the previous *Inventory*.

Planned Improvements

A key planned improvement for rice cultivation is to refine the model algorithms and re-calibration of the Tier 3 DayCent model using the latest observational data from experiments. Another improvement is collection of more information about water management and refinement of the application to incorporate mid-season drainage and alternate wetting and drying systems. Improvements are expected to be completed for the next *Inventory* (i.e., 2025 submission to the UNFCCC, 1990 through 2023 *Inventory*), pending prioritization of resources.

5.4 Agricultural Soil Management (CRT Source Category 3D)

Nitrous oxide is naturally produced in soils through the microbial processes of nitrification and denitrification that is driven by the availability of mineral nitrogen (N) (Firestone and Davidson 1989).[13] Mineral nitrogen is made available in soils through decomposition of soil organic matter and plant litter, as well as asymbiotic fixation of nitrogen from the atmosphere.[14] Several agricultural activities increase mineral nitrogen availability in soils that lead to direct N_2O emissions at the site of a management activity (see Figure 5-4) (Mosier et al. 1998). These activities include synthetic nitrogen fertilization; application of managed livestock manure; application of other organic materials such as biosolids (i.e., treated sewage sludge); deposition of manure on soils by domesticated animals in pastures, range, and paddocks (PRP) (i.e., unmanaged manure); retention of crop residues (nitrogen-fixing legumes and non-legume crops and forages); and drainage of organic soils[15] (i.e., Histosols) (IPCC 2006). Additionally, agricultural soil management activities, including irrigation, drainage, tillage practices, cover crops, and fallowing of land, can influence nitrogen mineralization from soil organic matter and levels of asymbiotic nitrogen fixation. Indirect emissions of N_2O occur when nitrogen is transported from a site and is subsequently converted to N_2O; there are two pathways for indirect emissions: (1) volatilization and subsequent atmospheric deposition of applied/mineralized nitrogen, and (2) surface runoff and leaching of applied/mineralized nitrogen

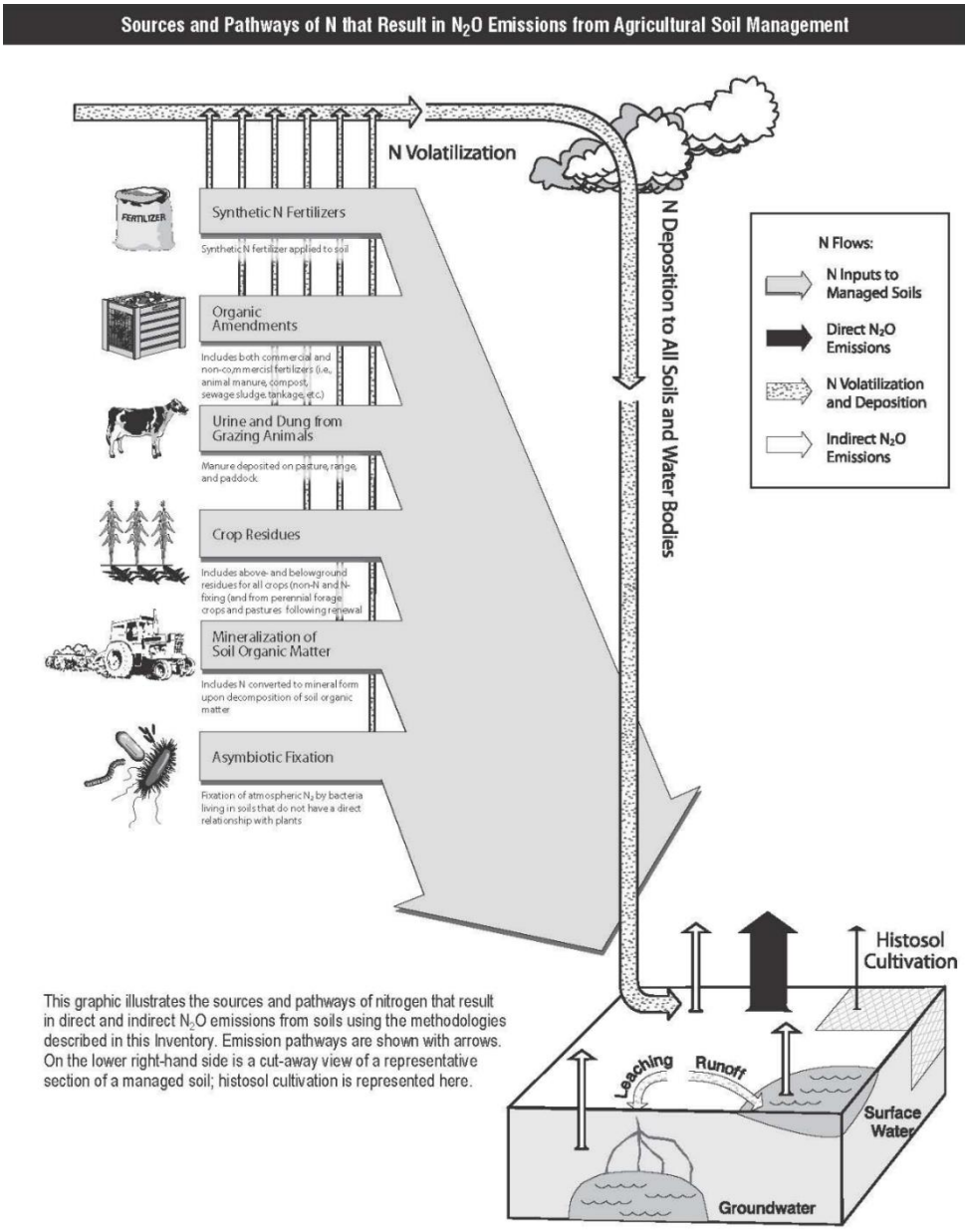
[13] Nitrification and denitrification are driven by the activity of microorganisms in soils. Nitrification is the aerobic microbial oxidation of ammonium (NH_4^+) to nitrate (NO_3^-), and denitrification is the anaerobic microbial reduction of nitrate to N_2. Nitrous oxide is a gaseous intermediate product in the reaction sequence of nitrification and denitrification.

[14] Asymbiotic nitrogen fixation is the fixation of atmospheric N_2 by bacteria living in soils that do not have a direct relationship with plants.

[15] Drainage of organic soils in former wetlands enhances mineralization of nitrogen-rich organic matter, thereby increasing N_2O emissions from these soils.

into groundwater and surface water.[16] Direct and indirect emissions from agricultural lands are included in this section (i.e., cropland and grassland as defined in Section 6.1). Nitrous oxide emissions from forest land and settlements soils are found in Sections 6.2 and 6.10, respectively.

Figure 5-4: Sources and Pathways of Nitrogen that Result in N_2O Emissions from Agricultural Soil Management



[16] These processes entail volatilization of applied or mineralized nitrogen as NH_3 and NO_x, transformation of these gases in the atmosphere (or upon deposition), and deposition of the nitrogen primarily in the form of particulate NH_4^+, nitric acid (HNO_3), and NO_x. In addition, hydrological processes lead to leaching and runoff of NO_3^- that is converted to N_2O in aquatic systems, e.g., wetlands, rivers, streams and lakes. Note: N_2O emissions are not estimated for aquatic systems associated with nitrogen inputs from terrestrial systems in order to avoid double-counting.

Agricultural soils produce the majority of N_2O emissions in the United States. Estimated emissions in 2022 are 290.8 MMT CO_2 Eq. (1,097 kt) (see Table 5-15 and Table 5-16). Annual N_2O emissions from agricultural soils are 3.2 percent greater in 2022 compared to 1990, but emissions fluctuated between 1990 and 2022 due to inter-annual variability largely associated with weather patterns, synthetic fertilizer use, and crop production. From 1990 to 2022, cropland accounted for 68 percent of total direct emissions on average from agricultural soil management, while grassland accounted for 32 percent. On average, 79 percent of indirect emissions are from croplands and 21 percent from grasslands. Estimated direct and indirect N_2O emissions by sub-source category are shown in Table 5-17 and Table 5-18.

Table 5-15: N_2O Emissions from Agricultural Soils (MMT CO_2 Eq.)

Activity	1990	2005	2018	2019	2020	2021	2022
Direct	**258.8**	**265.6**	**298.3**	**280.9**	**262.8**	**267.7**	**262.5**
Cropland	174.9	180.6	208.9	193.4	182.4	184.3	180.3
Grassland	83.9	85.1	89.4	87.5	80.3	83.4	82.1
Indirect	**29.9**	**28.4**	**35.1**	**34.7**	**29.4**	**30.3**	**28.3**
Cropland	23.6	22.3	28.1	28.0	23.3	24.1	22.2
Grassland	6.4	6.1	7.0	6.8	6.1	6.2	6.1
Total	**288.8**	**294.1**	**333.4**	**315.6**	**292.1**	**298.0**	**290.8**

Notes: Estimates for 2021 to 2022 are based on a data splicing method, except for other organic nitrogen amendments that are based on a data splicing method for 2018 to 2022 (see Methodology section). Totals may not sum due to independent rounding.

Table 5-16: N_2O Emissions from Agricultural Soils (kt N_2O)

Activity	1990	2005	2018	2019	2020	2021	2022
Direct	**977**	**1,002**	**1,126**	**1,060**	**992**	**1,010**	**990**
Cropland	660.0	681.4	788.3	729.9	688.5	695.4	680.6
Grassland	316.7	321.1	337.4	330.0	303.1	314.6	309.9
Indirect	**113**	**107**	**133**	**131**	**111**	**114**	**107**
Cropland	89.0	84.2	106.2	105.6	88.0	91.1	83.9
Grassland	24.0	23.1	26.4	25.5	22.9	23.3	22.9
Total	**1,090**	**1,110**	**1,258**	**1,191**	**1,102**	**1,124**	**1,097**

Notes: Estimates for 2021 to 2022 are based on a data splicing method, except for other organic nitrogen amendments that are based on a data splicing method for 2018 to 2022 (see Methodology section). Totals may not sum due to independent rounding.

Table 5-17: Direct N_2O Emissions from Agricultural Soils by Land Use Type and Nitrogen Input Type (MMT CO_2 Eq.)

Activity	1990	2005	2018	2019	2020	2021	2022
Cropland	**174.9**	**180.6**	**208.9**	**193.4**	**182.4**	**184.3**	**180.3**
Mineral Soils	**171.5**	**177.3**	**205.9**	**190.5**	**179.5**	**181.4**	**177.4**
Synthetic Fertilizer	61.0	64.3	70.3	65.7	63.2	63.4	62.0
Organic Amendment[a]	11.5	12.7	14.7	14.6	14.4	14.7	14.6
Residue N[b]	34.1	35.0	39.6	34.5	37.6	33.2	32.4
Mineralization and Asymbiotic Fixation	64.8	65.3	81.3	75.7	64.3	70.1	68.4
Drained Organic Soils	3.4	3.2	3.0	2.9	2.9	2.9	2.9
Grassland	**83.9**	**85.1**	**89.4**	**87.5**	**80.3**	**83.4**	**82.1**
Mineral Soils	**81.6**	**82.8**	**87.2**	**85.2**	**78.1**	**81.1**	**79.8**
Synthetic Fertilizer	+	+	+	+	+	+	+
PRP Manure	15.4	14.2	14.0	13.6	13.3	13.9	13.8
Managed Manure[c]	+	+	+	+	+	+	+

Biosolids (i.e., treated Sewage Sludge)	0.2	0.4	0.4	0.4	0.4	0.4	0.4
Residue N[d]	27.1	28.4	28.0	28.3	28.2	26.3	25.9
Mineralization and Asymbiotic Fixation	38.9	39.8	44.8	42.9	36.2	40.5	39.8
Drained Organic Soils	2.3	2.2	2.2	2.2	2.2	2.3	2.3
Total	**258.8**	**265.6**	**298.3**	**280.9**	**262.8**	**267.7**	**262.5**

+ Does not exceed 0.05 MMT CO_2 Eq.

[a] Organic amendment inputs include managed manure, daily spread manure, and commercial organic fertilizers (i.e., dried blood, dried manure, tankage, compost, and other).

[b] Cropland residue nitrogen inputs include nitrogen in unharvested cover crops as well as harvested crops.

[c] Managed manure inputs include managed manure and daily spread manure amendments that are applied to grassland soils.

[d] Grassland residue nitrogen inputs include residual biomass, both legumes and grasses, that is ungrazed and becomes dead organic matter.

Notes: Estimates for 2021 to 2022 are based on a data splicing method, except for other organic nitrogen amendments that are based on a data splicing method for 2018 to 2022 (see Methodology section). Totals may not sum due to independent rounding.

Table 5-18: Indirect N_2O Emissions from Agricultural Soils (MMT CO_2 Eq.)

Activity	1990	2005	2018	2019	2020	2021	2022
Cropland	**23.6**	**22.3**	**28.1**	**28.0**	**23.3**	**24.1**	**22.2**
Volatilization & Atm. Deposition	6.6	7.0	7.9	7.1	7.5	7.4	7.3
Surface Leaching & Run-Off	17.0	15.3	20.3	20.9	15.8	16.7	14.9
Grassland	**6.4**	**6.1**	**7.0**	**6.8**	**6.1**	**6.2**	**6.1**
Volatilization & Atm. Deposition	3.4	3.4	3.3	3.2	3.0	3.1	3.2
Surface Leaching & Run-Off	2.9	2.7	3.7	3.6	3.1	3.0	2.9
Total	**29.9**	**28.4**	**35.1**	**34.7**	**29.4**	**30.3**	**28.3**

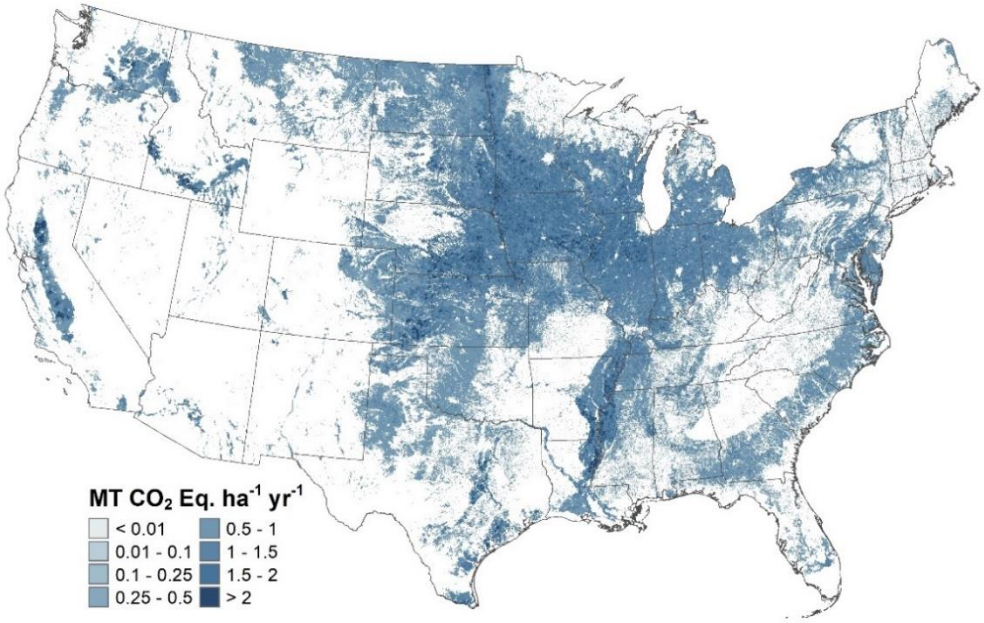
Notes: Estimates for 2021 to 2022 are based on a data splicing method, except for other organic nitrogen amendments that are based on a data splicing method for 2018 to 2022 (see Methodology section). Totals may not sum due to independent rounding.

Figure 5-5 and Figure 5-6 show regional patterns for direct N_2O emissions. Figure 5-7 and Figure 5-8 show indirect N_2O emissions from volatilization, and Figure 5-9 and Figure 5-10 show the indirect N_2O emissions from leaching and runoff in croplands and grasslands, respectively.

Direct N_2O emissions from croplands occur throughout all of the cropland regions but tend to be high in the Midwestern Corn Belt Region (particularly, Illinois, Iowa, Kansas, Minnesota, Nebraska), where a large portion of the land is used for growing highly fertilized corn and nitrogen-fixing soybean crops (see Figure 5-5). There are high emissions from the Southeastern region, and portions of the Great Plains. Emissions are also high in the Lower Mississippi River Basin from Missouri to Louisiana, and highly productive irrigated areas, such as Platte River, which flows from Colorado and Wyoming through Nebraska, Snake River Valley in Idaho, and the Central Valley in California. Direct emissions from croplands are low in mountainous regions of the Eastern United States because only a small portion of land is cultivated, and in much of the Western United States where rainfall and access to irrigation water are limited, in addition to mountainous, which are generally not suitable for crop production.

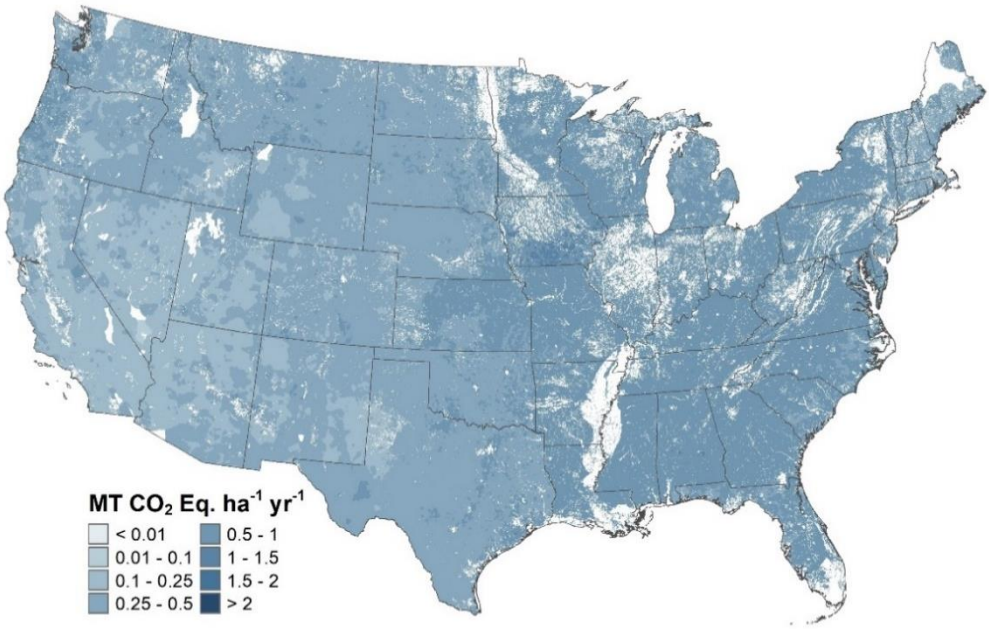
Direct N_2O emissions from grasslands are more evenly distributed throughout the United States compared to emissions from cropland due to suitable areas for grazing in most regions (see Figure 5-6). Total emissions tend be highest in the Great Plains and western United States where a large proportion of the land is dominated by grasslands with cattle and sheep grazing (particularly Kansas, Montana, Nebraska, New Mexico, Oklahoma, South Dakota, Texas).

Figure 5-5: Croplands, 2020 Annual Direct N_2O Emissions Estimated Using the Tier 3 DayCent Model



Note: Only national-scale emissions are estimated for 2022 using a splicing method, and therefore the fine-scale emission patterns in this map are based on *Inventory* data from 2020.

Figure 5-6: Grasslands, 2020 Annual Direct N_2O Emissions Estimated Using the Tier 3 DayCent Model

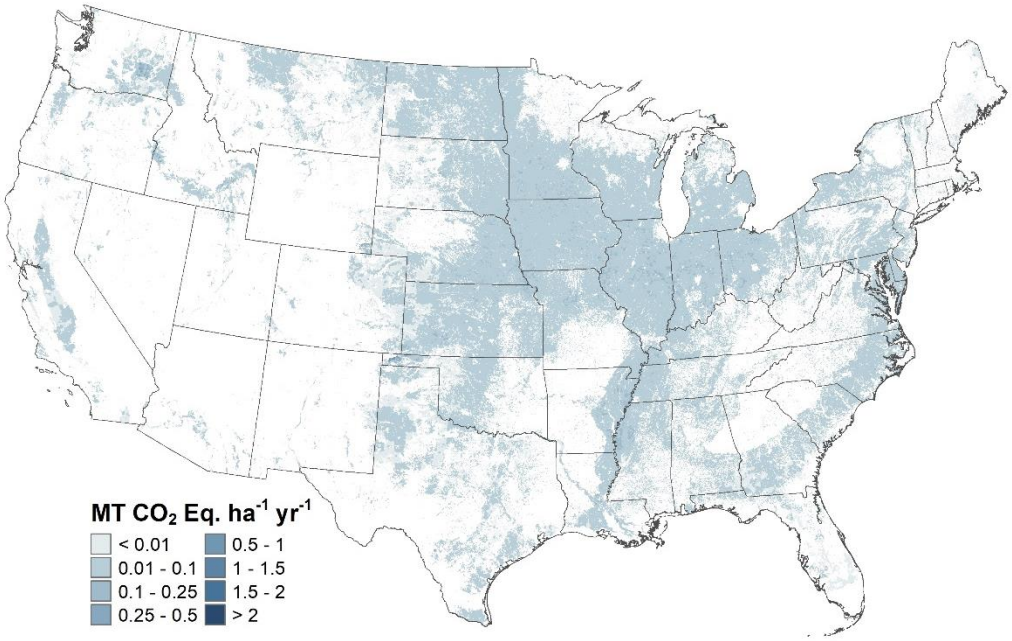


Note: Only national-scale emissions are estimated for 2022 using a splicing method, and therefore the fine-scale emission patterns in this map are based on *Inventory* data from 2020.

Indirect N_2O emissions from volatilization in croplands have a similar pattern as the direct N_2O emissions with higher emissions in the Midwestern Corn Belt, Lower Mississippi River Basin, Southeastern region, and parts of the Great Plains and irrigated areas of the Western United States. Indirect N_2O emissions from volatilization in grasslands are higher in the Eastern and Central United States, along with relatively small areas scattered around the Western United States. The higher emissions are partly due to large additions of PRP manure nitrogen, which in turn, stimulates NH_3 volatilization.

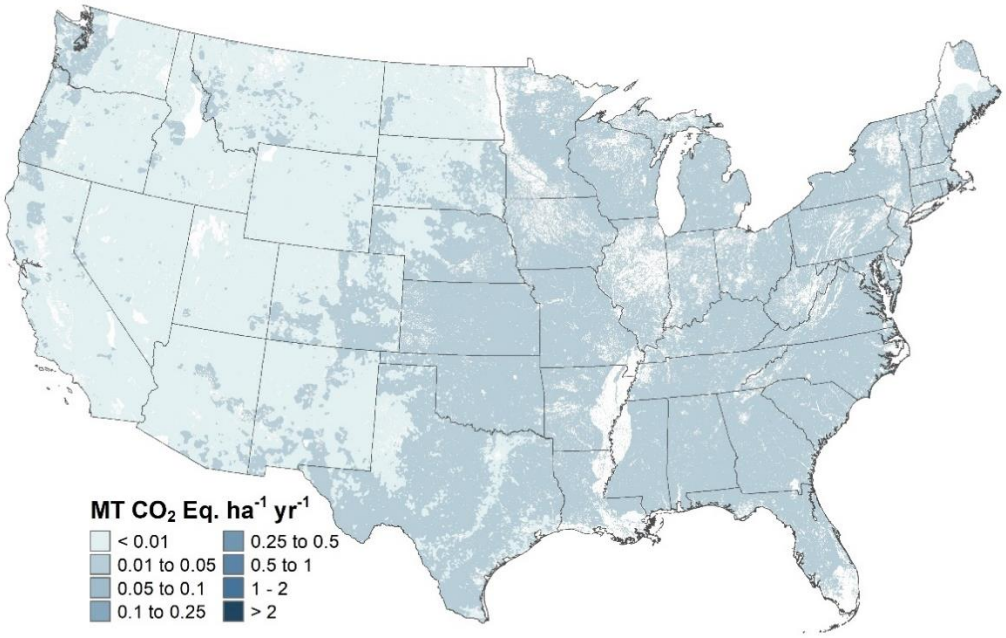
Indirect N_2O emissions from surface runoff and leaching of applied/mineralized nitrogen in croplands is highest in the Midwestern Corn Belt. There are also relatively high emissions associated with nitrogen management in the Lower Mississippi River Basin, Piedmont region of the Southeastern United States and the Mid-Atlantic states. In addition, areas of high emissions occur in portions of the Great Plains that have irrigated croplands with high leaching rates of applied/mineralized nitrogen. Indirect N_2O emissions from surface runoff and leaching of applied/mineralized nitrogen in grasslands are higher in the eastern United States and coastal Northwest region. These regions have greater precipitation and higher levels of leaching and runoff compared to arid to semi-arid regions in the Western United States.

Figure 5-7: Croplands, 2020 Annual Indirect N_2O Emissions from Volatilization Using the Tier 3 DayCent Model



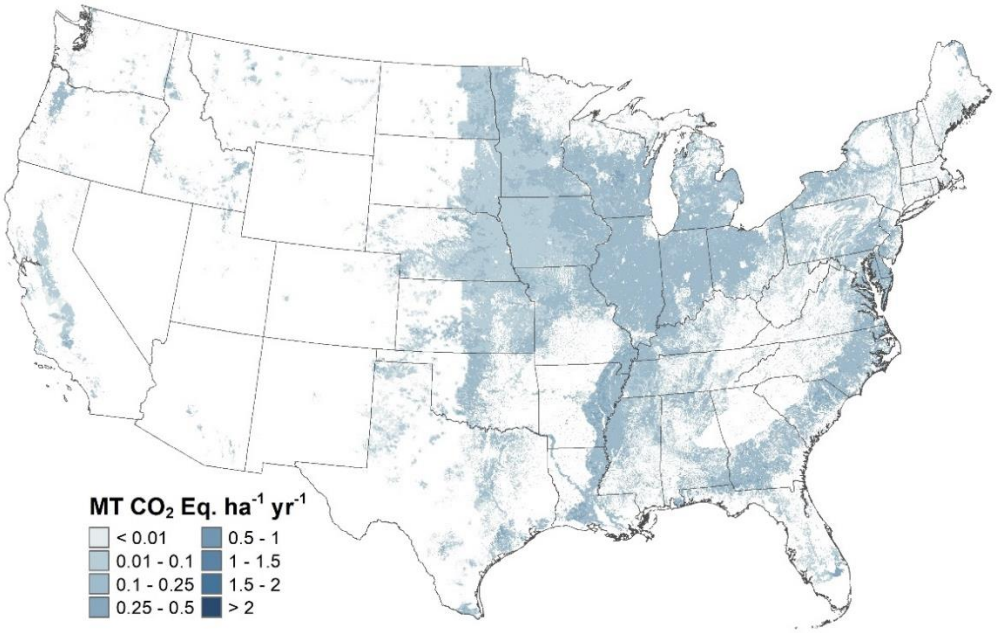
Note: Only national-scale emissions are estimated for 2022 using a splicing method, and therefore the fine-scale emission patterns in this map are based on *Inventory* data from 2020.

Figure 5-8: Grasslands, 2020 Annual Indirect N_2O Emissions from Volatilization Using the Tier 3 DayCent Model



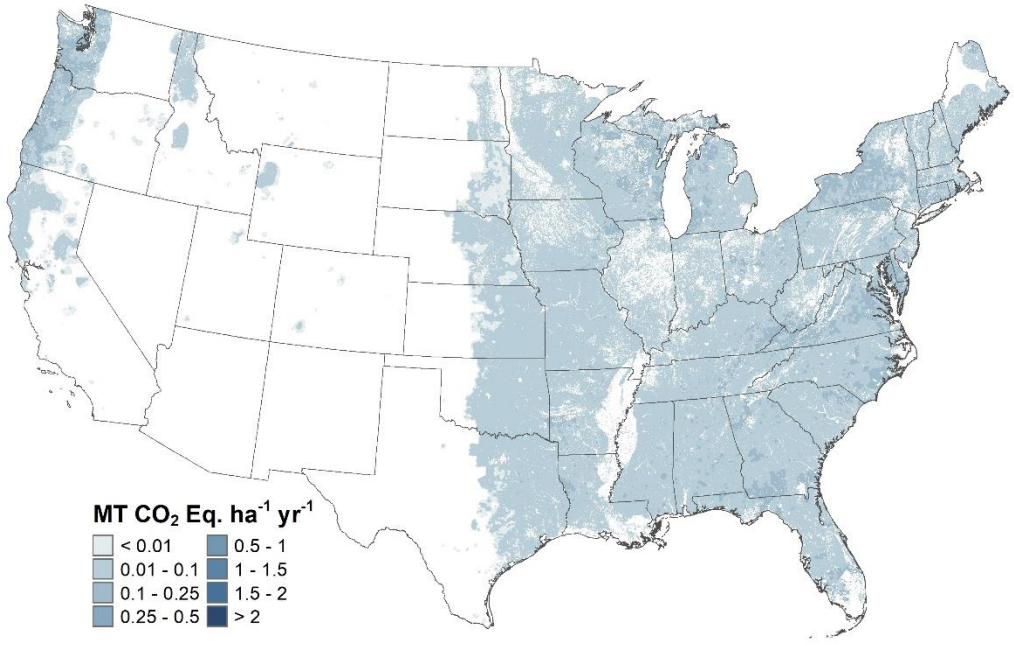
Note: Only national-scale emissions are estimated for 2022 using a splicing method, and therefore the fine-scale emission patterns in this map are based on *Inventory* data from 2020.

Figure 5-9: Croplands, 2020 Annual Indirect N_2O Emissions from Leaching and Runoff Using the Tier 3 DayCent Model



Note: Only national-scale emissions are estimated for 2022 using a splicing method, and therefore the fine-scale emission patterns in this map are based on *Inventory* data from 2020.

Figure 5-10: Grasslands, 2020 Annual Indirect N_2O Emissions from Leaching and Runoff Using the Tier 3 DayCent Model



Note: Only national-scale emissions are estimated for 2022 using a splicing method, and therefore the fine-scale emission patterns in this map are based on *Inventory* data from 2020.

Methodology and Time-Series Consistency

The *2006 IPCC Guidelines* (IPCC 2006) divide emissions from the agricultural soil management source category into five components, including (1) direct emissions from nitrogen additions to cropland and grassland mineral soils from synthetic fertilizers, biosolids (i.e., treated sewage sludge), crop residues (legume nitrogen-fixing and non-legume crops), and organic amendments; (2) direct emissions from soil organic matter mineralization due to land use and management change; (3) direct emissions from drainage of organic soils in croplands and grasslands; (4) direct emissions from soils due to manure deposited by livestock on PRP grasslands; and (5) indirect emissions from soils and water from nitrogen additions and manure deposition to soils that lead to volatilization, leaching, or runoff of nitrogen and subsequent conversion to N_2O.

In this source category, the United States reports on all croplands, as well as all managed grasslands, whereby anthropogenic greenhouse gas emissions are estimated in a manner consistent with the managed land concept (IPCC 2006), including direct and indirect N_2O emissions from asymbiotic fixation[17] and mineralization of nitrogen associated with decomposition of soil organic matter and residues. One recommendation from IPCC (2006) that has not been completely adopted is the estimation of emissions from grassland pasture renewal, which involves occasional plowing to improve forage production in pastures. Currently no data are available to address pasture renewal.

In addition, estimates of N_2O emissions from managed croplands and grasslands are not available for Alaska and Hawaii except for managed manure and PRP nitrogen, and biosolid additions for Alaska, and managed manure and

[17] Nitrogen inputs from asymbiotic nitrogen fixation are not directly addressed in *2006 IPCC Guidelines* but are a component of the nitrogen inputs and total emissions from managed lands and are included in the Tier 3 approach developed for this source.

PRP nitrogen, biosolids additions, and crop residue for Hawaii. There is a planned improvement to include the additional sources of emissions in a future *Inventory*.

Direct N_2O Emissions

The methodology used to estimate direct N_2O emissions from agricultural soil management in the United States is based on a combination of IPCC Tier 1 and 3 approaches, along with application of a splicing method for latter years in the *Inventory* time series (IPCC 2006; Del Grosso et al. 2010). A Tier 3 process-based model (DayCent) is used to estimate direct emissions from a variety of crops that are grown on mineral (i.e., non-organic) soils, as well as the direct emissions from non-federal grasslands except for applications of biosolids (i.e., treated sewage sludge) (Del Grosso et al. 2010). The Tier 3 approach has been specifically designed and tested to estimate N_2O emissions in the United States, accounting for more of the environmental and management influences on soil N_2O emissions than the IPCC Tier 1 method (see Box 5-3 for further elaboration). Moreover, the Tier 3 approach addresses direct N_2O emissions and soil carbon stock changes from mineral cropland soils in a single analysis. Carbon and nitrogen dynamics are linked in plant-soil systems through biogeochemical processes of microbial decomposition and plant production (McGill and Cole 1981). Coupling the two source categories (i.e., agricultural soil carbon and N_2O) in a single inventory analysis ensures that there is consistent activity data and treatment of the processes, and interactions are considered between carbon and nitrogen cycling in soils.

Crop and land use histories are based on the USDA National Resources Inventory (NRI) (USDA-NRCS 2020) and extended through 2020 using the USDA-NASS Crop Data Layer Product (USDA-NASS 2021; Johnson and Mueller 2010). The areas have been modified in the original NRI survey through a process in which the Forest Inventory and Analysis (FIA) survey data and the National Land Cover Dataset (Yang et al. 2018) are harmonized with the NRI data (Nelson et al. 2020). This process ensures that the land use areas are consistent across all land use categories (see Section 6.1).

The NRI is a statistically-based sample and includes 364,333 survey locations on agricultural land for the conterminous United States that are included in the Tier 3 method. The Tier 1 approach is used to estimate the emissions from an annual average of 239,757 locations in the NRI survey across the time series, which are designated as cropland or grassland (discussed later in this section). The Tier 1 method is used to estimate emissions for components that are not simulated by DayCent. DayCent has not been parametrized to simulate some crop types and soil types, as described below. Each survey location is associated with a survey weight that allows scaling of N_2O emissions from NRI survey locations to the entire country (i.e., each survey weight is an approximation of the amount of area with the same land-use/management history as the survey location). Each NRI survey location was sampled on a 5-year cycle from 1982 until 1997. For cropland, data were collected in 4 out of 5 years in the cycle (i.e., 1979 through 1982, 1984 through 1987, 1989 through 1992, and 1994 through 1997). In 1998, the NRI program began collecting annual data, which are currently available through 2017 (USDA-NRCS 2020). For 2018-2020, the time series is extended with the crop data provided in USDA-NASS CDL (USDA-NASS 2021). CDL data have a 30 to 58 m spatial resolution, depending on the year. Specifically, NRI survey locations are overlaid on the CDL in a geographic information system, and the crop types are extracted to extend the cropping histories for the inventory analysis.

Box 5-3: Tier 1 vs. Tier 3 Approach for Estimating N_2O Emissions

The IPCC (2006) Tier 1 approach is based on multiplying activity data on different nitrogen inputs (i.e., synthetic fertilizer, manure, nitrogen fixation, etc.) by the appropriate default IPCC emission factors to estimate N_2O emissions on an input-by-input basis. The Tier 1 approach requires a minimal amount of activity data, readily available in most countries (e.g., total nitrogen applied to crops); calculations are simple; and the methodology is highly transparent. In contrast, the Tier 3 approach developed for this *Inventory* is based on application of a process-based model (i.e., DayCent) that represents the interaction of nitrogen inputs, land use and management, as well as environmental conditions at specific locations, such as freeze-thaw effects that generate pulses of N_2O emissions (Wagner-Riddle et al. 2017; Del Grosso et al. 2022). Consequently, the Tier 3 approach accounts for land-use and management impacts and their interaction with environmental factors,

such as weather patterns and soil characteristics, in a more comprehensive manner, which will enhance or dampen anthropogenic influences. However, the Tier 3 approach requires more detailed activity data (e.g., crop-specific nitrogen fertilization rates), additional data inputs (e.g., daily weather, soil types), and considerable computational resources and programming expertise. The Tier 3 methodology is less transparent, and thus it is critical to evaluate the output of Tier 3 methods against measured data in order to demonstrate that the method is an improvement over lower tier methods for estimating emissions (IPCC 2006). Another important difference between the Tier 1 and Tier 3 approaches relates to assumptions regarding nitrogen cycling. Tier 1 assumes that nitrogen added to a system is subject to N_2O emissions only during that year and cannot be stored in soils and contribute to N_2O emissions in subsequent years. This is a simplifying assumption that may create bias in estimated N_2O emissions for a specific year. In contrast, the process-based model in the Tier 3 approach includes the legacy effect of nitrogen added to soils in previous years that is re-mineralized from soil organic matter and emitted as N_2O during subsequent years.

DayCent is used to estimate N_2O emissions associated with production of alfalfa hay, barley, corn, cotton, dry beans, grass hay, grass-clover hay, lentils, oats, onions, peanuts, peas, potatoes, rice, sorghum, soybeans, sugar beets, sunflowers, sweet potatoes, tobacco, tomatoes, and wheat, but is not applied to estimate N_2O emissions from other crops or rotations with other crops,[18] such as sugarcane, some vegetables, and perennial/horticultural crops. Areas that are converted between agriculture (i.e., cropland and grassland) and other land uses, such as forest land, wetland and settlements, are not simulated with DayCent. DayCent is also not used to estimate emissions from land areas with very gravelly, cobbly, or shaley soils in the topsoil (greater than 35 percent by volume in the top 30 cm of the soil profile), or to estimate emissions from drained organic soils (*Histosols*). The Tier 3 method has not been fully tested for estimating N_2O emissions associated with these crops and rotations, land uses, as well as organic soils or cobbly, gravelly, and shaley mineral soils. In addition, federal grassland areas are not simulated with DayCent due to limited activity data on land use histories. For areas that are not included in the DayCent simulations, Tier 1 methods are used to estimate emissions, including (1) direct emissions from nitrogen inputs for crops on mineral soils that are not simulated by DayCent; (2) direct emissions from PRP nitrogen additions on federal grasslands; (3) direct emissions for land application of biosolids (i.e., treated sewage sludge) to soils; and (4) direct emissions from drained organic soils in croplands and grasslands.

A splicing method is used to estimate soil N_2O emissions for 2021 to 2022 at the national scale because new activity data have not been incorporated into the analysis for those years. Specifically, linear regression models with autoregressive moving-average (ARMA) errors (Brockwell and Davis 2016) are used to estimate the relationship between surrogate data and the 1990 to 2020 emissions that are derived using the Tier 3 method. Surrogate data for these regression models includes corn and soybean yields from USDA-NASS statistics,[19] and weather data from the PRISM Climate Group (PRISM 2022). For the Tier 1 method, a linear-time series model is used to estimate emissions for 2021-2022 without surrogate data. In addition, the linear time series model is used to estimate emissions data for 2018 to 2022 for other organic nitrogen amendments (i.e., commercial organic fertilizer) due to a gap in the activity data during the latter part of the time series (TVA 1991 through 1994; AAPFCO 1995 through 2022). See Box 5-4 for more information about the splicing method. Emission estimates for years with imputed data will be recalculated in future *Inventory* reports when new NRI data and other organic amendment nitrogen data are available.

[18] A small proportion of the major commodity crop production, such as corn and wheat, is included in the Tier 1 analysis because these crops are rotated with other crops or land uses (e.g., forest lands) that are not simulated by DayCent.

[19] See https://quickstats.nass.usda.gov/.

Box 5-4: Data Splicing Method

An approach to extend the time series is needed for agricultural soil management because there are typically activity data gaps at the end of the time series. This is mainly because the NRI survey program, which provides critical information for estimating greenhouse gas emissions and removals, does not release data every year.

Splicing methods have been used to impute missing data at the end of the emission time series for both the Tier 1 and 3 methods. Specifically, a linear regression model with autoregressive moving-average (ARMA) errors (Brockwell and Davis 2016) is used to estimate emissions based on the emissions data that has been compiled using the inventory methods described in this section. The model to extend the time series is given by the equation:

$$Y = X\beta + \varepsilon,$$

where Y is the response variable (e.g., soil nitrous oxide), Xβ for the Tier 3 method contains specific surrogate data depending on the response variable, and ε is the remaining unexplained error. Models with a variety of surrogate data were tested, including commodity statistics, weather data, or other relevant information. The term Xβ for the Tier 1 method only contains year as a predictor of emission patterns over the time series (change in emissions per year), and therefore, is a linear time series model with no surrogate data. Parameters are estimated using standard statistical techniques, and used in the model described above to predict the missing emissions data.

A critical issue with splicing methods is to account for the additional uncertainty introduced by predicting emissions without compiling the full inventory. Specifically, uncertainty will increase for years with imputed estimates based on the splicing methods, compared to those years in which the full inventory is compiled. This additional uncertainty is quantified within the model framework using a Monte Carlo approach. Consequently, the uncertainty from the original inventory data is combined with the uncertainty in the data splicing model. The approach requires estimating parameters in the data splicing models in each Monte Carlo simulation for the full inventory (i.e., the surrogate data model is refit with the draws of parameters values that are selected in each Monte Carlo iteration, and used to produce estimates with inventory data). Therefore, the data splicing method generates emissions estimates from each surrogate data model in the Monte Carlo analysis, which are used to derive confidence intervals in the estimates for the missing emissions data. Furthermore, the 95 percent confidence intervals are estimated using the 3 sigma rules assuming a unimodal density (Pukelsheim 1994).

Tier 3 Approach for Mineral Cropland Soils

The DayCent biogeochemical model (Parton et al. 1998; Del Grosso et al. 2001 and 2011) is used to estimate direct N_2O emissions from mineral cropland soils that are managed for production of a wide variety of crops (see list in previous section) based on the crop histories in the 2017 NRI (USDA-NRCS 2020) and extended through 2020 using CDL (USDA-NASS 2021). Crops simulated by DayCent are grown on approximately 85 percent of total cropland area in the United States. The model simulates net primary productivity (NPP) using the NASA-CASA production algorithm MODIS Enhanced Vegetation Index (EVI) products, MOD13Q1 and MYD13Q1[20] (Potter et al. 1993, 2007). The model simulates soil temperature and water dynamics, using daily weather data from a 4-kilometer gridded product developed by the PRISM Climate Group (2022), and soil attributes from the Soil Survey Geographic

[20] Net Primary Production is estimated with the NASA-CASA algorithm for most of the cropland that is used to produce major commodity crops in the central United States from 2000 to 2020. Other regions and years prior to 2000 are simulated with a method that incorporates water, temperature, and moisture stress on crop production (see Metherell et al. 1993) but does not incorporate the additional information about crop condition provided with remote sensing data.

Database (SSURGO) (Soil Survey Staff 2020). DayCent is used to estimate direct N_2O emissions due to mineral nitrogen available from the following sources: (1) application of synthetic fertilizers; (2) application of livestock manure; (3) retention of crop residues in the field for nitrogen-fixing legumes and non-legume crops and subsequent mineralization of nitrogen during microbial decomposition (i.e., leaving residues in the field after harvest instead of burning or collecting residues); (4) mineralization of nitrogen from decomposition of soil organic matter; and (5) asymbiotic fixation.

Management activity data from several sources supplement the activity data from the NRI. The USDA-NRCS Conservation Effects and Assessment Project (CEAP) provides data on a variety of cropland management activities, and is used to inform the inventory analysis about tillage practices, mineral fertilization, manure amendments, cover crop management, as well as planting and harvest dates (USDA-NRCS 2022; USDA-NRCS 2018; USDA-NRCS 2012). CEAP data are collected at a subset of NRI survey locations, and currently provide management information from approximately 2002 to 2006 and 2013 to 2016. These data are combined with other datasets in an imputation analysis. This imputation analysis is comprised of three steps: a) determine the trends in management activity across the time series by combining information from several datasets (discussed below); b) use Gradient Boosting (Friedman 2001) to determine the likely management practice at a given NRI survey location; and c) assign management practices from the CEAP survey to the specific NRI locations using a predictive mean matching method for certain variables that are adapted to reflect the trending information (Little 1988, van Buuren 2012). Gradient boosting is a machine learning technique used in regression and classification tasks, among others. It combines predictions from multiple weak prediction models and outperforms many complicated machine learning algorithms. It makes the best predictions at specific NRI survey locations or at state or region level models. The predictive mean matching method identifies the most similar management activity recorded in the CEAP surveys that match the prediction from the gradient boosting algorithm. The matching ensures that imputed management activities are realistic for each NRI survey location, and not odd or physically unrealizable results that could be generated by the gradient boosting. There are six complete imputations of the management activity data using these methods.

To determine trends in mineral fertilization and manure amendments, CEAP data are combined with information on fertilizer use and rates by crop type for different regions of the United States from the USDA Economic Research Service. The data collection program was known as the Cropping Practices Surveys through 1995 (USDA-ERS 1997), and is now part of data collection known as the Agricultural Resource Management Surveys (ARMS) (USDA-ERS 2020). Additional data on fertilization practices are compiled through other sources particularly the National Agricultural Statistics Service (USDA-NASS 1992, 1999, 2004). To determine the trends in tillage management, CEAP data are combined with Conservation Technology Information Center data between 1989 and 2004 (CTIC 2004) and OpTIS Data Product[21] for 2008 to 2020 (Hagen et al. 2020). The CTIC data are adjusted for long-term adoption of no-till agriculture (Towery 2001). For cover crops, CEAP data are combined with information from USDA Census of Agriculture (USDA-NASS 2012, 2017) and the OpTIS[22] data (Hagen et al. 2020). It is assumed that cover crop management was minimal prior to 1990 and the rates increased linearly over the decade to the levels of cover crop management in the CEAP survey.

The IPCC method considers crop residue nitrogen inputs and nitrogen mineralized from soil organic matter as activity data. However, they are not treated as activity data in DayCent simulations because residue production, symbiotic nitrogen fixation (e.g., legumes), mineralization of nitrogen from soil organic matter, and asymbiotic nitrogen fixation are internally generated by the model as part of the simulation. In other words, DayCent accounts for the influence of symbiotic nitrogen fixation, mineralization of nitrogen from soil organic matter and crop residue retained in the field, and asymbiotic nitrogen fixation on N_2O emissions, but these are not model inputs.

The N_2O emissions from crop residues are reduced by approximately 3 percent (the assumed average burned portion for crop residues in the United States) to avoid double counting associated with non-CO_2 greenhouse gas

[21] OpTIS data on tillage practices provided by Regrow Agriculture, Inc.

[22] OpTIS data on cover crop management provided by Regrow Agriculture, Inc.

emissions from agricultural residue burning. Estimated levels of residue burning are based on state inventory data (ILENR 1993; Oregon Department of Energy 1995; Noller 1996; Wisconsin Department of Natural Resources 1993; Cibrowski 1996).

Uncertainty in the emission estimates from DayCent is associated with input uncertainty due to missing management data in the NRI survey that is imputed from other sources; model uncertainty due to incomplete specification of carbon and nitrogen dynamics in the DayCent model parameters and algorithms; and sampling uncertainty associated with the statistical design of the NRI survey. Uncertainty is estimated with two variance components (Ogle et al. 2010). The first variance component quantifies the uncertainty in management activity data, model structure and parameterization. To assess this uncertainty, carbon and nitrogen dynamics at each NRI survey location are simulated six times using the imputation product and other model driver data. Uncertainty in parameterization and model algorithms are determined using a structural uncertainty estimator derived from fitting a linear mixed-effect model (Ogle et al. 2007; Del Grosso et al. 2010). The data is combined in a Monte Carlo stochastic simulation with 1,000 iterations for 1990 through 2020. For each iteration, there is a random selection of management data from the imputation product (select one of the six imputations), and random selection of parameter values and random effects for the linear mixed-effect model (i.e., structural uncertainty estimator). The second variance component quantifies uncertainty in scaling from the NRI survey to the entire land base. The second variance component is computed using the replicate weights provided with the NRI survey data, and a standard variance estimator for a two-stage sample design (Särndal et al. 1992). The two variance components are summed to quantify the total uncertainty and produce confidence intervals associated with the estimated emissions.

In order to ensure time-series consistency, the DayCent model is applied from 1990 to 2020, and a linear extrapolation method is used to approximate emissions for 2021 to 2022 based on the pattern in emissions data from 1990 to 2020 (see Box 5-4). The pattern is determined using a linear regression model with moving-average (ARMA) errors. Linear extrapolation is a standard data splicing method for approximating missing values at the end of an inventory time series (IPCC 2006). The time series will be updated with the Tier 3 method in the future as new activity data are incorporated into the analysis.

Nitrous oxide emissions from managed agricultural lands are the result of interactions among anthropogenic activities (e.g., nitrogen fertilization, manure application, tillage) and other driving variables, such as weather and soil characteristics. These factors influence key processes associated with nitrogen dynamics in the soil profile, including immobilization of nitrogen by soil microbial organisms, decomposition of organic matter, plant uptake, leaching, runoff, and volatilization, as well as the processes leading to N_2O production (nitrification and denitrification). It is not possible to partition N_2O emissions into each anthropogenic activity directly from model outputs due to the complexity of the interactions (e.g., N_2O emissions from synthetic fertilizer applications cannot be distinguished from those resulting from manure applications). To approximate emissions by activity, the amount of synthetic nitrogen fertilizer added to the soil, or mineral nitrogen made available through decomposition of soil organic matter and plant litter, as well as asymbiotic fixation of nitrogen from the atmosphere, is determined for each nitrogen source and then divided by the total amount of mineral nitrogen in the soil according to the DayCent model simulation. For 2021 to 2022, the contribution of each nitrogen source is based on the average of values that are estimated for 2018 to 2020. The percentages are then multiplied by the total of direct N_2O emissions in order to approximate the portion attributed to nitrogen management practices. This approach is only an approximation because it assumes that all nitrogen made available in soil has an equal probability of being released as N_2O, regardless of its source, which is unlikely to be the case (Delgado et al. 2009). However, this approach allows for further disaggregation of emissions by source of nitrogen, which is valuable for reporting purposes and is analogous to the reporting associated with the IPCC (2006) Tier 1 method, in that it associates portions of the total soil N_2O emissions with individual sources of nitrogen.

Tier 1 Approach for Mineral Cropland Soils

The IPCC (2006) Tier 1 methodology is used to estimate direct N_2O emissions for mineral cropland soils that are not simulated by DayCent (e.g., DayCent has not been parametrized to simulate all crop types and some soil types such

as *Histosols*). For the Tier 1 method, estimates of direct N_2O emissions from nitrogen applications are based on mineral soil N that is made available from the following practices: (1) the application of synthetic commercial fertilizers; (2) application of managed manure and non-manure commercial organic fertilizers; and (3) decomposition and mineralization of nitrogen from above- and below-ground crop residues in agricultural fields (i.e., crop biomass that is not harvested). Non-manure commercial organic amendments are only included in the Tier 1 analysis because these data are not available at the county-level, which is necessary for the DayCent simulations. Consequently, all commercial organic fertilizer, as well as manure that is not added to crops in the DayCent simulations, are included in the Tier 1 analysis. The following sources are used to derive activity data:

- A process-of-elimination approach is used to estimate synthetic nitrogen fertilizer additions for crop areas that are not simulated by DayCent. The total amount of fertilizer used on farms has been estimated at the county-level by the USGS using sales records from 1990 to 2012 (Brakebill and Gronberg 2017). For 2013 through 2017, fertilizer sales data from AAPFCO (AAPFCO 2013 through 2022) [23] after adjusting for the proportion of on-farm application to determine the amount applied to crops. The amount of fertilizer applied after 2017 is estimated using the data splicing method described in Box 5-4 for the linear time series model. Then the portion of fertilizer applied to crops and grasslands simulated by DayCent is subtracted from the on-farm sales data (see Tier 3 Approach for mineral cropland soils and direct N_2O emissions from grassland soils sections for information on data sources), and the remainder of the total fertilizer used on farms is assumed to be applied to crops that are not simulated by DayCent. At a minimum, 3 percent of state-level on-farm fertilizer sales are assumed to be applied to cropland in the Tier 1 method.
- Similarly, a process-of-elimination approach is used to estimate manure nitrogen additions for crops that are not simulated by DayCent. The total amount of manure available for land application to soils has been estimated with methods described in the manure management section (Section 5.2) and annex (Annex 3.11). The amount of manure nitrogen applied in the Tier 3 approach to crops and grasslands is subtracted from total annual manure nitrogen available for land application (see Tier 3 Approach for mineral cropland soils and direct N_2O emissions from grassland soils sections for information on data sources). This difference is assumed to be applied to crops that are not simulated by DayCent.
- Commercial organic fertilizer additions are based on organic fertilizer consumption statistics through 2017,[24] which are converted from mass of fertilizer to units of nitrogen using average organic fertilizer nitrogen content, ranging between 2.3 to 4.2 percent across the time series (TVA 1991 through 1994; AAPFCO 1995 through 2022). Commercial fertilizers include dried manure and biosolids (i.e., treated sewage sludge), but the amounts are removed from the commercial fertilizer data to avoid double counting[25] with the manure nitrogen dataset described above and the biosolids (i.e., treated sewage sludge) amendment data discussed later in this section.
- Crop residue nitrogen is derived by combining amounts of above- and below-ground biomass, which are determined based on NRI crop area data (USDA-NRCS 2020), as extended using the CDL data (USDA-NASS 2021), crop production yield statistics (USDA-NASS 2023), dry matter fractions (IPCC 2006), linear equations to

[23] The fertilizer consumption data in AAPFCO are recorded in "fertilizer year" totals, (i.e., July to June), but are converted to calendar year totals. This is done by assuming that approximately 35 percent of fertilizer usage occurred from July to December and 65 percent from January to June (TVA 1992b).

[24] Soil N_2O emissions are imputed using data splicing methods for commercial fertilizers, i.e., other organic fertilizers, after 2017 because the activity data are not available.

[25] Commercial organic fertilizers include dried blood, tankage, compost, and other, but the dried manure and biosolids (i.e., treated sewage sludge) are also included in other datasets in this Inventory. Consequently, the proportions of dried manure and biosolids, which are provided in the reports (TVA 1991 through 1994; AAPFCO 1995 through 2022), are used to estimate the nitrogen amounts in dried manure and biosolids. To avoid double counting, the resulting nitrogen amounts for dried manure and biosolids are subtracted from the total nitrogen in commercial organic fertilizers before estimating emissions using the Tier 1 method.

estimate above-ground biomass given dry matter crop yields from harvest (IPCC 2006), ratios of below-to-above-ground biomass (IPCC 2006), and nitrogen contents of the residues (IPCC 2006). Nitrogen inputs from residue were reduced by 3 percent to account for average residue burning portions in the United States.

The total amounts of soil mineral nitrogen from applied synthetic and organic fertilizers, manure nitrogen additions and crop residues are multiplied by the IPCC (2006) default emission factor to derive an estimate of direct N_2O emissions using the Tier 1 method. Further elaboration on the methodology and data used to estimate N_2O emissions from mineral soils are described in Annex 3.12.

In order to ensure time-series consistency, the Tier 1 methods are applied from 1990 to 2020, and a linear extrapolation method[26] is used to approximate emissions for 2021 to 2022 based on the emission patterns between 1990 and 2020 (see Box 5-4). The exceptions include crop residue nitrogen which is estimating using the Tier 1 method for 1990 to 2022 with no linear extrapolation, and for other organic nitrogen fertilizers (i.e., commercial fertilizers), which are estimated with linear time series model for 2018 to 2022 due to a gap in the activity data during the latter part of the time series (TVA 1991 through 1994; AAPFCO 1995 through 2022). For the extrapolation, the emission pattern is determined using a linear regression model with moving-average (ARMA) errors. Linear extrapolation is a standard data splicing method for approximating missing values at the end of an inventory time series (IPCC 2006). As with the Tier 3 method, the time series that is based on the splicing methods will be recalculated in a future *Inventory* report with updated activity data.

Tier 1 and 3 Approaches from Mineral Grassland Soils

As with N_2O emissions from croplands, the Tier 3 process-based approach with application of the DayCent model and Tier 1 method described in IPCC (2006) are combined to estimate emissions from non-federal grasslands and PRP manure nitrogen additions for federal grasslands, respectively. Grassland includes pasture and rangeland that produce grass or mixed grass/legume forage primarily for livestock grazing. Rangelands are extensive areas of native grassland that are not intensively managed, while pastures are seeded grassland (possibly following tree removal) that may also have additional management, such as irrigation, fertilization, or inter-seeding legumes. DayCent is used to simulate N_2O emissions from NRI survey locations (USDA-NRCS 2020) on non-federal grasslands resulting from manure deposited by livestock directly onto pastures and rangelands (i.e., PRP manure), nitrogen fixation from legume seeding, managed manure amendments (i.e., manure other than PRP manure such as daily spread or manure collected from other animal waste management systems such as lagoons and digesters), and synthetic fertilizer application. Other nitrogen inputs are simulated within the DayCent framework, including nitrogen input from mineralization due to decomposition of soil organic matter and nitrogen inputs from senesced grass litter, as well as asymbiotic fixation of nitrogen from the atmosphere. The simulations used the same weather, soil, and synthetic nitrogen fertilizer data as discussed under the Tier 3 Approach in the mineral cropland soils section. Synthetic nitrogen fertilization rates are based on data from the Carbon Sequestration Rural Appraisals (CSRA) conducted by the USDA-NRCS (USDA-NRCS, unpublished data). The CSRA was a solicitation of expert knowledge from USDA-NRCS staff throughout the United States to support the *Inventory*. Biological nitrogen fixation is simulated within DayCent, and therefore is not an input to the model.

Manure nitrogen deposition from grazing animals in PRP systems (i.e., PRP manure nitrogen) is a key input of nitrogen to grasslands. The amounts of PRP manure nitrogen applied on non-federal grasslands for each NRI survey location are based on the amount of nitrogen excreted by livestock in PRP systems that is estimated in the manure management section (see Section 5.2 and Annex 3.11). The total amount of nitrogen excreted in each county is divided by the grassland area to estimate the nitrogen input rate associated with PRP manure. The resulting rates are a direct input into the DayCent simulations. The nitrogen input is subdivided between urine and dung based on a 50:50 split. DayCent simulations of non-federal grasslands accounted for approximately 71

percent of total PRP manure nitrogen in aggregate across the country.[27] The remainder of the PRP manure nitrogen in each state is assumed to be excreted on federal grasslands, and the N_2O emissions are estimated using the IPCC (2006) Tier 1 method.

Biosolids (i.e., treated sewage sludge) are assumed to be applied on grasslands.[28] Application of biosolids is estimated from data compiled by EPA (1993, 1999, 2003), McFarland (2001), and NEBRA (2007) (see Section 7.2 for a detailed discussion of the methodology for estimating treated sewage sludge available for land application application). Biosolids data are only available at the national scale, and it is not possible to associate application with specific soil conditions and weather at NRI survey locations. Therefore, DayCent could not be used to simulate the influence of biosolids on N_2O emissions from grassland soils, and consequently, emissions from biosolids are estimated using the IPCC (2006) Tier 1 method.

Soil N_2O emission estimates from DayCent are adjusted using a structural uncertainty estimator accounting for uncertainty in model algorithms and parameter values (Del Grosso et al. 2010). There is also sampling uncertainty for the NRI survey that is quantified with replicate sampling weights associated with the survey, as discussed for Tier 3 method associated with mineral cropland soils. N_2O emissions for the PRP manure nitrogen deposited on federal grasslands and applied biosolids nitrogen are estimated using the Tier 1 method by multiplying the nitrogen input by the default emission factor. Emissions from manure nitrogen are estimated at the state level and aggregated to the entire country, but emissions from biosolids nitrogen are calculated exclusively at the national scale. Further elaboration on the methodology and data used to estimate N_2O emissions from mineral soils are described in Annex 3.12.

Soil N_2O emissions and 95 percent confidence intervals are estimated for each year between 1990 and 2020 based on the Tier 1 and 3 methods, except for biosolids (discussed below). In order to ensure time-series consistency, emissions from 2021 to 2022 are estimated using a splicing method as described in Box 5-4, with a linear extrapolation based on the emission patterns in the 1990 to 2020 data. Linear extrapolation is a standard data splicing method for approximating emissions at the end of a time series (IPCC 2006). As with croplands, estimates for 2021 to 2022 will be recalculated in a future *Inventory* when the activity data are updated. Biosolids application data are compiled through 2022 in this *Inventory*, and therefore soil N_2O emissions and confidence intervals are estimated using the Tier 1 method for all years without application of the splicing method.

Tier 1 Approach for Drainage of Organic Soils in Croplands and Grasslands

The IPCC (2006) Tier 1 method is used to estimate direct N_2O emissions due to drainage of organic soils in croplands and grasslands at a state scale. State-scale estimates of the total area of drained organic soils are obtained from the 2017 NRI (USDA-NRCS 2020), and extended through 2022 using CDL (USDA-NASS 2021) and the Forest Inventory and Analysis (FIA) survey data, which is harmonized with the NRI data (Nelson et al. 2020). Organic soils are identified using soils data from the Soil Survey Geographic Database (SSURGO) (Soil Survey Staff 2020). The IPCC climate region map is used to subdivide areas into temperate and tropical climates according to the climate classification from IPCC (2006). To estimate annual emissions, the total temperate area is multiplied by the IPCC default emission factor for temperate regions, and the total tropical area is multiplied by the IPCC default emission factor for tropical regions (IPCC 2006). In order to ensure time-series consistency, the Tier 1 methods are applied from 1990 to 2022.

[27] A small amount of PRP nitrogen (less than 1 percent) is deposited in grazed pasture that is in rotation with annual crops and is reported in the grassland N_2O emissions.

[28] A portion of biosolids may be applied to croplands, but there is no national dataset to disaggregate the amounts between cropland and grassland.

Total Direct N_2O Emissions from Cropland and Grassland Soils

Annual direct emissions from the Tier 1 and 3 approaches for mineral and drained organic soils occurring in both croplands and grasslands are summed to obtain the total direct N_2O emissions from agricultural soil management (see Table 5-15 and Table 5-16). Further elaboration on the methodology and data used to estimate soil N_2O emissions are described in Annex 3.12.

Indirect N_2O Emissions Associated with Nitrogen Management in Cropland and Grasslands

Indirect N_2O emissions occur when synthetic nitrogen applied or made available through anthropogenic activity is transported from the soil either in gaseous or aqueous forms and later converted into N_2O. There are two pathways leading to indirect emissions. The first pathway results from volatilization of nitrogen as NO_x (nitrogen oxides) and NH_3 (ammonia) following application of synthetic fertilizer, organic amendments (e.g., manure, biosolids), and deposition of PRP manure. Nitrogen made available from mineralization of soil organic matter and residue, including nitrogen incorporated into crops and forage from symbiotic nitrogen fixation, and input of nitrogen from asymbiotic fixation also contributes to volatilized nitrogen emissions. Volatilized nitrogen can be returned to soils through atmospheric deposition, and a portion of the deposited nitrogen is emitted to the atmosphere as N_2O. The second pathway occurs via leaching and runoff of soil nitrogen (primarily in the form of NO_3^-, i.e., nitrate) that is made available through anthropogenic activity on managed lands, including organic and synthetic fertilization, organic amendments, mineralization of soil organic matter and residue, and inputs of nitrogen into the soil from asymbiotic fixation. Nitrate is subject to denitrification in water bodies, which leads to N_2O emissions. Regardless of the eventual location of the indirect N_2O emissions, the emissions are assigned to the original source of the nitrogen for reporting purposes, which here includes croplands and grasslands.

Tier 1 and 3 Approaches for Indirect N_2O Emissions from Atmospheric Deposition of Volatilized Nitrogen

The Tier 3 DayCent model and IPCC (2006) Tier 1 methods are combined to estimate the amount of nitrogen that is volatilized and eventually emitted as N_2O. DayCent is used to estimate nitrogen volatilization for land areas whose direct emissions are simulated with DayCent (i.e., most commodity and some specialty crops and most grasslands). The nitrogen inputs included are the same as described for direct N_2O emissions in the Tier 3 approach for mineral cropland and grassland soils sections. Nitrogen volatilization from all other areas is estimated using the Tier 1 method with default IPCC fractions for nitrogen subject to volatilization (i.e., synthetic and manure nitrogen on croplands not simulated by DayCent, other organic nitrogen inputs (i.e., commercial fertilizers), PRP manure nitrogen excreted on federal grasslands, and biosolids [i.e., treated sewage sludge] application on grasslands).

The IPCC (2006) default emission factor is multiplied by the amount of volatilized nitrogen generated from both DayCent and Tier 1 methods to estimate indirect N_2O emissions occurring with re-deposition of the volatilized nitrogen from 1990-2020 (see Table 5-18). A linear extrapolation data splicing method, described in Box 5-4, is applied to estimate emissions from 2021 to 2022 based on the emission patterns from 1990 to 2020. Linear extrapolation is a standard data splicing method for estimating emissions at the end of a time series (IPCC 2006). Further elaboration on the methodology and data used to estimate indirect N_2O emissions are described in Annex 3.12.

Tier 1 and 3 Approaches for Indirect N_2O Emissions from Leaching/Runoff

As with the calculations of indirect emissions from volatilized nitrogen, the Tier 3 DayCent model and IPCC (2006) Tier 1 method are combined to estimate the amount of nitrogen that is subject to leaching and surface runoff into water bodies, and eventually emitted as N_2O. DayCent is used to simulate the amount of nitrogen transported from lands in the Tier 3 Approach. Nitrogen transport from all other areas is estimated using the Tier 1 method and the IPCC (2006) default factor for the proportion of nitrogen subject to leaching and runoff associated with

nitrogen applications on croplands that are not simulated by DayCent, applications of biosolids on grasslands, other organic N fertilizer applications, crop residue nitrogen inputs, and PRP manure nitrogen excreted on federal grasslands.

For both the DayCent Tier 3 and IPCC (2006) Tier 1 methods, NO_3^- leaching is assumed to be an insignificant source of indirect N_2O in cropland and grassland systems in arid regions, as discussed in IPCC (2006). In the United States, the threshold for significant NO_3^- leaching is based on the potential evapotranspiration (PET) and rainfall amount, similar to IPCC (2006), and is assumed to be negligible in regions where the amount of precipitation does not exceed 80 percent of PET (Note: All irrigated systems are assumed to have significant amounts of leaching of nitrogen even in drier climates).

For leaching and runoff data estimated by the Tier 3 and Tier 1 approaches, the IPCC (2006) default emission factor is used to estimate indirect N_2O emissions that occur in groundwater and waterways (see Table 5-18). Further elaboration on the methodology and data used to estimate indirect N_2O emissions are described in Annex 3.12.

In order to ensure time-series consistency, indirect soil N_2O emissions are estimated using the Tier 1 and 3 approaches from 1990 to 2020 and then a linear extrapolation data splicing method, described in Box 5-4, is applied to estimate emissions from 2021 to 2022 based on the emission patterns from 1990 to 2020. Linear extrapolation is a standard data splicing method for estimating emissions at the end of a time series (IPCC 2006). As with the direct N_2O emissions, the time series will be recalculated in a future *Inventory* when new activity data are incorporated into the analysis.

Uncertainty

Uncertainty is estimated for each of the following five components of N_2O emissions from agricultural soil management: (1) direct emissions simulated by DayCent; (2) the components of indirect emissions (nitrogen volatilized and leached or runoff) simulated by DayCent; (3) direct emissions estimated with the IPCC (2006) Tier 1 method; (4) the components of indirect emissions (nitrogen volatilized and leached or runoff) estimated with the IPCC (2006) Tier 1 method; and (5) indirect emissions estimated with the IPCC (2006) Tier 1 method. Uncertainty in direct emissions as well as the components of indirect emissions that are estimated from DayCent are derived from two variance components (Ogle et al. 2010). For the first component, a Monte Carlo Analysis (consistent with IPCC Approach 2) is used to address uncertainties in management activity data as well as model parameterization and structure (Del Grosso et al. 2010). The second variance component is quantifying uncertainty in scaling from the NRI survey to the entire land base, and computed using a standard variance estimator for a two-stage sample design (Särndal et al. 1992). The two variance components are combined using simple error propagation methods provided by the IPCC (2006), i.e., by taking the square root of the sum of the squares of the standard deviations of the uncertain quantities. For 2021 to 2022 (and 2018 to 2022 for other organic nitrogen fertilizers) there is additional uncertainty propagated through the Monte Carlo Analysis associated with the splicing method (See Box 5-4) except for the Tier 1 method for biosolids and crop residue nitrogen inputs, which do not use the data splicing method for 2021 to 2022.

Simple error propagation methods (IPCC 2006) are used to derive confidence intervals for direct emissions estimated with the IPCC (2006) Tier 1 method, the proportion of volatilization and leaching or runoff estimated with the IPCC (2006) Tier 1 method, and indirect N_2O emissions. Uncertainty in the splicing method is also included in the error propagation for 2021-2022 (see Box 5-4). Additional details on the uncertainty methods are provided in Annex 3.12. Table 5-19 shows the combined uncertainty for soil N_2O emissions. The estimated direct soil N_2O emissions range from 28 percent below to 28 percent above the 2022 emission estimate of 262.5 MMT CO_2 Eq. The combined uncertainty for indirect soil N_2O emissions ranges from 51 percent below to 123 percent above the 2022 estimate of 28.3 MMT CO_2 Eq.

Table 5-19: Quantitative Uncertainty Estimates of N_2O Emissions from Agricultural Soil Management in 2022 (MMT CO_2 Eq. and Percent)

Source	Gas	2022 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate (MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Direct Soil N_2O Emissions	N_2O	262.5	189.6	335.3	-28%	+28%
Indirect Soil N_2O Emissions	N_2O	28.3	13.7	63.3	-51%	+123%

Note: Due to lack of data, uncertainties in PRP manure nitrogen production, other organic fertilizer amendments, and biosolids (i.e., treated sewage sludge) amendments to soils are currently treated as certain. These sources of uncertainty will be included in a future *Inventory* (IPCC 2006).

Additional uncertainty is associated with an incomplete estimation of N_2O emissions from managed croplands and grasslands in Hawaii and Alaska. The *Inventory* currently includes the N_2O emissions from managed manure and PRP nitrogen, and biosolid additions for Alaska and managed manure and PRP nitrogen, biosolid additions, and crop residue for Hawaii. Land areas used for agriculture in Alaska and Hawaii are small relative to major crop commodity states in the conterminous United States, so the emissions are likely to be minor for the other sources of nitrogen (e.g., synthetic fertilizer and crop residue inputs). Regardless, there is a planned improvement to include the additional sources of emissions in a future *Inventory*.

QA/QC and Verification

General (Tier 1) and category-specific (Tier 2) QA/QC activities were conducted consistent with the U.S. Inventory QA/QC plan outlined in Annex 8. DayCent results for N_2O emissions and NO_3^- leaching are compared with field data representing various cropland and grassland systems, soil types, and climate patterns (Del Grosso et al. 2005; Del Grosso et al. 2008), and further evaluated by comparing the model results to emission estimates produced using the IPCC (2006) Tier 1 method for the same sites. Nitrous oxide measurement data for cropland are available for 64 sites with 769 observations of management practice effects, and measurement data for grassland are available for 12 sites with 88 observations of management practice effects. Nitrate leaching data are available for 14 sites, representing 432 observations of management practice effects. In general, DayCent predicted N_2O emission and nitrate leaching for these sites reasonably well. See Annex 3.12 for more detailed information about the comparisons.

Databases containing input data and probability distribution functions required for DayCent simulations of croplands and grasslands and unit conversion factors have been checked. In addition, program scripts that are used to run the Monte Carlo uncertainty analysis have been checked. Errors were found in the synthetic nitrogen application rates for the Tier 3 method for a subset of years in some states, with overapplication based on comparisons to the synthetic fertilizer sales data. An error in the uncertainty calculation was found due to improper formulation of land area variances. A minor error was also identified in manure deposited in pasture, range, and paddock. Databases containing input data, emission factors, and calculations required for the Tier 1 method have been checked and updated as needed. Quality control identified a problem with error propagation in the Tier 1 uncertainty analysis associated with the emission factors. There was also an error identified in the leaching calculation based on irrigation status. All of these errors were corrected. Links between spreadsheets have also been checked, updated, and corrected as needed.

Recalculations Discussion

Several improvements have been implemented in this *Inventory* leading to recalculations, including a) updated time series of land representation data (Nelson et al. 2020), b) re-calibration of the soil carbon module in the DayCent model (See Annex 3.12); c) a more accurate output variable to estimate asymbiotic nitrogen fixation in

the Tier 3 method, and d) corrections associated with manure deposited on pasture, range and paddock in addition to estimation of leaching based on irrigation status. The combined impact from these changes resulted in an average annual increase in emissions of 3.3 MMT CO_2 Eq., or 1.1 percent, from 1990 to 2021 relative to the previous *Inventory*.

Planned Improvements

Several planned improvements are underway associated with improving the DayCent biogeochemical model. These improvements include a better representation of plant phenology, particularly senescence events following grain filling in crops. In addition, crop parameters associated with temperature and water stress effects on plant production will be further improved in DayCent with additional model calibration. In addition, there is an improvement underway to calibrate the nitrogen submodule in order to more accurately predict nitrogen-gas losses and nitrate leaching rates. Experimental study sites will continue to be added for quantifying model structural uncertainty with priority given to studies that have continuous (daily) measurements of N_2O (e.g., Scheer et al. 2013). In addition, improvements are underway to simulate crop residue burning in the DayCent model based on the amount of crop residues burned according to the data that is used in the Field Burning of Agricultural Residues source category (see Section 5.7).

For Tier 1, there is a planned improvement to include all sources of nitrogen for Alaska and Hawaii in the *Inventory* for agricultural soil management, which currently only addresses managed manure nitrogen and PRP nitrogen, and biosolids additions for grasslands in both states, in addition to crop residue nitrogen inputs for Hawaii. There is also an improvement to incorporate the Tier 1 emission factor for N_2O emissions from drained organic soils by using the revised factors in the *2013 Supplement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories: Wetlands* (IPCC 2014). There is a planned improvement for the Tier 1 method associated with estimating soil N_2O emissions from nitrogen mineralization due to soil organic matter decomposition that is accelerated with land use conversions to cropland and grassland. Lastly, a review of available data on biosolids (i.e., treated sewage sludge) application will also be undertaken to improve the distribution of biosolids application on croplands, grasslands and settlements.

Improvements are expected to be completed for the next *Inventory* (i.e., 2025 submission to the UNFCCC, 1990 through 2023 *Inventory*), pending prioritization of resources.

5.5 Liming (CRT Source Category 3G)

Crushed limestone ($CaCO_3$) and dolomite ($CaMg(CO_3)_2$) are added to soils by land managers to increase soil pH (i.e., to reduce acidification). Carbon dioxide emissions occur as these compounds react with hydrogen ions in soils. The rate of degradation of applied limestone and dolomite depends on the soil conditions, soil type, climate regime, and whether limestone or dolomite is applied. Emissions from limestone and dolomite that are used in industrial processes (e.g., cement production, glass production, etc.) are reported in the IPPU chapter. Emissions from liming of soils have fluctuated between 1990 and 2022 in the United States, ranging from 2.2 MMT CO_2 Eq. to 6.0 MMT CO_2 Eq. across the entire time series. In 2022, liming of soils in the United States resulted in emissions of 3.3 MMT CO_2 Eq. (0.9 MMT C), representing a 30 percent decrease in emissions since 1990 (see Table 5-20 and Table 5-21). The trend is driven by variation in the amount of limestone and dolomite applied to soils over the time period.

Table 5-20: Emissions from Liming (MMT CO_2 Eq.)

Source	1990	2005	2018	2019	2020	2021	2022
Limestone	4.1	3.9	2.0	1.9	2.5	2.0	2.9
Dolomite	0.6	0.4	0.2	0.3	0.4	0.4	0.3
Total	**4.7**	**4.4**	**2.2**	**2.2**	**2.9**	**2.4**	**3.3**

Note: Totals may not sum due to independent rounding.

Table 5-21: Emissions from Liming (MMT C)

Source	1990	2005	2018	2019	2020	2021	2022
Limestone	1.1	1.1	0.6	0.5	0.7	0.5	0.8
Dolomite	0.2	0.1	0.1	0.1	0.1	0.1	0.1
Total	**1.3**	**1.2**	**0.6**	**0.6**	**0.8**	**0.7**	**0.9**

+ Does not exceed 0.05 MMT C.

Note: Totals may not sum due to independent rounding.

Methodology and Time-Series Consistency

Carbon dioxide emissions from application of limestone and dolomite to soils were estimated using a Tier 2 methodology consistent with IPCC (2006). The annual amounts of limestone and dolomite, which are applied to soils (see Table 5-22), were multiplied by CO_2 emission factors from West and McBride (2005). These country-specific emission factors (0.059 metric ton C/metric ton limestone, 0.064 metric ton C/metric ton dolomite) are lower than the IPCC default emission factors because they account for the portion of carbonates that are transported from soils through hydrological processes and eventually deposited in ocean basins (West and McBride 2005). This analysis of lime dissolution is based on studies in the Mississippi River basin, where the vast majority of lime application occurs in the United States (West 2008). Moreover, much of the remaining lime application is occurring under similar precipitation regimes, and so the emission factors are considered a reasonable approximation for all lime application in the United States (West 2008) (see Box 5-5).

The annual application rates of limestone and dolomite were derived from estimates and industry statistics provided in the U.S. Geological Survey (USGS) *Minerals Yearbook* (Tepordei 1994 through 2015; Willett 2007a, 2007b, 2009, 2010, 2011a, 2011b, 2013a, 2014, 2015, 2016, 2017, 2020a, 2022a, 2022b, 2022c, 2023a), as well as preliminary data that will eventually be published in the *Minerals Yearbook* for the latter part of the time series (Willett 2023b). Data for the final year of the inventory is based on the *Mineral Industry Surveys*, as discussed below (USGS 2023). The U.S. Geological Survey (USGS; U.S. Bureau of Mines prior to 1997) compiled production and use information through surveys of crushed stone manufacturers. However, manufacturers provided different levels of detail in survey responses so the estimates of total crushed limestone and dolomite production and use were divided into three components: (1) production by end-use, as reported by manufacturers (i.e., "specified" production); (2) production reported by manufacturers without end-uses specified (i.e., "unspecified" production); and (3) estimated additional production by manufacturers who did not respond to the survey (i.e., "estimated" production).

Box 5-5: Comparison of the Tier 2 U.S. Inventory Approach and IPCC (2006) Default Approach

Emissions from liming of soils were estimated using a Tier 2 methodology based on emission factors specific to the United States that are lower than the IPCC (2006) default emission factors. Most lime application in the United States occurs in the Mississippi River basin, or in areas that have similar soil and rainfall regimes as the Mississippi River basin. Under these conditions, a significant portion of dissolved agricultural lime leaches through the soil into groundwater. Groundwater moves into channels and is transported to larger rivers and eventually the ocean where $CaCO_3$ precipitates to the ocean floor (West and McBride 2005). The U.S.-specific emission factors (0.059 metric ton C/metric ton limestone and 0.064 metric ton C/metric ton dolomite) are about half of the IPCC (2006) emission factors (0.12 metric ton C/metric ton limestone and 0.13 metric ton

C/metric ton dolomite). For comparison, the 2022 U.S. emission estimate from liming of soils is 3.3 MMT CO_2 Eq. using the country-specific factors. In contrast, emissions would be estimated at 6.6 MMT CO_2 Eq. using the IPCC (2006) default emission factors.

Data on "specified" limestone and dolomite amounts were used directly in the emission calculation because the end use is provided by the manufacturers and can be used to directly determine the amount applied to soils. However, it is not possible to determine directly how much of the limestone and dolomite is applied to soils for manufacturer surveys in the "unspecified" and "estimated" categories. For these categories, the amounts of crushed limestone and dolomite applied to soils were determined by multiplying the percentage of total "specified" limestone and dolomite production that is applied to soils, by the total amounts of "unspecified" and "estimated" limestone and dolomite production. In other words, the proportion of total "unspecified" and "estimated" crushed limestone and dolomite that was applied to soils is proportional to the amount of total "specified" crushed limestone and dolomite that was applied to soils.

In addition, data were not available for 1990, 1992, and 2022 on the fractions of total crushed stone production that were limestone and dolomite, and on the fractions of limestone and dolomite production that were applied to soils. To estimate the 1990 and 1992 data, a set of average fractions were calculated using the 1991 and 1993 data. These average fractions were applied to the quantity of "total crushed stone produced or used" reported for 1990 and 1992 in the 1994 *Minerals Yearbook* (Tepordei 1996). To estimate 2022 data, 2021 fractions were applied to the 2022 estimates of total crushed stone. The basis for these estimates is from the USGS *Mineral Industry Surveys: Crushed Stone and Sand and Gravel in the First Quarter of 2023* (USGS 2023).

The primary source for limestone and dolomite activity data is the *Minerals Yearbook*, published by the Bureau of Mines through 1996 and by the USGS from 1997 to the present. In 1994, the "Crushed Stone" chapter in the *Minerals Yearbook* began rounding (to the nearest thousand metric tons) quantities for total crushed stone produced or used. It then reported revised (rounded) quantities for each of the years from 1990 to 1993. In order to minimize the inconsistencies in the activity data, these revised production numbers have been used in all of the subsequent calculations.

Table 5-22: Applied Minerals (MMT)

Mineral	1990	2005	2018	2019	2020	2021	2022
Limestone	19.0	18.1	9.4	8.9	11.6	9.3	13.5
Dolomite	2.4	1.9	0.9	1.2	1.6	1.6	1.5

The same methods are applied throughout the time series. The activity data are extended in the last two years of the time series based on proportions of specified, unspecified and estimated agricultural limestone and dolomite so that estimates are consistent with the previous year's data. These years will be recalculated when additional data are available on the amounts of limestone and dolomite that are used for agricultural purposes.

Uncertainty

Uncertainty regarding the amount of limestone and dolomite applied to soils was estimated at ±15 percent with normal densities (Tepordei 2003; Willett 2013b). Analysis of the uncertainty associated with the emission factors included the fraction of lime dissolved by nitric acid versus the fraction that reacts with carbonic acid, and the portion of bicarbonate that leaches through the soil and is transported to the ocean. Uncertainty regarding the time associated with leaching and transport was not addressed in this analysis, but is assumed to be a relatively small contributor to the overall uncertainty (West 2005). The probability distribution functions for the fraction of lime dissolved by nitric acid and the portion of bicarbonate that leaches through the soil were represented as triangular distributions between ranges of zero and 100 percent of the estimates. The uncertainty surrounding these two components largely drives the overall uncertainty. The emission factor distributions were truncated at 0 so that emissions were not less than 0.

A Monte Carlo (Approach 2) uncertainty analysis was applied to estimate the uncertainty in CO_2 emissions from liming. The results of the Approach 2 quantitative uncertainty analysis are summarized in Table 5-23. Carbon dioxide emissions from carbonate lime application to soils in 2022 were estimated to be between 0.50 and 6.18 MMT CO_2 Eq. at the 95 percent confidence level. This confidence interval represents a range of 85 percent below to 89 percent above the 2022 emission estimate of 3.3 MMT CO_2 Eq. Some carbon in the carbonate lime applied to agricultural soils is not emitted to the atmosphere due to the dominance of the carbonate lime dissolving in carbonic acid rather than nitric acid (West and McBride 2005).

Table 5-23: Approach 2 Quantitative Uncertainty Estimates for CO_2 Emissions from Liming (MMT CO_2 Eq. and Percent)

Source	Gas	2022 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (MMT CO_2 Eq.)		Uncertainty Range Relative to Emission Estimate[a] (%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Liming	CO_2	3.3	0.50	6.18	-85%	+89%

[a] Range of emission estimates predicted by Monte Carlo stochastic simulation for a 95 percent confidence interval.

QA/QC and Verification

A source-specific QA/QC plan for liming has been developed and implemented, consistent with the U.S. Inventory QA/QC plan outlined in Annex 8. The quality control effort focused on the Tier 1 procedures for this *Inventory*, and no errors were identified in this *Inventory*.

Recalculations Discussion

Limestone and dolomite application data for 2020 and 2021 were updated with the recent published data from Willett, J.C. (2023a). With these revisions, the emissions decreased by 1 and 22 percent for 2020 and 2021 (respectively) relative to the previous *Inventory*.

Planned Improvements

At this time there are no specific planned improvements for estimating emissions from liming.

5.6 Urea Fertilization (CRT Source Category 3H)

The use of urea ($CO(NH_2)_2$) as a fertilizer leads to greenhouse gas emissions through the release of CO_2 that was fixed during the production of urea. In the presence of water and urease enzymes, urea that is applied to soils as fertilizer is converted into ammonium (NH_4^+), hydroxyl ion (OH), and bicarbonate (HCO_3^-). The bicarbonate then evolves into CO_2 and water. Emissions from urea fertilization in the United States were 5.3 MMT CO_2 Eq. (1.5 MMT C) in 2022 (Table 5-24 and Table 5-25). Carbon dioxide emissions have increased by 120 percent between 1990 and 2022 due to an increasing amount of urea that is applied to soils. The variation in emissions across the time series is driven by differences in the amounts of fertilizer applied to soils each year. Carbon dioxide emissions associated with urea used for non-agricultural purposes are reported in the IPPU chapter (Section 4.6).

Table 5-24: CO_2 Emissions from Urea Fertilization (MMT CO_2 Eq.)

Source	1990	2005	2018	2019	2020	2021	2022
Urea Fertilization	2.4	3.5	4.9	5.0	5.1	5.2	5.3

Table 5-25: CO_2 Emissions from Urea Fertilization (MMT C)

Source	1990	2005	2018	2019	2020	2021	2022
Urea Fertilization	0.7	1.0	1.3	1.4	1.4	1.4	1.5

Methodology and Time-Series Consistency

Carbon dioxide emissions from the application of urea to agricultural soils were estimated using the IPCC (2006) Tier 1 methodology following the *2006 IPCC Guidelines* Figure 11.5 decision tree for CO_2 emissions from urea fertilization.[29] The method assumes that carbon in the urea is released after application to soils and converted to CO_2. The annual amounts of urea applied to croplands (see Table 5-26) were derived from the state-level fertilizer sales data provided in *Commercial Fertilizer* reports (TVA 1991, 1992, 1993, 1994; AAPFCO 1995 through 2022).[30] These amounts were multiplied by the default IPCC (2006) emission factor (0.20 metric tons of carbon per metric ton of urea), which is equal to the carbon content of urea on an atomic weight basis. National estimates from urea fertilization also include emissions from Puerto Rico.

Fertilizer sales data are reported in fertilizer years (July previous year through June current year), so a calculation was performed to convert the data to calendar years (January through December). According to monthly fertilizer use data (TVA 1992b), 35 percent of total fertilizer used in any fertilizer year is applied between July and December of the previous calendar year, and 65 percent is applied between January and June of the current calendar year.

Fertilizer sales data for the 2018 through 2022 fertilizer years were not available for this *Inventory*. Therefore, urea application in the 2018 through 2022 fertilizer years were estimated using a linear, least squares trend of consumption over the data from the previous five years (2013 through 2017) at the state scale. A trend of five years was chosen as opposed to a longer trend as it best captures the current inter-annual variability in consumption. State-level estimates of CO_2 emissions from the application of urea to agricultural soils were summed to estimate total emissions for the entire United States. The fertilizer year data is then converted into calendar year (Table 5-26) data using the method described above.

Table 5-26: Applied Urea (MMT)

	1990	2005	2018	2019	2020	2021	2022
Urea Fertilizer[a]	3.3	4.8	6.7	6.9	7.0	7.1	7.3

[a] These numbers represent amounts applied to all agricultural land, including cropland remaining cropland, land converted to cropland, grassland remaining grassland, land converted to grassland, settlements remaining settlements, land converted to settlements, forest land remaining forest land and land converted to forest land, as it is not currently possible to apportion the data by land-use/conversion category.

The same methods were applied to the entire time series to ensure time-series consistency from 1990 through 2022. In addition, activity data are extended using a data splicing method with a linear extrapolation based on the last five years of urea fertilization data to ensure consistency in the time series. These years will be recalculated when additional data are available on urea fertilization.

[29] *2006 IPCC Guidelines* Volume 4, Chapter 11, Figure 11.5 (page 11.33)

[30] The amount of urea consumed for non-agricultural purposes in the United States is reported in the Industrial Processes and Product Use chapter, Section 4.6 Urea Consumption for Non-Agricultural Purposes.

Uncertainty

An Approach 2 Monte Carlo analysis is conducted as described by the IPCC (2006). The largest source of uncertainty is the default emission factor, which assumes that 100 percent of the carbon in $CO(NH_2)_2$ applied to soils is emitted as CO_2. The uncertainty surrounding this factor incorporates the possibility that some of the carbon may not be emitted to the atmosphere, and therefore the uncertainty range is set from 50 percent emissions to the maximum emission value of 100 percent using a triangular distribution. In addition, urea consumption data have uncertainty that is represented as a normal density. Due to the highly skewed distribution of the resulting emissions from the Monte Carlo uncertainty analysis, the estimated emissions are based on the analytical solution to the equation, and the confidence interval is approximated based on the values at 2.5 and 97.5 percentiles.

Carbon dioxide emissions from urea fertilization of agricultural soils in 2022 are estimated to be between 3.05 and 5.49 MMT CO_2 Eq. at the 95 percent confidence level. This indicates a range of 43 percent below to 3 percent above the 2022 emission estimate of 5.33 MMT CO_2 Eq. (Table 5-27).

Table 5-27: Quantitative Uncertainty Estimates for CO_2 Emissions from Urea Fertilization (MMT CO_2 Eq. and Percent)

Source	Gas	2022 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Urea Fertilization	CO_2	5.33	3.05	5.49	-43%	+3%

[a] Range of emission estimates predicted by Monte Carlo stochastic simulation for a 95 percent confidence interval.

There are additional uncertainties that are not quantified in this analysis. There is uncertainty surrounding the assumptions underlying conversion of fertilizer years to calendar years. These uncertainties are negligible over multiple years because an over- or under-estimated value in one calendar year is addressed with a corresponding increase or decrease in the value for the subsequent year. In addition, there is uncertainty regarding the fate of carbon in urea that is incorporated into solutions of urea ammonium nitrate (UAN) fertilizer. Emissions of CO_2 from UAN applications to soils are not estimated in the current *Inventory* (see Planned Improvements).

QA/QC and Verification

A source-specific QA/QC plan for Urea Fertilization has been developed and implemented, consistent with the U.S. Inventory QA/QC plan. No quality control problems were discovered in this process except a correction to the emissions factor value in documentation tables.

Recalculations Discussion

Fertilizer consumption data was updated with the latest published estimate. In turn, the fertilizer values were recalculated using the data splicing method for 2018 to 2021 based on the revised fertilizer amount for 2017. This update led to an average decrease in emissions for the years 2017 through 2021 of 0.01 MMT CO_2 Eq., or 0.1 percent. The remainder of the time series was not affected.

Planned Improvements

A key planned improvement is to incorporate Urea Ammonium Nitrate (UAN) in the estimation of Urea CO_2 emissions. Activity data for UAN have been identified, but additional information is needed to fully incorporate this type of fertilizer into the analysis, which will be completed in a future *Inventory*.

5.7 Field Burning of Agricultural Residues (CRT Source Category 3F)

Crop production creates large quantities of agricultural crop residues, which farmers manage in a variety of ways. For example, crop residues can be left in the field and possibly incorporated into the soil with tillage; collected and used as fuel, animal bedding material, supplemental animal feed, or construction material; composted and applied to soils; transported to landfills; or burned in the field. The *2006 IPCC Guidelines* does not consider field burning of crop residues to be a net source of CO_2 emissions because it is assumed the carbon released to the atmosphere as CO_2 during burning is reabsorbed during the next growing season by the crop (IPCC 2006). However, crop residue burning is a net source of CH_4, N_2O, CO, and NO_x, which are released during combustion.

In the United States, field burning of agricultural residues occurs in southeastern states, the Great Plains, and the Pacific Northwest (McCarty 2011). The primary crops that are managed with residue burning include corn, cotton, lentils, rice, soybeans, sugarcane and wheat (McCarty 2009). In 2022, CH_4 and N_2O emissions from field burning of agricultural residues were 0.6 MMT CO_2 Eq. (22 kt) and 0.2 MMT CO_2 Eq. (1 kt), respectively (Table 5-28 and Table 5-29). Annual emissions of CH_4 and N_2O have increased from 1990 to 2022 by 14 percent and 16 percent, respectively. The increase in emissions over time is partly due to higher yielding crop varieties with larger amounts of residue production and fuel loads, but also linked with an increase in the area burned for some crop types.

Table 5-28: CH_4 and N_2O Emissions from Field Burning of Agricultural Residues (MMT CO_2 Eq.)

Gas/Crop Type	1990	2005	2018	2019	2020	2021	2022
CH_4	**0.5**	**0.6**	**0.6**	**0.7**	**0.6**	**0.6**	**0.6**
Sugarcane	0.1	0.2	0.1	0.2	0.1	0.1	0.1
Wheat	0.2	0.2	0.1	0.1	0.1	0.1	0.1
Maize	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Rice	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Soybeans	+	+	+	+	+	+	+
Cotton	+	+	+	+	+	+	+
Sorghum	+	+	+	+	+	+	+
Other Small Grains	+	+	+	+	+	+	+
Peanuts	+	+	+	+	+	+	+
Legume Hay	+	+	+	+	+	+	+
Barley	+	+	+	+	+	+	+
Oats	+	+	+	+	+	+	+
Grass Hay	+	+	+	+	+	+	+
Tobacco	+	+	+	+	+	+	+
Vegetables	0.0	+	+	+	+	+	+
Peas	+	+	+	+	+	+	+
Sunflower	+	+	+	+	+	+	+
Potatoes	+	+	+	+	+	+	+
Dry Beans	+	+	+	+	+	+	+
Sugarbeets	+	+	+	+	+	+	+
Lentils	0.0	+	+	+	+	+	+
Chickpeas	0.0	0.0	0.0	0.0	0.0	0.0	0.0
N_2O	**0.2**	**0.2**	**0.2**	**0.2**	**0.2**	**0.2**	**0.2**
Wheat	0.1	0.1	+	+	+	+	+
Maize	+	+	+	+	+	+	+
Sugarcane	+	+	+	+	+	+	+
Rice	+	+	+	+	+	+	+
Soybeans	+	+	+	+	+	+	+
Cotton	+	+	+	+	+	+	+

Peanuts	+	+	+	+	+	+	+
Other Small Grains	+	+	+	+	+	+	+
Legume Hay	+	+	+	+	+	+	+
Sorghum	+	+	+	+	+	+	+
Grass Hay	+	+	+	+	+	+	+
Barley	+	+	+	+	+	+	+
Oats	+	+	+	+	+	+	+
Potatoes	+	+	+	+	+	+	+
Peas	+	+	+	+	+	+	+
Sugarbeets	+	+	+	+	+	+	+
Tobacco	+	+	+	+	+	+	+
Sunflower	+	+	+	+	+	+	+
Vegetables	0.0	+	+	+	+	+	+
Dry Beans	+	+	+	+	+	+	+
Lentils	0.0	+	+	+	+	+	+
Chickpeas	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Total	**0.7**	**0.8**	**0.8**	**0.9**	**0.8**	**0.8**	**0.8**

+ Does not exceed 0.05 MMT CO_2 Eq.

Note: Totals may not sum due to independent rounding.

Table 5-29: CH_4, N_2O, CO, and NO_x Emissions from Field Burning of Agricultural Residues (kt)

Gas/Crop Type	1990	2005	2018	2019	2020	2021	2022
CH_4	**19**	**23**	**22**	**23**	**22**	**22**	**22**
Sugarcane	4	6	5	6	5	5	5
Wheat	6	6	5	5	5	5	5
Maize	2	4	5	5	5	5	5
Rice	3	3	2	3	2	3	3
Soybeans	1	2	2	2	2	2	2
Cotton	1	2	1	1	1	1	1
Sorghum	+	+	+	+	+	+	+
Other Small Grains	+	+	+	+	+	+	+
Peanuts	+	+	+	+	+	+	+
Legume Hay	+	+	+	+	+	+	+
Barley	+	+	+	+	+	+	+
Oats	+	+	+	+	+	+	+
Grass Hay	+	+	+	+	+	+	+
Tobacco	+	+	+	+	+	+	+
Vegetables	0	+	+	+	+	+	+
Peas	+	+	+	+	+	+	+
Sunflower	+	+	+	+	+	+	+
Potatoes	+	+	+	+	+	+	+
Dry Beans	+	+	+	+	+	+	+
Sugarbeets	+	+	+	+	+	+	+
Lentils	0	+	+	+	+	+	+
Chickpeas	0	0	0	0	0	0	0
N_2O	**1**	**1**	**1**	**1**	**1**	**1**	**1**
Wheat	+	+	+	+	+	+	+
Maize	+	+	+	+	+	+	+
Sugarcane	+	+	+	+	+	+	+
Rice	+	+	+	+	+	+	+
Soybeans	+	+	+	+	+	+	+
Cotton	+	+	+	+	+	+	+
Peanuts	+	+	+	+	+	+	+
Other Small Grains	+	+	+	+	+	+	+
Legume Hay	+	+	+	+	+	+	+
Sorghum	+	+	+	+	+	+	+

Grass Hay	+	+	+	+	+	+	+
Barley	+	+	+	+	+	+	+
Oats	+	+	+	+	+	+	+
Potatoes	+	+	+	+	+	+	+
Peas	+	+	+	+	+	+	+
Sugarbeets	+	+	+	+	+	+	+
Tobacco	+	+	+	+	+	+	+
Sunflower	+	+	+	+	+	+	+
Vegetables	0	+	+	+	+	+	+
Dry Beans	+	+	+	+	+	+	+
Lentils	0	+	+	+	+	+	+
Chickpeas	0	0	0	0	0	0	0
CO	**407**	**480**	**433**	**468**	**446**	**480**	**501**
NOx	**16**	**18**	**17**	**18**	**17**	**18**	**19**

+ Does not exceed 0.5 kt CO_2 Eq.

Note: Totals may not sum due to independent rounding.

Methodology and Time-Series Consistency

A country-specific Tier 2 method is used to estimate greenhouse gas emissions from field burning of agricultural residues from 1990 to 2014 (for more details comparing the country-specific approach to the IPCC (2006) default approach, see Box 5-6), and a data splicing method with a linear extrapolation is applied to complete the emissions time series from 2015 to 2022. The exception is sugarcane for which emissions have been estimated from 1990 to 2020, with 2021 to 2022 estimated with the data splicing method. The following equation is used to estimate the amounts of carbon and nitrogen released (R_i, where *i* is *C* or *N*) from burning.

Equation 5-1: Elemental C or N Released through Oxidation of Crop Residues

$$R_i = CP \times RCR \times DMF \times F_i \times FB \times CE$$

$$FB = \frac{AB}{CAH}$$

where,

Crop Production (CP)	=	Annual production of crop, by state, kt crop production
Residue: Crop Ratio (RCR)	=	Amount of residue produced per unit of crop production, kt residue/kt crop production
Dry Matter Fraction (DMF)	=	Amount of dry matter per unit of residue biomass for a crop, kt residue dry matter/ kt residue biomass
Fraction C or N (F_i)	=	Fraction of C or N per unit of dry matter for a crop, kt C or N /kt residue dry matter
Fraction Burned (FB)	=	Proportion of residue biomass consumed, unitless
Combustion Efficiency (CE)	=	Proportion of residue actually burned, unitless
Area Burned (AB)	=	Total area of crop burned, by state, ha
Crop Area Harvested (CAH)	=	Total area of crop harvested, by state, ha

Crop production data are available by state and year from USDA-NASS (2019) for 22 crops that are burned in the conterminous United States, including maize, rice, wheat, barley, oats, other small grains, sorghum, cotton, grass hay, legume hay, peas, sunflower, tobacco, vegetables, chickpeas, dry beans, lentils, peanuts, soybeans, potatoes,

sugarbeets, and sugarcane.[31] Crop area data are based on the 2015 and 2017 National Resources Inventories (NRI) (USDA-NRCS 2018; USDA-NRCS 2020). To estimate total crop production, the crop yield data from USDA Quick Stats (USDA-NASS 2019) are multiplied by the area data for these crops from the NRI survey. The production data for the crop types are presented in Table 5-30. Alaska and Hawaii are not included in the current analysis, but there is a planned improvement to estimate residue burning emissions for these two states in a future *Inventory*.

The amount of elemental carbon or nitrogen released through oxidation of the crop residues is used in the following equation to estimate the amount of CH_4, CO, N_2O, and NO_x emissions (E_g, where g is the specific gas, i.e., CH_4, CO, N_2O, and NO_x) from the field burning of agricultural residues:

Equation 5-2: Emissions from Crop Residue Burning

$$E_g = R_i \times EF_g \times CF$$

where,

Emission ratio (EF_g) = emission ratio by gas, g CH_4-C or CO-C/g C released, or g N_2O-N or NO_x-N/g N released

Conversion Factor (CF) = conversion by molecular weight ratio of CH_4-C to C (16/12), CO-C to C (28/12), N_2O-N to N (44/28), or NO_x-N to N (30/14)

Box 5-6: Comparison of Tier 2 U.S. Inventory Approach and IPCC (2006) Default Approach

Emissions from Field Burning of Agricultural Residues are calculated using a Tier 2 methodology that is based on the method developed by the IPCC/UNEP/OECD/IEA (1997). The rationale for using the IPCC/UNEP/OECD/IEA (1997) approach rather than the method provided in the *2006 IPCC Guidelines* is as follows: (1) the equations from both guidelines rely on the same underlying variables (though the formats differ); (2) the IPCC (2006) equation was developed to be broadly applicable to all types of biomass burning, and, thus, is not specific to agricultural residues; (3) the IPCC (2006) method provides emission factors based on the dry matter content rather than emission rates related to the amount of carbon and nitrogen in the residues; and (4) the IPCC (2006) default factors are provided only for four crops (corn, rice, sugarcane, and wheat) while this *Inventory* includes emissions from twenty-one crops.

A comparison of the methods in the current Inventory and the default IPCC (2006) approach was undertaken for 2014 to determine the difference in estimates between the two approaches. To estimate greenhouse gas emissions from field burning of agricultural residues using the IPCC (2006) methodology, the following equation—cf. IPCC (2006) Equation 2.27—was used with default factors and country-specific values for mass of fuel.

Equation 5-3: Estimation of Greenhouse Gas Emissions from Fire

$$Emissions\ (kt) = AB \times M_B \times C_f \times G_{ef} \times 10^{-6}$$

where,

Area Burned (AB) = Total area of crop burned (ha)

[31] Kentucky bluegrass (produced on farms for turf grass installations) may have small areas of burning that are not captured in the sample of locations that were used in the remote sensing analysis (see Planned Improvements).

Mass of Fuel (M_B) = U.S.- Specific Values using NASS Statistics[32] (metric tons dry matter)

Combustion Factor (C_f) = IPCC (2006) default combustion factor with fuel biomass consumption (metric tons dry matter ha^{-1})

Emission Factor (G_{ef}) = IPCC (2006) emission factor (g kg^{-1} dry matter burnt)

The IPCC (2006) Tier 1 method approach resulted in 21 percent lower emissions of CH_4 and 40 percent lower emissions of N_2O compared to this *Inventory*. In summary, the IPCC/UNEP/OECD/IEA (1997) method is considered more appropriate for U.S. conditions because it is more flexible for incorporating country-specific data. Emissions are estimated based on specific carbon and nitrogen content of the fuel, which is converted into CH_4, CO, N_2O and NO_x, compared to IPCC (2006) approach that is based on dry matter rather than elemental composition.

Emissions from field burning of agricultural residues are calculated using a Tier 2 methodology that is based on the method developed by the IPCC/UNEP/OECD/IEA (1997). The rationale for using the IPCC/UNEP/OECD/IEA (1997) approach rather than the method provided in the *2006 IPCC Guidelines* is as follows: (1) the equations from both guidelines rely on the same underlying variables (though the formats differ); (2) the IPCC (2006) equation was developed to be broadly applicable to all types of biomass burning, and, thus, is not specific to agricultural residues; (3) the IPCC (2006) method provides emission factors based on the dry matter content rather than emission rates related to the amount of carbon and nitrogen in the residues; and (4) the IPCC (2006) default factors are provided only for four crops (corn, rice, sugarcane, and wheat) while this *Inventory* includes emissions from 21 crops.

A comparison of the methods in the current *Inventory* and the default IPCC (2006) approach was undertaken for 2014 to determine the difference in estimates between the two approaches. To estimate greenhouse gas emissions from field burning of agricultural residues using the IPCC (2006) methodology, the following equation—cf. IPCC (2006) Equation 2.27—was used with default factors and country-specific values for mass of fuel.

Equation 5-4: Estimation of Greenhouse Gas Emissions from Fire

$$Emissions\ (kt) = AB \times M_B \times C_f \times G_{ef} \times 10^{-6}$$

where,

Area Burned (AB) = Total area of crop burned (ha)

Mass of Fuel (M_B) = U.S.- Specific Values using NASS Statistics[33] (metric tons dry matter)

Combustion Factor (C_f) = IPCC (2006) default combustion factor with fuel biomass consumption (metric tons dry matter ha^{-1})

Emission Factor (G_{ef}) = IPCC (2006) emission factor (g kg^{-1} dry matter burnt)

The IPCC (2006) Tier 1 method approach resulted in 21 percent lower emissions of CH_4 and 40 percent lower emissions of N_2O compared to this *Inventory*. In summary, the IPCC/UNEP/OECD/IEA (1997) method is considered more appropriate for U.S. conditions because it is more flexible for incorporating country-specific data. Emissions are estimated based on specific carbon and nitrogen content of the fuel, which is converted into

[32] NASS yields are used to derive mass of fuel values because IPCC (2006) only provides default values for 4 of the 21 crops included in the *Inventory*.

[33] NASS yields are used to derive mass of fuel values because IPCC (2006) only provides default values for 4 of the 21 crops included in the *Inventory*.

CH_4, CO, N_2O and NO_x, compared to IPCC (2006) approach that is based on dry matter rather than elemental composition.

Table 5-30: Agricultural Crop Production (kt of Product)

Crop	1990	2005	2010	2018	2019	2020
Maize	296,065	371,256	398,618	NE	NE	NE
Rice	9,543	11,751	11,976	NE	NE	NE
Wheat	79,805	68,077	68,530	NE	NE	NE
Barley	9,281	5,161	3,942	NE	NE	NE
Oats	5,969	2,646	2,364	NE	NE	NE
Other Small Grains	2,651	2,051	1,803	NE	NE	NE
Sorghum	23,687	14,382	14,052	NE	NE	NE
Cotton	4,605	6,106	4,638	NE	NE	NE
Grass Hay	44,150	49,880	46,761	NE	NE	NE
Legume Hay	90,360	91,819	85,813	NE	NE	NE
Peas	51	660	839	NE	NE	NE
Sunflower	1,015	1,448	1,212	NE	NE	NE
Tobacco	1,154	337	470	NE	NE	NE
Vegetables	+	1,187	1,469	NE	NE	NE
Chickpeas	+	5	+	NE	NE	NE
Dry Beans	467	1,143	1,461	NE	NE	NE
Lentils	+	101	254	NE	NE	NE
Peanuts	1,856	2,176	1,925	NE	NE	NE
Soybeans	56,612	86,980	95,198	NE	NE	NE
Potatoes	18,924	20,026	19,279	NE	NE	NE
Sugarbeets	24,951	25,635	33,336	NE	NE	NE
Sugarcane	26,047	38,928	34,252	36,680	37,361	42,400

+ Absolute value does not exceed 0.05 MMT CO_2 Eq.
NE (Not Estimated)
Note: The amount of crop production has not been compiled for 2015 to 2021 so a data splicing method is used to estimate emissions for this portion of the time series.

The area burned is determined based on an analysis of remote sensing products (McCarty et al. 2009, 2010, 2011). The presence of fires has been analyzed at 3,600 survey locations in the NRI from 1990 to 2002 with LANDFIRE data products developed from 30 m Landsat imagery (LANDFIRE 2008), and from 2003 through 2014 using 1 km Moderate Resolution Imaging Spectroradiometer imagery (MODIS) Global Fire Location Product (MCD14ML), combining observations from Terra and Aqua satellites (Giglio et al. 2006). A sample of states are included in the analysis with high, medium and low burning rates for agricultural residues, including Arkansas, California, Florida, Indiana, Iowa and Washington. The area burned is determined directly from the analysis for these states for all crops, with the exception of sugarcane as discussed later in this section.

For other states within the conterminous United States, the area burned for the 1990 through 2014 portion of the time series is estimated from a logistical regression model that has been developed from the data collected from the remote sensing products for the six states. The logistical regression model is used to predict occurrence of fire events. Several variables are tested in the logistical regression including a) the historical level of burning in each state (high, medium or low levels of burning) based on an analysis by McCarty et al. (2011), b) year that state laws limit burning of fields, in addition to c) mean annual precipitation and mean annual temperature from a 4-kilometer gridded product from the PRISM Climate Group (2015). A K-fold model fitting procedure is used due to low frequency of burning and likelihood that outliers could influence the model fit. Specifically, the model is trained with a random selection of sample locations and evaluated with the remaining sample. This process is repeated ten times to select a model that is most common among the set of ten, and avoid models that appear to be influenced by outliers due to the random draw of survey locations for training the model. In order to address

uncertainty, a Monte Carlo analysis is used to sample the parameter estimates for the logistical regression model and produce one thousand estimates of burning for each crop in the remaining forty-two states included in this *Inventory*. State-level area burned data are divided by state-level crop area data to estimate the percent of crop area burned by crop type for each state. Table 5-31 shows the resulting percentage of crop residue burned at the national scale by crop type. State-level estimates are also available upon request.

Table 5-31: U.S. Average Percent Crop Area Burned by Crop (Percent)

Crop	1990	2005	2010	2018	2019	2020
Maize	+	+	+	NE	NE	NE
Rice	12%	11%	12%	NE	NE	NE
Wheat	3%	3%	2%	NE	NE	NE
Barley	1%	1%	1%	NE	NE	NE
Oats	1%	1%	1%	NE	NE	NE
Other Small Grains	5%	4%	4%	NE	NE	NE
Sorghum	1%	1%	1%	NE	NE	NE
Cotton	7%	10%	9%	NE	NE	NE
Grass Hay	+	+	+	NE	NE	NE
Legume Hay	+	+	+	NE	NE	NE
Peas	1%	1%	1%	NE	NE	NE
Sunflower	+	+	+	NE	NE	NE
Tobacco	1%	1%	1%	NE	NE	NE
Vegetables	+	+	+	NE	NE	NE
Chickpeas	+	+	+	NE	NE	NE
Dry Beans	+	+	+	NE	NE	NE
Lentils	+	1%	1%	NE	NE	NE
Peanuts	5%	5%	5%	NE	NE	NE
Soybeans	1%	1%	1%	NE	NE	NE
Potatoes	+	+	+	NE	NE	NE
Sugarbeets	+	+	+	NE	NE	NE
Sugarcane	6%	5%	6%	4%	6%	4%

+ Does not exceed 0.5 percent.
NE (Not Estimated)

The method for estimating burned area of sugarcane is similar to the approach for other crops. Areas with sugarcane production are identified in the 2017 USDA NRI survey (USDA-NRCS 2020) based on Cropland Data Layer (USDA-NASS 2021).[34] We use the MODIS burned area product from 2002 to 2020 to identify NRI survey locations with sugarcane production that have residue burning, similar to the process for other crops described above (Giglio et al. 2015). However, area of residue burning for sugarcane was estimated for 1990 to 2001 using a linear extrapolation of the area burned from 2002 to 2020, instead of analyzing the remote sensing data for this portion of the time series. This approach is a common data splicing method for filling data gaps in time series (IPCC 2006).

Additional parameters are needed to estimate emissions from the area that has residue burning, including residue: crop ratios, dry matter fractions, carbon fractions, nitrogen fractions and combustion efficiency. Residue: crop product mass ratios, residue dry matter fractions, and the residue N contents are obtained from several sources (IPCC 2006 and sources at bottom of Table 5-32). The residue carbon contents for all crops are based on IPCC (2006) default value for herbaceous biomass. The combustion efficiency is assumed to be 90 percent for all crop types (IPCC/UNEP/OECD/IEA 1997). See Table 5-32 for a summary of the crop-specific conversion factors. Emission ratios and mole ratio conversion factors for all gases are based on the *Revised 1996 IPCC Guidelines* (IPCC/UNEP/OECD/IEA 1997) (see Table 5-33).

[34] USDA-NRI program aggregates sugarcane with other crops, but areas planted with sugarcane are identified in the USDA-NASS Crop Data Layer.

Table 5-32: Parameters for Estimating Emissions from Field Burning of Agricultural Residues

Crop	Residue/Crop Ratio	Dry Matter Fraction	Carbon Fraction	Nitrogen Fraction	Combustion Efficiency (Fraction)
Maize	0.707	0.56	0.47	0.01	0.90
Rice	1.340	0.89	0.47	0.01	0.90
Wheat	1.725	0.89	0.47	0.01	0.90
Barley	1.181	0.89	0.47	0.01	0.90
Oats	1.374	0.89	0.47	0.01	0.90
Other Small Grains	1.777	0.88	0.47	0.01	0.90
Sorghum	0.780	0.60	0.47	0.01	0.90
Cotton	7.443	0.93	0.47	0.01	0.90
Grass Hay	0.208	0.90	0.47	0.02	0.90
Legume Hay	0.290	0.67	0.47	0.01	0.90
Peas	1.677	0.91	0.47	0.01	0.90
Sunflower	1.765	0.88	0.47	0.01	0.90
Tobacco	0.300	0.87	0.47	0.01	0.90
Vegetables	0.708	0.08	0.47	0.01	0.90
Chickpeas	1.588	0.91	0.47	0.01	0.90
Dry Beans	0.771	0.90	0.47	0.01	0.90
Lentils	1.837	0.91	0.47	0.02	0.90
Peanuts	1.600	0.94	0.47	0.02	0.90
Soybeans	1.500	0.91	0.47	0.01	0.90
Potatoes	0.379	0.25	0.47	0.02	0.90
Sugarbeets	0.196	0.22	0.47	0.02	0.90
Sugarcane	0.410	0.25	0.47	0.02	0.90

NE (Not Estimated)

Notes: Chickpeas: IPCC (2006), Table 11.2; values are for Beans & pulses.

Cotton: Combined sources (Heitholt et al. 1992; Halevy 1976; Wells and Meredith 1984; Sadras and Wilson 1997; Pettigrew and Meredith 1997; Torbert and Reeves 1994; Gerik et al. 1996; Brouder and Cassmen 1990; Fritschi et al. 2003; Pettigrew et al. 2005; Bouquet and Breitenbeck 2000; Mahroni and Aharonov 1964; Bange and Milroy 2004; Hollifield et al. 2000; Mondino et al. 2004; Wallach et al. 1978).

Lentils: IPCC (2006), Table 11.2; Beans & pulses.

Peas: IPCC (2006), Table 11.2; values are for Beans & pulses.

Peanuts: IPCC (2006); Table 11.2; Root ratio and belowground N content values are for Root crops, other.

Sugarbeets: IPCC (2006); Table 11.2; values are for Tubers.

Sunflower: IPCC (2006), Table 11.2; values are for Grains.

Sugarcane: combined sources (Wiedenfels 2000, Dua and Sharma 1976; Singels & Bezuidenhout 2002; Stirling et al. 1999; Sitompul et al. 2000).

Tobacco: combined sources (Beyaert 1996; Moustakas and Ntzanis 2005; Crafts-Brandner et al. 1994; Hopkinson 1967; Crafts-Brandner et al. 1987).

Vegetables (Combination of carrots, lettuce/cabbage, melons, onions, peppers and tomatoes):

Carrots: McPharlin et al. (1992); Gibberd et al. (2003); Reid and English (2000); Peach et al. (2000); see IPCC Tubers for R:S and N fraction.

Lettuce, cabbage: combined sources (Huett and Dettman 1991; De Pinheiro Henriques & Marcelis 2000; Huett and Dettman 1989; Peach et al. 2000; Kage et al. 2003; Tan et al. 1999; Kumar et al. 1994; MacLeod et al. 1971; Jacobs et al. 2004; Jacobs et al. 2001; Jacobs et al. 2002); values from IPCC Grains used for N fraction.

Melons: Valantin et al. (1999); squash for R:S; IPCC Grains for N fraction.

Onion: Peach et al. (2000), Halvorson et al. (2002); IPCC (2006) Tubers for N fraction.

Peppers: combined sources (Costa and Gianquinto 2002; Marcussi et al. 2004; Tadesse et al. 1999; Diaz-Perez et al. 2008); IPCC Grains for N fraction.

Tomatoes: Scholberg et al. (2000a,b); Akintoye et al. (2005); values for AGR-N and BGR-N are from Grains.

Table 5-33: Greenhouse Gas Emission Ratios and Conversion Factors

Gas	Emission Ratio	Conversion Factor
CH_4:C	0.005[a]	16/12
CO:C	0.060[a]	28/12
N_2O:N	0.007[b]	44/28
NO_x:N	0.121[b]	30/14

[a] Mass of C compound released (units of C) relative to mass of total C released from burning (units of C).
[b] Mass of N compound released (units of N) relative to mass of total N released from burning (units of N).

To ensure time-series consistency, the same method is applied from 1990 to 2014 for all crops except sugarcane in which the method was applied for 1990 to 2020. For this *Inventory*, new activity data on the burned areas have not been analyzed for 2015 to 2022 for individual crops. The exception is sugarcane in which burned areas have not been analyzed for 2021 to 2022. To complete the emissions time series, a linear extrapolation of the trend is applied to estimate the emissions for the latter part of the time series. Specifically, a linear regression model with autoregressive moving-average (ARMA) errors is used to estimate the trend in emissions over time from 1990 through 2014, and the trend is used to approximate the CH_4, N_2O, CO and NO_x from 2015 to 2022 for all crops except for sugarcane, which was estimated using this method for 2021 to 2022 (Brockwell and Davis 2016). This extrapolation method is consistent with data splicing methods in IPCC (2006). The Tier 2 method described previously will be applied to recalculate the emissions for the latter part of the time series in a future *Inventory*.

Uncertainty

Emissions are estimated using a linear regression model with autoregressive moving-average (ARMA) errors for 2022. The linear regression ARMA model produced estimates of the upper and lower bounds to quantify uncertainty, and the results are summarized in Table 5-34. Methane emissions from field burning of agricultural residues in 2022 are between 0.55 and 0.70 MMT CO_2 Eq. at a 95 percent confidence level. This indicates a range of 11 percent below and 11 percent above the 2022 emission estimate of 0.6 MMT CO_2 Eq. Nitrous oxide emissions are between 0.18 and 0.23 MMT CO_2 Eq., or approximately 13 percent below and 13 percent above the 2022 emission estimate of 0.2 MMT CO_2 Eq.

Table 5-34: Approach 2 Quantitative Uncertainty Estimates for CH_4 and N_2O Emissions from Field Burning of Agricultural Residues (MMT CO_2 Eq. and Percent)

Source	Gas	2022 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Field Burning of Agricultural Residues	CH_4	0.6	0.55	0.70	-11%	+11%
Field Burning of Agricultural Residues	N_2O	0.2	0.18	0.23	-13%	+13%

[a] Range of emission estimates predicted by Monte Carlo stochastic simulation for a 95 percent confidence interval.

Due to data limitations, there are additional uncertainties in agricultural residue burning, particularly the potential omission of burning associated with Kentucky bluegrass (produced on farms for turf grass installation).

QA/QC and Verification

A source-specific QA/QC plan for field burning of agricultural residues is implemented with Tier 1 analyses, consistent with the U.S. Inventory QA/QC plan outlined in Annex 8. Quality control measures included checking input data, model scripts, and results to ensure data are properly handled throughout the inventory process.

Inventory reporting forms and text are reviewed and revised as needed to correct transcription errors. An error was identified in the calculation of the emissions using the IPCC (2006) equation after the initial compilation, which was corrected in Box 5.6. An error was also found with the estimation of non-CO_2 emissions from burning of sugarcane residue related to the GWP factors. This error was corrected.

Recalculations Discussion

Recalculations have been conducted for this *Inventory* associated with the addition of residue burning from sugarcane, which was not included in the previous *Inventory*. As a result of this change, CH_4 emissions increased by an annual average of 0.14 MMT CO_2 Eq., or 32 percent, over the time series from 1990 to 2021 compared to the previous *Inventory*. In addition, N_2O emissions increased by an annual average of 0.03 MMT CO_2 Eq., or 21 percent, over the time series from 1990 to 2021 compared to the previous *Inventory*.

Planned Improvements

A key planned improvement is to estimate the emissions associated with field burning of agricultural residues in the states of Alaska and Hawaii. In addition, a method is in development that will directly link agricultural residue burning with the Tier 3 methods that are used in several other source categories, including agricultural soil management, cropland remaining cropland, and land converted to cropland chapters of the *Inventory*. The method is based on simulating burning events directly within the DayCent process-based model framework using information derived from remote sensing fire products as described in the Methodology section. This improvement will lead to greater consistency in the methods across sources, ensuring mass balance of carbon and nitrogen in the *Inventory* analysis.

6. Land Use, Land-Use Change, and Forestry

This chapter provides an assessment of the greenhouse gas fluxes resulting from land use and land-use change in the United States.[1] The Intergovernmental Panel on Climate Change's *2006 IPCC Guidelines for National Greenhouse Gas Inventories* (IPCC 2006) recommends reporting fluxes according to changes within and conversions between all land use types including: forest land, cropland, grassland, wetlands, and settlements (as well as other land).

The greenhouse gas flux from forest land remaining forest land is reported for all forest ecosystem carbon (C) pools (i.e., aboveground biomass, belowground biomass, dead wood, litter, and mineral and organic soils), harvested wood pools, and non-carbon dioxide (non-CO_2) emissions from forest fires, the application of synthetic nitrogen fertilizers to forest soils, and the draining of organic soils. Fluxes from land converted to forest land are included for aboveground biomass, belowground biomass, dead wood, litter, and carbon stock changes from mineral soils, while carbon stock changes from drained organic soils and all non-CO_2 emissions from land converted to forest land are included in the fluxes from forest land remaining forest land as it is not currently possible to separate these fluxes by conversion category (e.g., grassland converted to forestland).

Fluxes are reported for four agricultural land use/land-use change categories: cropland remaining cropland, land converted to cropland, grassland remaining grassland, and land converted to grassland. The reported greenhouse gas fluxes from these agricultural lands include changes in soil organic carbon stocks in mineral and organic soils due to land use and management, and for the subcategories of forest land converted to cropland and forest land converted to grassland, the changes in aboveground biomass, belowground biomass, dead wood, and litter carbon stocks are also reported. The greenhouse gas flux from grassland remaining grassland also includes estimates of non-CO_2 emissions from grassland fires occurring on both grassland remaining grassland and land converted to grassland.

Fluxes from wetlands remaining wetlands include changes in carbon stocks and methane (CH_4) and nitrous oxide (N_2O) emissions from managed peatlands, aboveground and belowground biomass, dead organic matter, soil carbon stock changes and CH_4 emissions from coastal wetlands, as well as N_2O emissions from aquaculture. In addition, CH_4 emissions from reservoirs and other constructed waterbodies are included for the subcategory flooded land remaining flooded land. Estimates for land converted to wetlands include aboveground and belowground biomass, dead organic matter and soil carbon stock changes, and CH_4 emissions from land converted to vegetated coastal wetlands. CO_2 and CH_4 emissions are included for reservoirs and other constructed waterbodies under the subcategory land converted to flooded land. See Section 6.1 for additional information on wetlands included in this *Inventory*.

[1] The term "flux" is used to describe the exchange of CO_2 to and from the atmosphere, with net flux of CO_2 being either positive or negative depending on the overall balance. Removal and long-term storage of CO_2 from the atmosphere is also referred to as "carbon sequestration."

Fluxes from settlements remaining settlements include changes in carbon stocks from organic soils, N_2O emissions from nitrogen fertilizer additions to soils, and CO_2 fluxes from settlement trees and landfilled yard trimmings and food scraps. The reported greenhouse gas flux from land converted to settlements includes changes in carbon stocks in mineral and organic soils due to land use and management for all land use conversions to settlements, and the carbon stock changes in aboveground biomass, belowground biomass, dead wood, and litter are also included for the subcategory forest land converted to settlements.

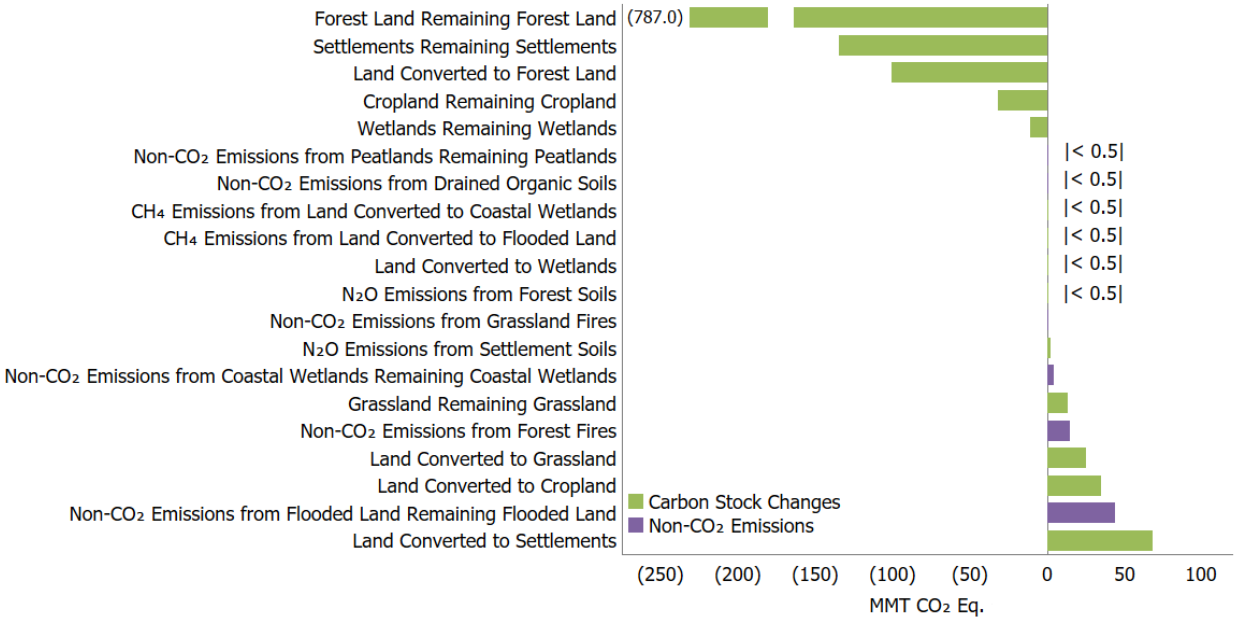
In 2022, the Land Use, Land-Use Change, and Forestry (LULUCF) sector resulted in a net increase in carbon stocks (i.e., net CO_2 removals) of 921.8 MMT CO_2 Eq.[2] This represents an offset of approximately 14.5 percent of total (i.e., gross) greenhouse gas emissions in 2022. Emissions of CH_4 and N_2O from LULUCF activities in 2022 were 58.4 and 9.1 MMT CO_2 Eq., respectively, and combined represent 1.1 percent of total greenhouse gas emissions.[3] In 2022, the overall net flux from LULUCF resulted in a removal of 854.2 MMT CO_2 Eq. Emissions, removals and net greenhouse gas flux from LULUCF are summarized in Figure 6-1 and Table 6-1 by land use and category, and Table 6-2 and Table 6-3 by gas in MMT CO_2 Eq. and kt, respectively. Trends in LULUCF sources and sinks over the 1990 to 2022 time series are shown in Figure 6-2.

Flooded land remaining flooded land was the largest source of non-CO_2 emissions from LULUCF in 2022, accounting for 65.5 percent of the LULUCF sector non-CO_2 emissions. Non-CO_2 emissions from forest fires are the second largest source of LULUCF sector emissions; these emissions have increased 155.2 percent since 1990 and accounted for 21.9 percent of LULUCF non-CO_2 emissions in 2022. Coastal wetlands remaining coastal wetlands and settlements remaining settlements soils accounted for 6.6 and 3.8 percent of non-CO_2 emissions from LULUCF in 2022, respectively, and the remaining sources account for less than one percent each.

[2] LULUCF carbon stock change is the net carbon stock change from the following categories: forest land remaining forest land, land converted to forest land, cropland remaining cropland, land converted to cropland, grassland remaining grassland, land converted to grassland, wetlands remaining wetlands, land converted to wetlands, settlements remaining settlements, and land converted to settlements.

[3] LULUCF emissions include the CH_4 and N_2O emissions reported for peatlands remaining peatlands, forest fires, drained organic soils, grassland fires, and coastal wetlands remaining coastal wetlands; CH_4 emissions from land converted to coastal wetlands, flooded land remaining flooded land, and land converted to flooded land; and N_2O emissions from forest soils and settlement soils.

Figure 6-1: 2022 LULUCF Chapter Greenhouse Gas Sources and Sinks



Note: Parentheses in horizontal axis indicate net sequestration.

Figure 6-2: Trends in Emissions and Removals (Net CO_2 Flux) from Land Use, Land-Use Change, and Forestry

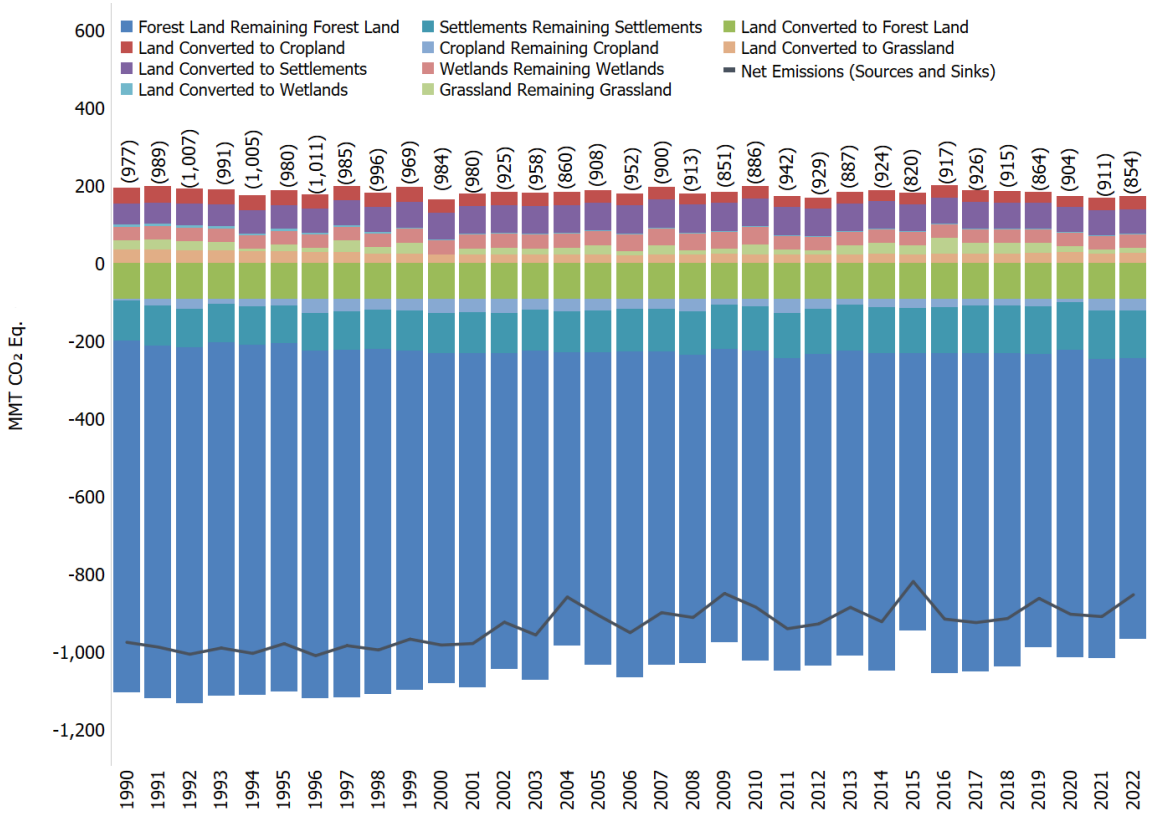


Table 6-1: Emissions and Removals (Net Flux) from Land Use, Land-Use Change, and Forestry (MMT CO_2 Eq.)

Land-Use Category	1990	2005	2018	2019	2020	2021	2022
Forest Land Remaining Forest Land	**(968.8)**	**(860.0)**	**(863.4)**	**(807.0)**	**(846.3)**	**(823.8)**	**(771.7)**
Changes in Forest Carbon Stocks[a]	(974.8)	(876.0)	(873.5)	(813.2)	(862.0)	(844.2)	(787.0)
Non-CO_2 Emissions from Forest Fires[b]	5.8	15.5	9.7	5.7	15.3	19.9	14.8
N_2O Emissions from Forest Soils[c]	0.1	0.4	0.4	0.4	0.4	0.4	0.4
Non-CO_2 Emissions from Drained Organic Soils[d]	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Land Converted to Forest Land	**(100.2)**	**(100.2)**	**(100.4)**	**(100.3)**	**(100.3)**	**(100.3)**	**(100.3)**
Changes in Forest Carbon Stocks[e]	(100.2)	(100.2)	(100.4)	(100.3)	(100.3)	(100.3)	(100.3)
Cropland Remaining Cropland	**(5.0)**	**(31.6)**	**(17.8)**	**(19.4)**	**(8.8)**	**(32.0)**	**(31.7)**
Changes in Mineral and Organic Soil Carbon Stocks	(5.0)	(31.6)	(17.8)	(19.4)	(8.8)	(32.0)	(31.7)
Land Converted to Cropland	**45.4**	**34.5**	**31.9**	**31.4**	**29.3**	**34.9**	**35.1**
Changes in all Ecosystem Carbon Stocks[f]	45.4	34.5	31.9	31.4	29.3	34.9	35.1
Grassland Remaining Grassland	**24.6**	**24.9**	**29.7**	**28.9**	**17.1**	**11.5**	**14.0**
Changes in Mineral and Organic Soil Carbon Stocks	24.4	24.1	28.6	28.5	16.1	10.6	13.4
Non-CO_2 Emissions from Grassland Fires[g]	0.2	0.8	1.1	0.3	1.1	0.9	0.6
Land Converted to Grassland	**35.3**	**21.8**	**25.2**	**25.4**	**28.7**	**24.5**	**25.6**
Changes in all Ecosystem Carbon Stocks[f]	35.3	21.8	25.2	25.4	28.7	24.5	25.6
Wetlands Remaining Wetlands	**36.8**	**39.4**	**38.2**	**38.1**	**38.1**	**38.1**	**38.1**
Changes in Organic Soil Carbon Stocks in Peatlands	1.1	1.1	0.7	0.6	0.6	0.5	0.6
Non-CO_2 Emissions from Peatlands Remaining Peatlands	+	+	+	+	+	+	+
Changes in Biomass, DOM, and Soil Carbon Stocks in Coastal Wetlands	(10.8)	(10.1)	(11.1)	(11.1)	(11.1)	(11.1)	(11.1)
CH_4 Emissions from Coastal Wetlands Remaining Coastal Wetlands	4.2	4.2	4.3	4.3	4.3	4.3	4.3
N_2O Emissions from Coastal Wetlands Remaining Coastal Wetlands	0.1	0.2	0.1	0.1	0.1	0.1	0.1
CH_4 Emissions from Flooded Land Remaining Flooded Land	42.3	44.0	44.2	44.2	44.2	44.2	44.2
Land Converted to Wetlands	**7.2**	**1.8**	**0.7**	**0.7**	**0.7**	**0.7**	**0.7**
Changes in Biomass, DOM, and Soil Carbon Stocks in Land Converted to Coastal Wetlands	0.5	0.5	(+)	(+)	(+)	(+)	(+)
CH_4 Emissions from Land Converted to Coastal Wetlands	0.3	0.3	0.2	0.2	0.2	0.2	0.2
Changes in Land Converted to Flooded Land	3.6	0.6	0.3	0.3	0.3	0.3	0.3
CH_4 Emissions from Land Converted to Flooded Land	2.9	0.4	0.2	0.2	0.2	0.2	0.2
Settlements Remaining Settlements	**(109.1)**	**(115.2)**	**(131.0)**	**(131.5)**	**(131.8)**	**(132.3)**	**(132.3)**
Changes in Organic Soil Carbon Stocks	9.9	10.1	14.4	14.6	15.1	15.4	15.4
Changes in Settlement Tree Carbon Stocks	(96.6)	(117.0)	(134.4)	(135.6)	(136.7)	(137.8)	(138.5)
N_2O Emissions from Settlement Soils[h]	2.1	3.1	2.4	2.5	2.5	2.5	2.5
Changes in Yard Trimming and Food Scrap Carbon Stocks in Landfills	(24.5)	(11.4)	(13.4)	(13.1)	(12.8)	(12.5)	(11.8)
Land Converted to Settlements	**57.2**	**77.1**	**71.4**	**70.2**	**68.8**	**68.2**	**68.2**
Changes in all Ecosystem Carbon Stocks[f]	57.2	77.1	71.4	70.2	68.8	68.2	68.2
LULUCF Emissions[i]	**58.0**	**68.9**	**62.8**	**58.0**	**68.4**	**72.9**	**67.6**
CH_4	53.1	58.5	55.5	52.5	59.3	62.1	58.4
N_2O	4.8	10.3	7.3	5.5	9.1	10.7	9.1

LULUCF Carbon Stock Change[j]	**(1,034.7)**	**(976.6)**	**(978.3)**	**(921.6)**	**(972.8)**	**(983.4)**	**(921.8)**
LULUCF Sector Net Total[k]	**(976.7)**	**(907.7)**	**(915.5)**	**(863.6)**	**(904.4)**	**(910.6)**	**(854.2)**

+ Absolute value does not exceed 0.05 MMT CO_2 Eq.

[a] Includes the net changes to carbon stocks stored in all forest ecosystem pools (estimates include carbon stock changes from drained organic soils from both forest land remaining forest land and land converted to forest land) and harvested wood products.

[b] Estimates include CH_4 and N_2O emissions from fires on both forest land remaining forest land and land converted to forest land.

[c] Estimates include N_2O emissions from N fertilizer additions on both forest land remaining forest land and land converted to forest land.

[d] Estimates include CH_4 and N_2O emissions from drained organic soils on both forest land remaining forest land and land converted to forest land. Carbon stock changes from drained organic soils are included with the forest land remaining forest land forest ecosystem pools.

[e] Includes the net changes to carbon stocks stored in all forest ecosystem pools.

[f] Includes changes in mineral and organic soil carbon stocks for all land-use conversions to cropland, grassland, and settlements. Also includes aboveground/belowground biomass, dead wood, and litter carbon stock changes for conversion of forest land to cropland, grassland, and settlements.

[g] Estimates include CH_4 and N_2O emissions from fires on both grassland remaining grassland and land converted to grassland.

[h] Estimates include N_2O emissions from nitrogen fertilizer additions on both settlements remaining settlements and land converted to settlements because it is not possible to separate the activity data at this time.

[i] LULUCF emissions include the CH_4 and N_2O emissions reported for peatlands remaining peatlands, forest fires, drained organic soils, grassland fires, and coastal wetlands remaining coastal wetlands; CH_4 emissions from land converted to coastal wetlands, flooded land remaining flooded land, and land converted to flooded land; and N_2O emissions from forest soils and settlement soils.

[j] LULUCF carbon stock change includes any carbon stock gains and losses from all land use and land-use conversion categories.

[k] The LULUCF sector net total is the net sum of all LULUCF CH_4 and N_2O emissions to the atmosphere plus LULUCF net carbon stock changes in units of MMT CO_2 Eq.

Notes: Totals may not sum due to independent rounding. Parentheses indicate net sequestration.

The carbon stock changes and emissions of CH_4 and N_2O from LULUCF are summarized in Table 6-2 (MMT CO_2 Eq.) and Table 6-3 (kt). Total net carbon sequestration in the LULUCF sector decreased by approximately 10.9 percent between 1990 and 2022. This decrease was primarily due to a decline in the rate of net carbon accumulation in forest land, as well as an increase in emissions from land converted to settlements.[4] Specifically, there was a net carbon accumulation in settlements remaining settlements, which increased from 1990 to 2022, while the net carbon accumulation in forest land remaining forest land and land converted to wetlands slowed over this period. Net carbon accumulation remained steady from 1990 to 2022 in land converted to forest land, cropland remaining cropland, land converted to cropland, and wetlands remaining wetlands, while net carbon accumulation fluctuated in grassland remaining grassland.

Flooded land remaining flooded land was the largest source of CH_4 emissions from LULUCF in 2022, totaling 44.2 MMT CO_2 Eq. (1,579 kt of CH_4). Forest fires resulted in CH_4 emissions of 9.1 MMT CO_2 Eq. (325 kt of CH_4).

For N_2O emissions, forest fires were the largest source from LULUCF in 2022, totaling 5.7 MMT CO_2 Eq. (22 kt of N_2O). Nitrous oxide emissions from fertilizer application to settlement soils in 2022 totaled to 2.5 MMT CO_2 Eq. (10 kt of N_2O). This represents an increase of 22.8 percent since 1990. Additionally, the application of synthetic fertilizers to forest soils in 2022 resulted in N_2O emissions of 0.4 MMT CO_2 Eq. (2 kt of N_2O). Nitrous oxide emissions from fertilizer application to forest soils have increased by 455.1 percent since 1990, but still account for a relatively small portion of overall emissions.

[4] Carbon sequestration estimates are net figures. The carbon stock in a given pool fluctuates due to both gains and losses. When losses exceed gains, the carbon stock decreases, and the pool acts as a source. When gains exceed losses, the carbon stock increases, and the pool acts as a sink; also referred to as net carbon sequestration or removal.

Table 6-2: Emissions and Removals from Land Use, Land-Use Change, and Forestry by Gas (MMT CO_2 Eq.)

Gas/Land-Use Category	1990	2005	2018	2019	2020	2021	2022
Carbon Stock Change (CO_2)[a]	**(1,034.7)**	**(976.6)**	**(978.3)**	**(921.6)**	**(972.8)**	**(983.4)**	**(921.8)**
Forest Land Remaining Forest Land	(974.8)	(876.0)	(873.5)	(813.2)	(862.0)	(844.2)	(787.0)
Land Converted to Forest Land	(100.2)	(100.2)	(100.4)	(100.3)	(100.3)	(100.3)	(100.3)
Cropland Remaining Cropland	(5.0)	(31.6)	(17.8)	(19.4)	(8.8)	(32.0)	(31.7)
Land Converted to Cropland	45.4	34.5	31.9	31.4	29.3	34.9	35.1
Grassland Remaining Grassland	24.4	24.1	28.6	28.5	16.1	10.6	13.4
Land Converted to Grassland	35.3	21.8	25.2	25.4	28.7	24.5	25.6
Wetlands Remaining Wetlands	(9.8)	(9.0)	(10.5)	(10.5)	(10.5)	(10.6)	(10.6)
Land Converted to Wetlands	4.1	1.1	0.3	0.3	0.3	0.3	0.3
Settlements Remaining Settlements	(111.2)	(118.3)	(133.5)	(134.0)	(134.3)	(134.8)	(134.8)
Land Converted to Settlements	57.2	77.1	71.4	70.2	68.8	68.2	68.2
CH_4	**53.1**	**58.6**	**55.6**	**52.5**	**59.3**	**62.2**	**58.4**
Forest Land Remaining Forest Land: Forest Fires[b]	3.4	9.2	6.0	3.4	9.8	12.7	9.1
Forest Land Remaining Forest Land: Drained Organic Soils[c]	+	+	+	+	+	+	+
Grassland Remaining Grassland: Grassland Fires[d]	0.1	0.4	0.6	0.2	0.6	0.5	0.3
Wetlands Remaining Wetlands: Flooded Land Remaining Flooded Land	42.3	44.0	44.2	44.2	44.2	44.2	44.2
Wetlands Remaining Wetlands: Coastal Wetlands Remaining Coastal Wetlands	4.2	4.2	4.3	4.3	4.3	4.3	4.3
Wetlands Remaining Wetlands: Peatlands Remaining Peatlands	+	+	+	+	+	+	+
Land Converted to Wetlands: Land Converted to Flooded Lands	2.9	0.4	0.2	0.2	0.2	0.2	0.2
Land Converted to Wetlands: Land Converted to Coastal Wetlands	0.3	0.3	0.2	0.2	0.2	0.2	0.2
N_2O	**4.8**	**10.4**	**7.2**	**5.5**	**9.1**	**10.8**	**9.1**
Forest Land Remaining Forest Land: Forest Fires[b]	2.4	6.3	3.7	2.3	5.5	7.2	5.7
Forest Land Remaining Forest Land: Forest Soils[e]	0.1	0.4	0.4	0.4	0.4	0.4	0.4
Forest Land Remaining Forest Land: Drained Organic Soils[c]	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Grassland Remaining Grassland: Grassland Fires[d]	0.1	0.4	0.5	0.1	0.5	0.4	0.3
Wetlands Remaining Wetlands: Coastal Wetlands Remaining Coastal Wetlands	0.1	0.2	0.1	0.1	0.1	0.1	0.1
Wetlands Remaining Wetlands: Peatlands Remaining Peatlands	+	+	+	+	+	+	+
Settlements Remaining Settlements: Settlement Soils[f]	2.1	3.1	2.4	2.5	2.5	2.5	2.5
LULUCF Carbon Stock Change[a]	**(1,034.7)**	**(976.6)**	**(978.3)**	**(921.6)**	**(972.8)**	**(983.4)**	**(921.8)**
LULUCF Emissions[g]	**57.9**	**68.9**	**62.8**	**58.0**	**68.4**	**72.9**	**67.5**
LULUCF Sector Net Total[h]	**(976.7)**	**(907.6)**	**(915.5)**	**(863.6)**	**(904.4)**	**(910.5)**	**(854.3)**

+ Absolute value does not exceed 0.05 MMT CO_2 Eq.

[a] LULUCF carbon stock change is the net carbon stock change from the following categories: forest land remaining forest land, land converted to forest land, cropland remaining cropland, land converted to cropland, grassland remaining grassland, land converted to grassland, wetlands remaining wetlands, land converted to wetlands, settlements remaining

settlements, and land converted to settlements.

[b] Estimates include CH_4 and N_2O emissions from fires on both forest land remaining forest land and land converted to forest land.

[c] Estimates include CH_4 and N_2O emissions from drained organic soils on both forest land remaining forest land and land converted to forest land.

[d] Estimates include CH_4 and N_2O emissions from fires on both grassland remaining grassland and land converted to grassland.

[e] Estimates include N_2O emissions from nitrogen fertilizer additions on both forest land remaining forest land and land converted to forest land.

[f] Estimates include N_2O emissions from nitrogen fertilizer additions on both settlements remaining settlements and land converted to settlements.

[g] LULUCF emissions include the CH_4 and N_2O emissions reported for peatlands remaining peatlands, forest fires, drained organic soils, grassland fires, and coastal wetlands remaining coastal wetlands; CH_4 emissions from flooded land remaining flooded land, land converted to flooded land, and land converted to coastal wetlands; and N_2O emissions from forest soils and settlement soils.

[h] The LULUCF sector net total is the net sum of all LULUCF CH_4 and N_2O emissions to the atmosphere plus LULUCF net carbon stock changes in units of MMT CO_2 Eq.

Notes: Totals may not sum due to independent rounding. Parentheses indicate net sequestration.

Table 6-3: Emissions and Removals from Land Use, Land-Use Change, and Forestry by Gas (kt)

Gas/Land-Use Category	1990	2005	2018	2019	2020	2021	2022
Carbon Stock Change (CO_2)[a]	**(1,034,678)**	**(976,578)**	**(978,287)**	**(921,607)**	**(972,765)**	**(983,418)**	**(921,792)**
Forest Land Remaining Forest Land	(974,778)	(876,001)	(873,508)	(813,183)	(862,033)	(844,194)	(787,006)
Land Converted to Forest Land	(100,216)	(100,151)	(100,409)	(100,284)	(100,297)	(100,305)	(100,294)
Cropland Remaining Cropland	(5,042)	(31,622)	(17,786)	(19,418)	(8,819)	(31,970)	(31,710)
Land Converted to Cropland	45,403	34,501	31,936	31,376	29,297	34,893	35,110
Grassland Remaining Grassland	24,366	24,071	28,557	28,536	16,086	10,566	13,352
Land Converted to Grassland	35,255	21,792	25,178	25,404	28,696	24,542	25,621
Wetlands Remaining Wetlands	(9,770)	(8,984)	(10,469)	(10,509)	(10,535)	(10,582)	(10,559)
Land Converted to Wetlands	4063	1069	304	309	305	309	313
Settlements Remaining Settlements	(111,203)	(118,335)	(133,464)	(134,000)	(134,301)	(134,842)	(134,812)
Land Converted to Settlements	57,242	77,081	71,373	70,161	68,836	68,165	68,195
CH_4	**1,898**	**2,091**	**1,983**	**1,875**	**2,118**	**2,218**	**2,087**
Forest Land Remaining Forest Land: Forest Fires[b]	122	328	213	120	349	452	327
Forest Land Remaining Forest Land: Drained Organic Soils[c]	1	1	1	1	1	1	1
Grassland Remaining Grassland: Grassland Fires[d]	4	15	22	6	20	18	12
Wetlands Remaining Wetlands: Flooded Land Remaining Flooded Land	1,509	1,569	1,578	1,579	1,579	1,579	1,579
Wetlands Remaining Wetlands: Coastal Wetlands Remaining Coastal Wetlands	149	151	153	153	154	154	154
Wetlands Remaining Wetlands: Peatlands Remaining Peatlands	+	+	+	+	+	+	+
Land Converted to Wetlands: Land Converted to Flooded Lands	102	16	8	8	8	8	8
Land Converted to Wetlands: Land Converted to Coastal Wetlands	10	10	7	7	7	6	6
N_2O	**18**	**39**	**27**	**21**	**34**	**41**	**34**
Forest Land Remaining Forest Land: Forest Fires[b]	9	24	14	9	21	27	21
Forest Land Remaining Forest Land: Forest Soils[e]	+	2	2	2	2	2	2

Forest Land Remaining Forest Land: Drained Organic Soils[c]	+	+	+	+	+	+	+
Grassland Remaining Grassland: Grassland Fires[d]	+	1	2	1	2	2	1
Wetlands Remaining Wetlands: Coastal Wetlands Remaining Coastal Wetlands	+	1	1	1	1	1	1
Wetlands Remaining Wetlands: Peatlands Remaining Peatlands	+	+	+	+	+	+	+
Settlements Remaining Settlements: Settlement Soils[f]	8	12	9	9	9	10	10

+ Absolute value does not exceed 0.5 kt.

[a] LULUCF carbon stock change is the net carbon stock change from the following categories: forest land remaining forest land, land converted to forest land, cropland remaining cropland, land converted to cropland, grassland remaining grassland, land converted to grassland, wetlands remaining wetlands, land converted to wetlands, settlements remaining settlements, and land converted to settlements.

[b] Estimates include CH_4 and N_2O emissions from fires on both forest land remaining forest land and land converted to forest land.

[c] Estimates include CH_4 and N_2O emissions from drained organic soils on both forest land remaining forest land and land converted to forest land.

[d] Estimates include CH_4 and N_2O emissions from fires on both grassland remaining grassland and land converted to grassland.

[e] Estimates include N_2O emissions from nitrogen fertilizer additions on both forest land remaining forest land and land converted to forest land.

[f] Estimates include N_2O emissions from nitrogen fertilizer additions on both settlements remaining settlements and land converted to settlements.

Notes: Parentheses indicate net sequestration. Totals may not sum due to independent rounding.

Each year, some emission and sink estimates in the LULUCF sector of the *Inventory* are recalculated and revised with improved methods and/or data. In general, recalculations are made to the U.S. greenhouse gas emissions and removals estimates either to incorporate new methodologies or, most commonly, to update recent historical data. These improvements are implemented consistently across the previous *Inventory's* time series (i.e., 1990 to 2021) to ensure that the trend is accurate. Of the updates implemented for this *Inventory*, the most significant include (1) managed forest land in Hawaii and several U.S. Territories[5] were included for the first time in the current *Inventory* which resulted in an increase in managed forest land area of approximate 1.3 M ha and associated increases in carbon stocks of 286 MMT C for the year 2023 in this *Inventory;* (2) updated methodological framework and accounting of carbon in structural components of trees across the United States for total tree cubic-foot volume, biomass, and carbon which led to an increase in estimated forest carbon stocks; and (3) incorporating new U.S. Department of Agriculture (USDA) National Resources Inventory (NRI) data through 2017, incorporating USDA-Natural Resources Conservation Service (NRCS) Conservation Effects Assessment Program (CEAP) survey data for 2013 to 2016, incorporating cover crop and tillage management information from the OpTIS remote-sensing data product from 2008 to 2020, in addition to other methodological updates for the estimation of croplands and grasslands described further in those respective category sections. Together, these and other updates increased total carbon sequestration estimates by an average of 133.6 MMT CO_2 Eq. (15.5 percent) and decreased total non-CO_2 emissions by 2.2 MMT CO_2 Eq. (2.6 percent) across the time series, compared to the previous *Inventory* (i.e., 1990 to 2021). For more information on specific methodological updates, please see the Recalculations Discussion within the respective category section of this chapter.

Emissions and removals reported in the LULUCF chapter include those from all states; however, for Hawaii and Alaska some emissions and removals from land use and land-use change are not included in most cases (see chapter sections on Uncertainty and Planned Improvements for more details). In addition, U.S. Territories are not included for most categories. EPA continues to review available data on an ongoing basis to include emissions and

[5] American Samoa, Guam, Norther Mariana Islands, U.S. Virgin Islands, and Puerto Rico

removals from U.S. Territories in future *Inventories* to the extent they are occurring (e.g., see Box 6-2). See Annex 5 for more information on EPA's assessment of the emissions and removals not included in this *Inventory*.

Box 6-1: Methodological Approach for Estimating and Reporting U.S. Emissions and Removals

Consistent with Article 13.7(a) of the Paris Agreement and Article 4.1(a) of the UNFCCC as well as relevant decisions under those agreements, the gross emissions total presented in this report for the United States excludes emissions and removals from LULUCF. The LULUCF Sector Net Total presented in this report for the United States includes emissions and removals from LULUCF. All emissions and removals estimates are calculated using internationally accepted methods in the *2006 IPCC Guidelines for National Greenhouse Gas Inventories (2006 IPCC Guidelines), 2013 Supplement to the 2006 IPCC Guidelines for National GHG Inventories: Wetlands,* and the *2019 Refinement to the 2006 IPCC Guidelines for National GHG Inventories*. Additionally, the calculated emissions and removals in a given year for the United States are presented in a common manner in line with the reporting guidelines for the reporting of inventories under the Paris Agreement and the UNFCCC.[6] The Parties' use of consistent methods to calculate emissions and removals for their inventories helps to ensure that these reports are comparable. The presentation of emissions and removals provided in the Land Use Land-Use Change and Forestry chapter does not preclude alternative examinations. Rather, this chapter presents emissions and removals in a common format consistent with how Parties are to report their national inventories under the Paris Agreement and the UNFCCC. The report itself, and this chapter, follow this common format, and provides an explanation of the application of methods used to calculate emissions and removals.

6.1 Representation of the U.S. Land Base

A national land use representation system that is consistent and complete, both temporally and spatially, is needed in order to assess land use and land-use change status and the associated greenhouse gas fluxes over the *Inventory* time series. This system should be consistent with IPCC (2006), such that all countries reporting on national greenhouse gas fluxes to the UNFCCC should: (1) describe the methods and definitions used to determine areas of managed and unmanaged lands in the country (Table 6-4), (2) describe and apply a consistent set of definitions for land-use categories over the entire national land base and time series (i.e., such that increases in the land areas within particular land-use categories are balanced by decreases in the land areas of other categories unless the national land base is changing) (Table 6-5), and (3) account for greenhouse gas fluxes on all managed lands. The IPCC (2006, Vol. IV, Chapter 1) considers all anthropogenic greenhouse gas emissions and removals associated with land use and management to occur on managed land, and all emissions and removals on managed land should be reported based on this guidance (see IPCC (2010), Ogle et al. (2018) for further discussion). Consequently, managed land serves as a proxy for anthropogenic emissions and removals. This proxy is intended to provide a practical framework for conducting an inventory, even though some of the greenhouse gas emissions and removals on managed land are influenced by natural processes that may or may not be interacting with the anthropogenic drivers. This section of the *Inventory* has been developed in order to comply with this guidance. While the *2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories* (IPCC 2019) provide guidance for factoring out natural emissions and removals, the United States does not apply this guidance and estimates all emissions/removals on managed land regardless of whether the driver was natural.

[6] See http://unfccc.int/resource/docs/2013/cop19/eng/10a03.pdf.

Three databases are used to track land management in the United States and are used as the basis to classify United States land area into the thirty-six IPCC land use and land-use change categories (Table 6-5) (IPCC 2006). The three primary databases are the U.S. Department of Agriculture (USDA) National Resources Inventory (NRI),[7] the USDA Forest Service (USFS) Forest Inventory and Analysis (FIA)[8] Database, and the Multi-Resolution Land Characteristics Consortium (MRLC) National Land Cover Dataset (NLCD).[9] See Table 6-6 for an overview of the land area databases used to characterize land use in federal and non-federal lands in the conterminous United States, Alaska, and Hawaii.

The total land area included in the United States *Inventory* is 936 million hectares across the 50 states.[10] Approximately 886 million hectares of this land base is considered *managed* and 50 million hectares is *unmanaged*, a distribution that has remained stable over the time series of the *Inventory* (Table 6-5). In 2022, the United States had a total of 281 million hectares of managed forest land (0.47 percent decrease compared to 1990). There are 160 million hectares of cropland (8.3 percent decrease compared to 1990), 339 million hectares of managed grassland (0.35 percent increase compared to 1990), 39 million hectares of managed wetlands (3 percent increase compared to 1990), 47 million hectares of settlements (41 percent increase compared to 1990), and 21 million hectares of managed other land (1.2 percent decrease compared to 1990) (Table 6-5).

Wetlands are not differentiated between managed and unmanaged with the exception of remote areas in Alaska, and so are classified and reported mostly as managed land within the coterminous United States.[11] In addition, carbon stock changes are not currently estimated for the entire managed land base, which leads to discrepancies between the managed land area data presented here and in the subsequent sections of the *Inventory* (e.g., grassland remaining grassland within interior Alaska).[12,13] Planned improvements are under development to estimate carbon stock changes and greenhouse gas emissions on all managed land and to ensure consistency between the total area of managed land in the land-representation description and the remainder of the *Inventory*.

Dominant land uses vary by region, largely due to climate patterns, soil types, geology, proximity to coastal regions, and historical settlement and economic patterns (Figure 6-3). Forest land tends to be more common in the eastern United States, mountainous regions of the western United States, and Alaska. Cropland is concentrated in the mid-continent region of the United States, and grassland is more common in the western United States and Alaska. Wetlands are fairly ubiquitous throughout the United States, though they are more common in the upper

[7] NRI data are available at https://www.nrcs.usda.gov/wps/portal/nrcs/main/national/technical/nra/nri/.

[8] FIA data are available at https://www.fia.fs.usda.gov/tools-data/index.php.

[9] NLCD data are available at http://www.mrlc.gov/ and MRLC is a consortium of several U.S. government agencies.

[10] The current land representation does not include areas from U.S. Territories, but there are planned improvements to include these regions in future *Inventories*. U.S. Territories represent approximately 0.1 percent of the total land base for the United States. See Box 6-2.

[11] According to the IPCC (2006), wetlands are considered managed if they are created through human activity, such as dam construction, or the water level is artificially altered by human activity. Distinguishing between managed and unmanaged wetlands in the conterminous United States and Alaska is difficult due to limited data availability. Wetlands are not characterized within the NRI with information regarding water table management. As a result, all wetlands in the conterminous United States and Hawaii are reported as managed in the land representation, but emission/removal estimates only developed for those wetlands that are included under the flooded lands, coastal wetlands or peat extraction categories. Efforts are underway to better reflect wetland estimates in the future *Inventories*. See the Planned Improvements section of the *Inventory* for future refinements to the wetland area estimates.

[12] Other discrepancies occur because the coastal wetlands analysis is based on another land use product (NOAA C-CAP) that is not currently incorporated into the land representation analysis for this section, which relies on the NRI and NLCD for wetland areas. EPA anticipates addressing these discrepancies in future *Inventories*.

[13] These "managed area" discrepancies also occur in the Common Reporting Tables (CRTs) submitted to the UNFCCC.

Midwest and eastern portions of the country, as well as coastal regions. Settlements are more concentrated along the coastal margins and in the eastern states.

Table 6-4: Managed and Unmanaged Land Area by Land-Use Categories for All 50 States (Thousands of Hectares)

Land Use Categories	1990	2005	2018	2019	2020	2021	2022
Managed Lands	**886,533**	**886,530**	**886,531**	**886,531**	**886,531**	**886,531**	**886,531**
Forest	282,375	281,806	280,971	280,440	281,067	281,071	281,041
Croplands	174,498	165,632	161,394	160,693	160,112	160,079	160,033
Grasslands	337,867	340,022	338,927	339,801	339,562	339,260	339,048
Settlements	33,427	40,172	45,971	46,312	46,641	46,960	47,185
Wetlands	37,456	38,310	38,495	38,551	38,430	38,478	38,566
Other	20,911	20,588	20,773	20,734	20,718	20,682	20,657
Unmanaged Lands	**49,708**	**49,711**	**49,710**	**49,710**	**49,710**	**49,710**	**49,710**
Forest	9,766	9,782	9,814	9,815	9,817	9,818	9,819
Croplands	0	0	0	0	0	0	0
Grasslands	25,090	25,154	25,268	25,266	25,265	25,264	25,262
Settlements	0	0	0	0	0	0	0
Wetlands	4,118	4,057	3,936	3,935	3,935	3,935	3,936
Other	10,734	10,718	10,693	10,693	10,693	10,693	10,693
Total Land Areas	**936,241**	**936,241**	**936,241**	**936,241**	**936,241**	**936,241**	**936,241**
Forest	292,140	291,588	290,784	290,255	290,883	290,889	290,861
Croplands	174,498	165,632	161,394	160,693	160,112	160,079	160,033
Grasslands	362,957	365,176	364,195	365,068	364,827	364,524	364,310
Settlements	33,427	40,172	45,971	46,312	46,641	46,960	47,185
Wetlands	41,574	42,366	42,430	42,486	42,365	42,413	42,502
Other	31,645	31,306	31,466	31,428	31,411	31,375	31,350

Table 6-5: Land Use and Land-Use Change for the U.S. Managed Land Base for All 50 States (Thousands of Hectares)

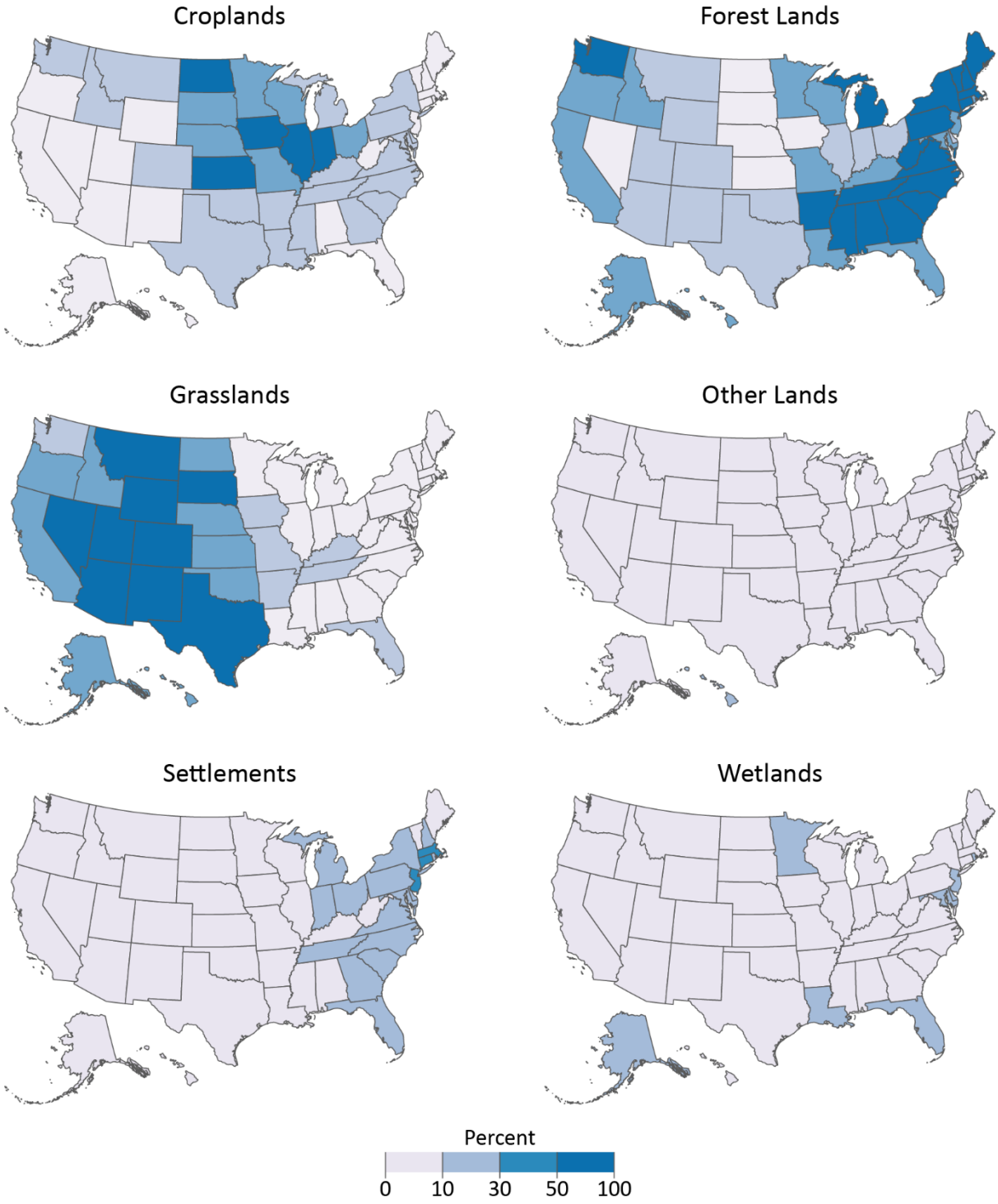
Land Use & Land-Use Change Categories[a]	1990	2005	2018	2019	2020	2021	2022
Total Forest Land	**282,375**	**281,806**	**280,971**	**280,440**	**281,067**	**281,071**	**281,041**
FF	281,290	280,587	279,683	279,167	279,818	279,829	279,802
CF	208	137	101	88	77	77	76
GF	775	968	1,038	1,048	1,036	1,037	1,040
WF	15	23	21	18	16	15	15
SF	11	18	20	21	20	19	20
OF	77	73	108	98	99	94	89
Total Cropland	**174,498**	**165,632**	**161,394**	**160,693**	**160,112**	**160,079**	**160,033**
CC	162,273	150,417	149,721	149,503	149,823	150,591	151,276
FC	173	77	63	64	60	63	65
GC	11,673	14,623	11,231	10,758	9,914	9,132	8,418
WC	119	178	99	98	86	81	75
SC	75	102	107	105	101	97	94
OC	186	235	173	166	129	115	107
Total Grassland	**337,867**	**340,022**	**338,927**	**339,801**	**339,562**	**339,260**	**339,048**
GG	328,566	315,931	318,960	320,255	320,856	321,910	322,779
FG	572	1,663	4,184	4,202	4,177	4,162	3,894
CG	8,177	17,746	13,594	13,491	13,205	12,200	11,444
WG	168	466	181	172	159	143	134
SG	43	525	230	190	139	100	93
OG	341	3,692	1,778	1,491	1,026	746	705
Total Wetlands	**37,456**	**38,310**	**38,495**	**38,551**	**38,430**	**38,478**	**38,566**

WW	36,900	36,288	37,236	37,425	37,448	37,626	37,783
FW	37	71	96	85	83	78	76
CW	145	637	362	310	261	221	187
GW	326	1,169	564	501	415	342	314
SW	0	38	17	14	10	2	2
OW	47	107	220	216	212	210	204
Total Settlements	**33,427**	**40,172**	**45,971**	**46,312**	**46,641**	**46,960**	**47,185**
SS	30,562	31,445	40,769	41,615	42,466	43,189	43,748
FS	301	466	468	455	448	446	440
CS	1,231	3,604	1,917	1,726	1,528	1,366	1,228
GS	1,276	4,371	2,630	2,349	2,062	1,830	1,648
WS	4	59	30	25	18	14	14
OS	54	229	157	141	120	115	108
Total Other Land	**20,911**	**20,588**	**20,773**	**20,734**	**20,718**	**20,682**	**20,657**
OO	20,177	17,022	18,050	18,293	18,553	18,805	18,874
FO	51	77	98	101	101	108	111
CO	287	603	629	582	540	489	444
GO	371	2,764	1,772	1,541	1,309	1,068	1,018
WO	22	100	206	206	205	204	200
SO	2	21	17	11	10	10	10
Grand Total	**886,533**	**886,530**	**886,531**	**886,531**	**886,531**	**886,531**	**886,531**

[a] The abbreviations are "F" for forest land, "C" for cropland, "G" for grassland, "W" for wetlands, "S" for settlements, and "O" for other lands. Lands remaining in the same land-use category are identified with the land-use abbreviation given twice (e.g., "FF" is forest land remaining forest land), and land-use change categories are identified with the previous land use abbreviation followed by the new land-use abbreviation (e.g., "CF" is Cropland Converted to Forest Land).

Notes: All land areas reported in this table are considered managed. A planned improvement is underway to deal with an exception for wetlands, which based on the definitions for the current U.S. Land Representation assessment includes both managed and unmanaged lands. U.S. Territories have not been classified into land uses and are not included in the U.S. Land Representation Assessment. See the Planned Improvements section for discussion on plans to include U.S. Territories in future *Inventories*. In addition, carbon stock changes are not currently estimated for the entire land base, which leads to discrepancies between the managed land area data presented here and in the subsequent sections of the *Inventory* (see land use chapters e.g., Forest Land Remaining Forest Land for more information). Totals may not sum due to independent rounding.

Figure 6-3: Percent of Total Land Area for Each State in the General Land Use Categories for 2022



Methodology and Time-Series Consistency

IPCC (2006) describes three approaches for representing land areas. Approach 1 provides data on the total area for each individual land use category, but does not provide detailed information on transfer of land area between categories following land-use change and is not spatially explicit other than at the national or regional level. With Approach 1, total net conversions between categories can be detected, but not the individual changes (i.e., additions and/or losses) between the land-use categories that led to those net changes. Approach 2 introduces tracking of individual land-use changes between the categories (e.g., forest land converted to cropland, cropland converted to forest land, and grassland converted to cropland), using survey samples or other forms of data, but does not provide spatially-explicit location data. Approach 3 extends Approach 2 by providing spatially-explicit location data, such as surveys with spatially identified sample locations and maps obtained from remote sensing products. The three approaches are not presented as hierarchical tiers and are not mutually exclusive.

According to IPCC (2006), the approach or mix of approaches selected by an inventory agency should reflect calculation needs and national circumstances. For this analysis, the NRI, FIA, and the NLCD have been combined to provide a complete representation of land use for managed lands. These data sources are described in more detail later in this section. NRI, FIA and NLCD are Approach 3 data sources that provide spatially-explicit representations of land use and land-use conversions. Lands are treated as remaining in the same category (e.g., cropland remaining cropland) if a land-use change has not occurred in the last 20 years, consistent with the IPCC guidelines (2006). Otherwise, the land is classified in a land-use change category based on the current use and most recent use before conversion to the current use (e.g., cropland converted to forest land).

Definitions of Land Use in the United States

Managed and Unmanaged Land

The United States definition of managed land is similar to the general definition of managed land provided by the IPCC (2006), but with some additional elaboration to reflect national circumstances. Based on the following definitions, most lands in the United States are classified as managed:

- *Managed Land*: Land is considered managed if direct human intervention has influenced its condition. Direct intervention occurs mostly in areas accessible to human activity and includes altering or maintaining the condition of the land to produce commercial or non-commercial products or services; to serve as transportation corridors or locations for buildings, landfills, or other developed areas for commercial or non-commercial purposes; to extract resources or facilitate acquisition of resources; or to provide social functions for personal, community, or societal objectives where these areas are readily accessible to society.[14]
- *Unmanaged Land*: All other land is considered unmanaged. Unmanaged land is largely comprised of areas inaccessible to society due to the remoteness of the locations. Though these lands may be influenced

[14] Wetlands are an exception to this general definition, because these lands, as specified by IPCC (2006), are only considered managed if they are created through human activity, such as dam construction, or the water level is artificially altered by human activity. Distinguishing between managed and unmanaged wetlands in the United States is difficult due to limited data availability. Wetlands are not characterized within the NRI with information regarding water table management or origin (i.e., constructed rather than natural origin). Therefore, unless wetlands are converted into cropland or grassland, it is not possible to know if they are artificially created or if the water table is managed based on the use of NRI data. As a result, most wetlands are reported as managed with the exception of wetlands in remote areas of Alaska, but emissions from managed wetlands are only reported for coastal regions, flooded lands (e.g., reservoirs) and peatlands where peat extraction occurs due to insufficient activity data to estimate emissions and limited resources to improve the *Inventory*. See the Planned Improvements section of the *Inventory* for future refinements to the wetland area estimates.

indirectly by human actions such as atmospheric deposition of chemical species produced in industry or CO_2 fertilization, they are not influenced by a direct human intervention.[15]

In addition, land that is previously managed remains in the managed land base for 20 years before re-classifying the land as unmanaged in order to account for legacy effects of management on carbon stocks.[16] Unmanaged land is also re-classified as managed over time if anthropogenic activity is introduced into the area based on the definition of managed land.

Land-Use Categories

As with the definition of managed lands, IPCC (2006) provides general non-prescriptive definitions for the six main land-use categories: forest land, cropland, grassland, wetlands, settlements and other land. In order to reflect national circumstances, country-specific definitions have been developed, based predominantly on criteria used in the land-use surveys for the United States. Specifically, the definition of forest land is based on the FIA definition of forest,[17] while definitions of cropland, grassland, and settlements are based on the NRI.[18] The definitions for other land and wetlands are based on the IPCC (2006) definitions for these categories.

- *Forest Land*: A land-use category that includes areas at least 120 feet (36.6 meters) wide and at least one acre (0.4 hectare) in size with at least ten percent cover (or equivalent stocking) by live trees including land that formerly had such tree cover and that will be naturally or artificially regenerated. Trees are woody plants having a more or less erect perennial stem(s) capable of achieving at least 3 inches (7.6 cm) in diameter at breast height, or 5 inches (12.7 cm) diameter at root collar, and a height of 16.4 feet (5 m) at maturity in situ. Forest land includes all areas recently having such conditions and currently regenerating or capable of attaining such condition in the near future. Forest land also includes transition zones, such as areas between forest and non-forest lands, that have at least ten percent cover (or equivalent stocking) with live trees and forest areas adjacent to urban and built-up lands. Unimproved roads and trails, streams, and clearings in forest areas are classified as forest if they are less than 120 feet (36.6 m) wide or an acre (0.4 ha) in size. However, land is not classified as forest land if completely surrounded by urban or developed lands, even if the criteria are consistent with the tree area and cover requirements for forest land. These areas are classified as settlements. In addition, forest land does not include land that is predominantly under an agricultural land use (Nelson et al. 2020).
- *Cropland*: A land-use category that includes areas used for the production of adapted crops for harvest; this category includes both cultivated and non-cultivated lands. Cultivated crops include row crops or close-grown crops and also pasture in rotation with cultivated crops. Non-cultivated cropland includes continuous hay, perennial crops (e.g., orchards) and horticultural cropland. Cropland also includes land with agroforestry, such as alley cropping and windbreaks,[19] if the dominant use is crop production, assuming the stand or woodlot does not meet the criteria for forest land. Lands in temporary fallow or

[15] There are some areas, such as forest land and grassland in Alaska that are classified as unmanaged land due to the remoteness of their location.

[16] There are examples of managed land transitioning to unmanaged land in the United States. For example, in 2018, 100 hectares of managed grassland converted to unmanaged because data indicated that no further grazing occurred. Livestock data are collected annually by the Department of Agriculture, and no livestock had occurred in the area since the mid-1970s, and therefore there was no longer active management through livestock grazing. The area is also remote, at least 10 miles from roads and settlements, and therefore the land was no longer managed based on the implementation criteria.

17 See https://www.fia.fs.usda.gov/library/field-guides-methods-proc/docs/2022/core_ver9-2_9_2022_SW_HW%20table.pdf, page 23.

[18] See https://www.nrcs.usda.gov/wps/portal/nrcs/main/national/technical/nra/nri/.

[19] Currently, there is no data source to account for biomass carbon stock change associated with woody plant growth and losses in alley cropping systems and windbreaks in cropping systems, although these areas are included in the cropland land base.

enrolled in conservation reserve programs (i.e., set-asides[20]) are also classified as cropland, as long as these areas do not meet the forest land criteria. Roads through cropland, including interstate highways, state highways, other paved roads, gravel roads, dirt roads, and railroads are excluded from cropland area estimates and are, instead, classified as settlements.

- *Grassland*: A land-use category on which the plant cover is composed principally of grasses, grass-like plants (i.e., sedges and rushes), forbs, or shrubs suitable for grazing and browsing, and includes both pastures and native rangelands. This includes areas where practices such as clearing, burning, chaining, and/or chemicals are applied to maintain the grass vegetation. Land is also categorized as grassland if there have been three or fewer years of continuous hay production.[21] Savannas, deserts, and tundra are considered grassland. Drained wetlands are considered grassland if the dominant vegetation meets the plant cover criteria for grassland. Woody plant communities of low forbs, shrubs and woodlands, such as sagebrush, mesquite, chaparral, mountain shrubland, and pinyon-juniper, are also classified as grassland if they do not meet the criteria for forest land. Grassland includes land managed with agroforestry practices, such as silvopasture and windbreaks, if the land is principally grass, grass-like plants, forbs, and shrubs suitable for grazing and browsing, and assuming the stand or woodlot does not meet the criteria for forest land. Roads through grassland, including interstate highways, state highways, other paved roads, gravel roads, dirt roads, and railroads are excluded from grassland and are, instead, classified as settlements.
- *Wetlands*: A land-use category that includes land covered or saturated by water for all or part of the year, in addition to lakes, reservoirs, and rivers. In addition, all coastal wetlands are considered managed regardless of whether the water level is changed or if they were created by human activity. Certain areas that fall under the managed wetlands definition are included in other land uses based on the IPCC guidance and national circumstances, including lands that are flooded for most or just part of the year in croplands (e.g., rice cultivation and cranberry production), grasslands (e.g., wet meadows dominated by grass cover) and forest lands (e.g., riparian forests near waterways). See Section 6.8 for more information.
- *Settlements*: A land-use category representing developed areas consisting of units equal to or greater than 0.25 acres (0.1 ha) that includes residential, industrial, commercial, and institutional land; construction sites; public administrative sites; railroad yards; cemeteries; airports; golf courses; sanitary landfills; sewage treatment plants; water control structures and spillways; parks within urban and built-up areas; and highways, railroads, and other transportation facilities. Also included are all tracts that may meet the definition of forest land, and tracts of less than ten acres (4.05 ha) that may meet the definitions for cropland, grassland, or other land but are completely surrounded by urban or built-up land, and so are included in the settlements category. Rural transportation corridors located within other land uses (e.g., forest land, cropland, and grassland) are also included in settlements.
- *Other Land*: A land-use category that includes bare soil, rock, ice, and all land areas that do not fall into any of the other five land-use categories. Following the guidance provided by the IPCC (2006), carbon stock changes and non-CO_2 emissions are not estimated for other lands because these areas are largely devoid of biomass, litter and soil carbon pools. However, carbon stock changes and non-CO_2 emissions should be estimated for land converted to other land during the first 20 years following conversion to account for legacy effects.

[20] A set-aside is cropland that has been taken out of active cropping and converted to some type of vegetative cover, including, for example, native grasses or trees, but is still classified as cropland based on national circumstances.

[21] Areas with four or more years of continuous hay production are cropland because the land is typically more intensively managed with cultivation, greater amounts of inputs, and other practices. Occasional harvest of hay from grasslands typically does not involve cultivation or other intensive management practices.

Land Use Data Sources: Description and Application to U.S. Land Area Classification

U.S. Land Use Data Sources

The three main sources for land use data in the United States are the NRI, FIA, and the NLCD (Table 6-6). These data sources are combined to account for land use in all 50 states. FIA and NRI data are used when available for an area because these surveys contain additional information on management, site conditions, crop types, biometric measurements, and other data that are needed to estimate carbon stock changes, N_2O, and CH_4 emissions on those lands. If NRI and FIA data are not available for an area, however, then the NLCD product is used to represent the land use. Sources of land use data included in the land representation in this *Inventory* are consistent with those included in the previous *Inventory.*

Table 6-6: Data Sources Used to Determine Land Use and Land Area for the Conterminous United States, Hawaii, and Alaska

	NRI	FIA	NLCD
Forest Land			
Conterminous United States			
Non-Federal		•	
Federal		•	
Hawaii			
Non-Federal	•		
Federal			•
Alaska			
Non-Federal		•	
Federal		•	
Croplands, Grasslands, Other Lands, Settlements, and Wetlands			
Conterminous United States			
Non-Federal	•		
Federal			•
Hawaii			
Non-Federal	•		
Federal			•
Alaska			
Non-Federal			•
Federal			•

National Resources Inventory

For the *Inventory*, the NRI is the official source of data for land use and land-use change on non-federal lands in the conterminous United States and Hawaii, and is also used to determine the total land base for the conterminous United States and Hawaii. The NRI is a statistically-based survey conducted by the USDA Natural Resources Conservation Service and is designed to assess soil, water, and related environmental resources on non-federal lands. The NRI has a stratified multi-stage sampling design, where primary sample units are stratified on the basis of county and township boundaries defined by the United States Public Land Survey (Nusser and Goebel 1997). Within a primary sample unit (typically a 160 acre [64.75 ha] square quarter-section), three sample points are selected according to a restricted randomization procedure. Each point in the survey is assigned an area weight (expansion factor) based on other known areas and land use information (Nusser and Goebel 1997). The NRI survey utilizes data obtained from remote sensing imagery and site visits in order to provide detailed information on land use and management, particularly for croplands and grasslands (i.e., agricultural lands), and is used as the

basis to account for carbon stock changes in agricultural lands (except federal grasslands). The NRI survey was conducted every five years between 1982 and 1997, but shifted to annualized data collection in 1998. The land use between five-year periods from 1982 and 1997 are assumed to be the same for a five-year time period if the land use is the same at the beginning and end of the five-year period (note: most of the data have the same land use at the beginning and end of the five-year periods). If the land use had changed during a five-year period, then the change is assigned at random to one of the five years. For crop histories, years with missing data are estimated based on the sequence of crops grown during years preceding and succeeding a missing year in the NRI history. This gap-filling approach allows for development of a full time series of land use data for non-federal lands in the conterminous United States and Hawaii. This *Inventory* incorporates data through 2017 from the NRI. The land use patterns are assumed to remain the same from 2018 through 2022 for this *Inventory*, but the time series will be updated when new data are integrated into the land representation analysis.

Forest Inventory and Analysis

The FIA program, conducted by the USFS, is the official source of data on forest land area and management data for the *Inventory* and is another statistically-based survey for the United States. The Forest Inventory and Analysis engages in a hierarchical system of sampling, with sampling categorized as Phases 1 through 3, in which sample points for each consecutive phase are subsets of the previous phase. Phase 1 refers to collection of remotely-sensed data (either aerial or satellite imagery) primarily to classify land into forest or non-forest and to identify landscape patterns like fragmentation and urbanization. Phase 2 is the collection of field data on a network of ground plots that enable classification and summarization of area, tree, and other attributes associated with forest land uses. Phase 3 plots are a subset of Phase 2 plots where data on indicators of forest health are measured. Data from all three phases are also used to estimate carbon stock changes for forest land. Historically, FIA inventory surveys have been conducted periodically, with all plots in a state being measured at a frequency of every five to ten years. A new national plot design and annual sampling design was introduced by the FIA program in 1998 and is now used in all states. Annualized sampling means that a portion of plots throughout each state is sampled each year, with the goal of measuring all plots once every five to seven years in the eastern United States and once every ten years in the western United States. See Annex 3.13 for the specific survey data available by state. The most recent year of available data varies state by state (range of most recent data is from 2019 through 2022; see Table A-202 in Annex 3.13).

National Land Cover Dataset

As noted above, while the NRI survey sample covers the conterminous United States and Hawaii, land use data are only collected on non-federal lands. Gaps exist in the land representation when the NRI and FIA datasets are combined, such as federal grasslands operated by Bureau of Land Management (BLM), USDA, and National Park Service, as well as Alaska.[22] The NLCD is used to account for land use on federal lands in the conterminous United States and Hawaii, in addition to federal and non-federal lands in Alaska with the exception of forest lands in Alaska.

NLCD products provide land-cover for 1992, 2001, 2004, 2006, 2008, 2011, 2013, 2016, 2019, and 2021 in the conterminous United States (Yang et al. 2018; Fry et al. 2011; Homer et al. 2007, 2015, Dewitz, 2023), and also for Alaska in 2001, 2011, and 2016 and Hawaii in 2001. Note that the 2021 NLCD product was not available at the time the land representation was begun for this *Inventory* so it was not included. A NLCD change product is not available for Hawaii because data are only available for one year, i.e., 2001. The NLCD products are based primarily on Landsat Thematic Mapper imagery at a 30-meter resolution, and the land-cover categories have been aggregated into the 36 IPCC land-use categories for the conterminous United States and Alaska, and into the six IPCC land-use categories for Hawaii. The land-use patterns are assumed to remain the same after the last year of

[22] The NRI survey program does not include U.S. Territories with the exception of non-federal lands in Puerto Rico. The FIA program recently began implementing surveys of forest land in U.S. Territories and those data will be used in the years ahead. Furthermore, NLCD does not include coverage for all U.S. Territories.

data in the time series, which is 2001 for Hawaii, 2019 for the conterminous United States and 2016 for Alaska, but the time series will be updated when new data are released.

For the conterminous United States, the aggregated maps of IPCC land-use categories obtained from the NLCD products were used in combination with the NRI database to represent land use and land-use change for federal lands, with the exception of forest lands, which are based on FIA. Specifically, NRI survey locations designated as federal lands were assigned a land use/land-use change category based on the NLCD maps that had been aggregated into the IPCC categories. This analysis addressed shifts in land ownership across years between federal or non-federal classes as represented in the NRI survey (i.e., the ownership is classified for each survey location in the NRI). The sources of these additional data are discussed in subsequent sections of the report.

Managed Land Designation

Lands are designated as managed in the United States based on the definition provided earlier in this section. The following criteria are used in order to apply the definition in an analysis of managed land:

- All croplands and settlements are designated as managed so only grassland, forest land, wetlands or other lands may be designated as unmanaged land;[23]
- All forest lands with active fire protection are considered managed;
- All forest lands designated for timber harvests are considered managed;
- All grasslands are considered managed at a county scale if there are grazing livestock in the county;
- Other areas are considered managed if accessible based on the proximity to roads and other transportation corridors, and/or infrastructure;
- Protected lands maintained for recreational and conservation purposes are considered managed (i.e., managed by public and/or private organizations);
- Lands with active and/or past resource extraction are considered managed; and
- Lands that were previously managed but subsequently classified as unmanaged remain in the managed land base for 20 years following the conversion to account for legacy effects of management on carbon stocks.

The analysis of managed lands, based on the criteria listed above, is conducted using a geographic information system (Ogle et al. 2018). Lands that are used for crop production or settlements are determined from the NLCD (Fry et al. 2011; Homer et al. 2007; Homer et al. 2015). Forest lands with active fire management are determined from maps of federal and state management plans from the National Atlas (U.S. Department of Interior 2005) and Alaska Interagency Fire Management Council (1998). It is noteworthy that all forest lands in the conterminous United States have active fire protection, and are therefore designated as managed regardless of accessibility or other criteria. In addition, forest lands with timber harvests are designated as managed based on county-level estimates of timber products in the U.S. Forest Service Timber Products Output Reports (U.S. Department of Agriculture 2012). Timber harvest data lead to additional designation of managed forest land in Alaska. The designation of grasslands as managed is based on grazing livestock population data at the county scale from the USDA National Agricultural Statistics Service (U.S. Department of Agriculture 2015). Accessibility is evaluated based on a 10-km buffer surrounding road and train transportation networks using the ESRI Data and Maps product (ESRI 2008), and a 10-km buffer surrounding settlements using NLCD.

Lands maintained for recreational purposes are determined from analysis of the Protected Areas Database (U.S. Geological Survey 2012). The Protected Areas Database includes lands protected from conversion of natural habitats to anthropogenic uses and describes the protection status of these lands. Lands are considered managed

[23] All wetlands are considered managed in this *Inventory* with the exception of remote areas in Alaska. Distinguishing between managed and unmanaged wetlands in the conterminous United States and Hawaii is difficult due to limited data availability. Wetlands are not characterized within the NRI with information regarding water table management. Regardless, a planned improvement is underway to subdivide managed and unmanaged wetlands.

that are protected from development if the regulations allow for extractive or recreational uses or suppression of natural disturbance (e.g., forest lands with active fire protection). Lands that are protected from development and not accessible to human intervention, including no suppression of disturbances or extraction of resources, are not included in the managed land base.

Multiple data sources are used to determine lands with active resource extraction: Alaska Oil and Gas Information System (Alaska Oil and Gas Conservation Commission 2009), Alaska Resource Data File (U.S. Geological Survey 2012), Active Mines and Mineral Processing Plants (U.S. Geological Survey 2005), and *Coal Production and Preparation Report* (U.S. Energy Information Administration 2011). A buffer of 3,300 and 4,000 meters is established around petroleum extraction and mine locations, respectively, to account for the footprint of operation and impacts of activities on the surrounding landscape. The buffer size is based on visual analysis of disturbance to the landscape for approximately 130 petroleum extraction sites and 223 mines. After applying the criteria identified above, the resulting managed land area is overlaid on the NLCD to estimate the area of managed land by land use for both federal and non-federal lands in Alaska. The remaining land represents the unmanaged land base. The resulting spatial product is also used to identify NRI survey locations that are considered managed and unmanaged for the conterminous United States and Hawaii.[24]

Approach for Combining Data Sources

The managed land base in the United States has been classified into the 36 IPCC land use/land-use conversion categories (Table 6-5) using definitions developed to meet national circumstances, while adhering to IPCC guidelines (2006).[25] In practice, the land was initially classified into land-use subcategories within the NRI, FIA, and NLCD datasets, and then aggregated into the 36 broad land use and land-use change categories identified in IPCC (2006).

All three datasets provide information on forest land areas in the conterminous United States, but the area data from FIA serve as the official dataset for forest land. Therefore, another step in the analysis is to address the inconsistencies in the representation of the forest land among the three databases. NRI and FIA have different criteria for classifying forest land in addition to different sampling designs, leading to discrepancies in the resulting estimates of forest land area on non-federal land in the conterminous United States. Similarly, there are discrepancies between the NLCD and FIA data for defining and classifying forest land on federal lands. Any change in forest land area in the NRI and NLCD also requires a corresponding change in other land use areas because of the dependence between the forest land area and the amount of land designated as other land uses, such as the amount of grassland, cropland, and wetlands (i.e., areas for the individual land uses must sum to the total managed land area of the country).

FIA is the main database for forest statistics, and consequently, the NRI and NLCD are adjusted to achieve consistency with FIA estimates of forest land in the conterminous United States. Adjustments are made in the forest land remaining forest land, land converted to forest land, and forest land converted to other uses (i.e., grassland, cropland, settlements, other lands, and wetlands). All adjustments are made at the state scale to address the discrepancies in areas associated with forest land and conversions to and from forest land. There are three steps in this process. The first step involves adjustments to land converted to forest land (grassland, cropland, settlements, other lands, and wetlands), followed by a second step in which there are adjustments in forest land converted to another land use (i.e., grassland, cropland, settlements, other lands, and wetlands), and the last step is to adjust forest land remaining forest land.

In the first step, land converted to forest land in the NRI and NLCD are adjusted to match the state-level estimates in the FIA data for non-federal and federal land converted to forest land, respectively. FIA data have not provided

[24] The exception is cropland and settlement areas in the NRI, which are classified as managed, regardless of the managed land base obtained from the spatial analysis described in this section.

[25] Definitions are provided in the previous section.

specific land-use categories that are converted to forest land in the past, but rather a sum of all land converted to forest land.[26] The NRI and NLCD provide information on specific land-use conversions, such as grassland converted to forest land. Therefore, adjustments at the state level to NRI and NLCD are made proportional to the amount of specific land-use conversions into forest land for the state, prior to any further adjustments. For example, if 50 percent of the land-use change to forest land is associated with grassland converted to forest land in a state according to NRI or NLCD, then half of the discrepancy with FIA data in the area of land converted to forest land is addressed by increasing or decreasing the area in grassland converted to forest land. Moreover, any increase or decrease in grassland converted to forest land in NRI or NLCD is addressed by a corresponding change in the area of grassland remaining grassland, so that the total amount of managed area is not changed within an individual state. Since the sum of all land converted to forest land is used to adjust specific land-use conversions into forest land for the state-level estimates in the NRI and NLCD, there is the potential for differences in area estimates in states where specific land-use conversions into forest land do not exist in the FIA data.

In the second step, state-level areas are adjusted in the NRI and NLCD to address discrepancies with FIA data for forest land converted to other uses. Similar to land converted to forest land, FIA have not provided information on the specific land-use changes in the past,[27] so areas associated with forest land conversion to other land uses in NRI and NLCD are adjusted proportional to the amount of area in each conversion class in these datasets. Since the sum of all forest land converted to other uses is used to adjust specific land-used conversions out of forest land for the state-level estimates in the NRI and NLCD, there is the potential for differences in area estimates in states where a specific land-use conversion out of forest land does not exist in the FIA data.

In the final step, the area of forest land remaining forest land in each state according to the NRI and NLCD is adjusted to match the FIA estimates for non-federal and federal land, respectively. It is assumed that the majority of the discrepancy in forest land remaining forest land is associated with less-precise estimates of grassland remaining grassland and wetlands remaining wetlands in the NRI and NLCD. This step also assumes that there are no changes in the land-use conversion categories. Therefore, corresponding adjustments are made in the area estimates of grassland remaining grassland and wetlands remaining wetlands from the NRI and NLCD. This adjustment balances the change in forest land remaining forest land area, which ensures no change in the overall amount of managed land within an individual state. The adjustments are based on the proportion of land within each of these land-use categories at the state level according to NRI and NLCD (i.e., a higher proportion of grassland led to a larger adjustment in grassland area).

The modified NRI data are then aggregated to provide the land use and land-use change data for non-federal lands in the conterminous United States, and the modified NLCD data are aggregated to provide the land use and land-use change data for federal lands. Data for all land uses in Hawaii are based on NRI for non-federal lands and on NLCD for federal lands. Land use data in Alaska are based on the NLCD data after adjusting this dataset to be consistent with forest land areas in the FIA (Table 6-6). The result is land use and land-use change data for the conterminous United States, Hawaii, and Alaska.

A summary of the details on the approach used to combine data sources for each land use are described below.

- *Forest Land*: Land representation for both non-federal and federal forest lands in the conterminous United States and Alaska are based on the FIA. The FIA is used as the basis for both forest land area data as well as to estimate carbon stocks and fluxes on forest land in the conterminous United States and Alaska. The FIA does have survey plots in Alaska that are used to determine the carbon stock changes, and the associated area data for this region are harmonized with NLCD using the methods described above. NRI is used in the current report to provide forest land areas on non-federal lands in Hawaii, and NLCD is

[26] The FIA program has started to collect data on the specific land uses that are converted to forest land, which will be further investigated and incorporated into a future *Inventory*.

[27] The FIA program has started to collect data on the specific land uses following conversion from forest land, which will be further investigated and incorporated into a future *Inventory*.

used for federal lands. In Hawaii and the U.S. Territories, FIA data are being collected; these data were used to compile area estimates and emissions and removals for forest land in this *Inventory*.

- *Cropland*: Cropland is classified using the NRI, which covers all non-federal lands within 49 states (excluding Alaska), including state and local government-owned land as well as tribal lands. The NRI is used as the basis for both cropland area data as well as to estimate soil carbon stocks and fluxes on cropland. The NLCD is used to determine cropland area and soil carbon stock changes on federal lands in the conterminous United States and Hawaii. The NLCD is also used to determine croplands in Alaska, but carbon stock changes are not estimated for this region in the current *Inventory*.
- *Grassland*: Grassland on non-federal lands is classified using the NRI within 49 states (excluding Alaska), including state and local government-owned land as well as tribal lands. The NRI is used as the basis for both grassland area data as well as to estimate soil carbon stocks and non-CO_2 greenhouse emissions on grassland. Grassland area and soil carbon stock changes are determined using the classification provided in the NLCD for federal land within the conterminous United States. The NLCD is also used to estimate the areas of federal and non-federal grasslands in Alaska, and the federal grasslands in Hawaii, but the current *Inventory* does not include carbon stock changes in these areas.
- *Wetlands*: The NRI captures wetlands on non-federal lands within 49 states (excluding Alaska), while the land representation data for federal wetlands and wetlands in Alaska are based on the NLCD.[28]
- *Settlements*: The NRI captures non-federal settlement area in 49 states (excluding Alaska). If areas of forest land or grassland under ten acres (4.05 ha) are contained within settlements or urban areas, they are classified as settlements (urban) in the NRI database. If these parcels exceed the ten-acre (4.05 ha) threshold and are grassland, they are classified as grassland by NRI. Regardless of size, a forested area is classified as non-forest by FIA if it is located within an urban area. Land representation for settlements on federal lands and Alaska is based on the NLCD.
- *Other Land*: Any land that is not classified into one of the previous five land-use categories is categorized as other land using the NRI for non-federal areas in the conterminous United States and Hawaii and using the NLCD for the federal lands in all regions of the United States and for non-federal lands in Alaska.

Some lands can be classified into one or more categories due to multiple uses that meet the criteria of more than one definition. However, a ranking has been developed for assignment priority in these cases. The ranking process is from highest to lowest priority based on the following order:

Settlements > Cropland > Forest Land > Grassland > Wetlands > Other Land

Settlements are given the highest assignment priority because they are extremely heterogeneous with a mosaic of patches that include buildings, infrastructure, and travel corridors, but also open grass areas, forest patches, riparian areas, and gardens. The latter examples could be classified as grassland, forest land, wetlands, and cropland, respectively, but when located in close proximity to settlement areas, they tend to be managed in a unique manner compared to non-settlement areas. Consequently, these areas are assigned to the settlements land-use category. Cropland is given the second assignment priority, because cropping practices tend to dominate management activities on areas used to produce food, forage, or fiber. The consequence of this ranking is that crops in rotation with pasture are classified as cropland, and land with woody plant cover that is used to produce crops (e.g., orchards) is classified as cropland, even though these areas may also meet the definitions of grassland or forest land, respectively. Similarly, wetlands are considered croplands if they are used for crop production, such as rice or cranberries. Forest land occurs next in the priority assignment because traditional forestry practices tend to be the focus of the management activity in areas with woody plant cover that are not croplands (e.g., orchards)

[28] This analysis does not distinguish between managed and unmanaged wetlands except for remote areas in Alaska, but there is a planned improvement to subdivide managed and unmanaged wetlands for the entire land base.

or settlements (e.g., housing subdivisions with significant tree cover). Grassland occurs next in the ranking, while wetlands and then other land complete the list.

The assignment priority does not reflect the level of importance for reporting greenhouse gas emissions and removals on managed land, but is intended to classify all areas into a discrete land-use category. Currently, the IPCC does not make provisions in the guidelines for assigning land to multiple uses. For example, a wetland is classified as forest land if the area has sufficient tree cover to meet the stocking and stand size requirements. Similarly, wetlands are classified as cropland if they are used for crop production, such as rice, or as grassland if they are composed principally of grasses, grass-like plants (i.e., sedges and rushes), forbs, or shrubs suitable for grazing and browsing. Regardless of the classification, emissions and removals from these areas should be included in the *Inventory* if the land is considered managed, and therefore impacted by anthropogenic activity in accordance with the guidance provided by the IPCC (2006).

QA/QC and Verification

The land base obtained from the NRI, FIA, and NLCD was compared to the Topologically Integrated Geographic Encoding and Referencing (TIGER) Survey (U.S. Census Bureau 2010). The United States Census Bureau gathers data on the population and economy and has a database of land areas for the country. The area estimates of land-use categories, based on NRI, FIA, and NLCD, are obtained from remote sensing data instead of the land survey approach used by the United States Census Survey. The Census does not provide a time series of land-use change data or land management information, which is needed for estimating greenhouse gas emissions from land use and land-use change. Regardless, the Census does provide sufficient information to provide a quality assurance check on the *Inventory* data. There are 46 million more hectares of land in the United States according to the Census, compared to the total area estimate of 936 million hectares obtained from the combined NRI, FIA, and NLCD data, a 4.8 percent difference. Much of this difference is associated with open water in coastal regions and the Great Lakes, which is included in the TIGER Survey of the Census, but not included in the land representation using the NRI, FIA and NLCD. There is only a 0.4 percent difference when open water in coastal regions is removed from the TIGER data. General QC procedures for data gathering and data documentation also were applied consistent with the QA/QC and Verification Procedures described in Annex 8.

Recalculations Discussion

The land representation estimates were recalculated from the previous *Inventory* with the following datasets: a) updated FIA data from 1990 to 2022 for the conterminous United States and Alaska, b) NRI data from 1990 to 2017 for the conterminous United States and Hawaii, and c) NLCD data for the conterminous United States from 2001 through 2019 and Alaska from 2001 through 2016. There were several changes in methods that resulted in small changes between this *Inventory* and the previous *Inventory*. First, pasture land was previously classified as cropland in the compilation of forest land conversion estimates using FIA data and is now classified as grassland to align with methods and definitions used to classify grasslands using NRI data. This led to a decrease in total managed cropland area and an increase in grassland area. Second, FIA data are now used to classify forest land and conversions to and from forest land in coastal southeast and southcentral Alaska which resulted in minor changes, primarily between forest land, wetlands, and grasslands, between this *Inventory* and the previous *Inventory*. Lastly, methods for classifying wetlands using FIA data were refined so that all water bodies are now classified as wetlands (previously some water bodies were classified as other lands) aligning with methods and definitions in the NRI. Collectively, these refinements in FIA methods to better align with methods for the other data sources (i.e., NRI and NLCD) resulted in changes throughout the entire representation of land (see "Approach for Combining Data Sources"). Specifically, managed wetland area decreased, on average over the time series, by 1.2 percent. Grassland and forest land increased by 0.1 percent and 0.04 percent, respectively. Settlement area decreased by 0.05 percent and cropland and managed other lands were essentially unchanged in the latest *Inventory*.

Planned Improvements

Research is underway to harmonize NRI and FIA sampling frames to improve consistency and facilitate estimation using multi-frame sampling. This includes development of a common land use classification schema between the two land inventories that can be used in the harmonization process. These steps will allow for population estimation exclusive of auxiliary information (e.g., NLCD). The multi-frame sample will also serve as reference data for the development of spatially explicit and spatially continuous map products for each year in the *Inventory* time series. Another key planned improvement for the *Inventory* is to fully incorporate area data by land-use type for U.S. Territories. Although most of the managed land in the United States is included in the current land use data for the conterminous United States, Alaska, and Hawaii, a complete reporting of all lands in the United States, including U.S. Territories, is a key goal for the near future. An initial assessment of data sources for land use area data for U.S. Territories by land-use category are provided in Box 6-2. In addition, this *Inventory* includes forest land areas estimated for American Samoa, Guam, Hawaii, Northern Marianas Islands, U.S. Virgin Islands, and Puerto Rico using periodic inventories from the FIA program. These estimates are included in the forest land category, and the methods for compiling these area estimates and the associated carbon stocks and fluxes and integration of these estimates into the land representation will be refined to compensate for data limitations in the time series while also taking advantage of new data and data products. See Box 6-2.

Box 6-2: Preliminary Estimates of Land Use in U.S. Territories

Several programs have developed land-cover maps for U.S. Territories using remote sensing imagery, including the Gap Analysis Program, Caribbean Land Cover project, National Land Cover Dataset (NLCD), USFS Pacific Islands Imagery Project, and the National Oceanic and Atmospheric Administration (NOAA) Coastal Change Analysis Program (C-CAP). Land-cover data can be used to inform a land use classification if there is a time series to evaluate the dominant practices. For example, land that is principally used for timber production with tree cover over most of the time series is classified as forest land even if there are a few years of grass dominance following timber harvest. These products were reviewed and evaluated for use in the national *Inventory* as a step towards implementing a planned improvement to include U.S. Territories in the land representation for the *Inventory*. Recommendations are to use the NOAA C-CAP Regional Land Cover Database for the smaller island Territories (U.S. Virgin Islands, Guam, Northern Marianas Islands, and American Samoa) because this program is ongoing and therefore will be continually updated. The C-CAP product does not cover the entire territory of Puerto Rico, so the NLCD was used for this area. Results are presented below (in hectares). The total land area of all U.S. Territories is 1.05 million hectares, representing 0.1 percent of the total land base for the United States (see Table 6-7).

Table 6-7: Total Land Area (Hectares) by Land Use Category for U.S. Territories

	Puerto Rico	U.S. Virgin Islands	Guam	Northern Marianas Islands	American Samoa	Total
Cropland	19,712	138	236	289	389	20,764
Forest Land	404,004	13,107	24,650	25,761	15,440	482,962
Grasslands	299,714	12,148	15,449	13,636	1,830	342,777
Other Land	5,502	1,006	1,141	5,186	298	13,133
Settlements	130,330	7,650	11,146	3,637	1,734	154,496
Wetlands	24,525	4,748	1,633	260	87	31,252
Total	**883,788**	**38,796**	**54,255**	**48,769**	**19,777**	**1,045,385**

Note: Totals may not sum due to independent rounding.

Methods in the *2013 Supplement to the 2006 Guidelines for National Greenhouse Gas Inventories: Wetlands* (IPCC 2014) have been applied to estimate emissions and removals from coastal wetlands. Specifically, greenhouse gas emissions from coastal wetlands have been developed for the *Inventory* using the NOAA C-CAP land-cover product. The NOAA C-CAP product is not used directly in the land representation analysis, however, so a planned improvement for future Inventories is to reconcile the coastal wetlands data from the C-CAP product with the wetlands area data provided in the NRI, FIA and NLCD. Estimates from flooded lands are also included in this *Inventory*, but data are not directly used in the land representation analysis at this time; this is a planned improvement to include for future inventories. In addition, the current *Inventory* does not include a classification of managed and unmanaged wetlands, except for remote areas in Alaska. Consequently, there is a planned improvement to classify managed and unmanaged wetlands for the conterminous United States and Hawaii, and more detailed wetlands datasets will be evaluated and integrated into the analysis to meet this objective.

6.2 Forest Land Remaining Forest Land (CRT Category 4A1)

Changes in Forest Carbon Stocks (CRT Category 4A1)

Delineation of Carbon Pools

For estimating carbon stocks or stock change (flux), carbon in forest ecosystems can be divided into the following five storage pools (IPCC 2006):

- Aboveground biomass, which includes all living biomass above the soil including stem, stump, branches, bark, seeds, and foliage. This category includes live understory.
- Belowground biomass, which includes all living biomass of coarse living roots greater than 2 millimeters (mm) diameter.
- Dead wood, which includes all non-living woody biomass either standing, lying on the ground (but not including litter), or in the soil.
- Litter, which includes all duff, humus, and fine woody debris above the mineral soil as well as woody fragments with diameters of up to 7.5 cm.
- Soil organic carbon (SOC), including all organic material in soil to a depth of 1 meter but excluding the coarse roots of the belowground pools. Organic (e.g., peat and muck) soils have a minimum of 12 to 20 percent organic matter by mass and develop under poorly drained conditions of wetlands. All other soils are classified as mineral soil types and typically have relatively low amounts of organic matter.

In addition, there are two harvested wood pools included when estimating carbon flux:

- Harvested wood products (HWP) in use.
- HWP in solid waste disposal sites (SWDS).

Forest Carbon Cycle

Carbon is continuously cycled among the previously defined carbon storage pools and the atmosphere as a result of biogeochemical processes in forests (e.g., photosynthesis, respiration, decomposition, and disturbances such as fires or pest outbreaks) and anthropogenic activities (e.g., harvesting, thinning, and replanting). As trees photosynthesize and grow, carbon is removed from the atmosphere and stored in living tree biomass. As trees die

and otherwise deposit litter and debris on the forest floor, carbon is released to the atmosphere and is also transferred to the litter, dead wood, and soil pools by organisms that facilitate decomposition.

The net change in forest carbon is not equivalent to the net flux between forests and the atmosphere because timber harvests do not cause an immediate flux of all harvested biomass carbon to the atmosphere. Instead, harvesting transfers a portion of the carbon stored in wood to a "product pool." Once in a product pool, the carbon is emitted over time as CO_2 in the case of decomposition and as CO_2, CH_4, N_2O, CO, and NO_x when the wood product combusts. The rate of emission varies considerably among different product pools. For example, if timber is harvested to produce energy, combustion releases carbon immediately, and these emissions are reported for information purposes in the Energy sector while the harvest (i.e., the associated reduction in forest carbon stocks) and subsequent combustion are implicitly estimated in the Land Use, Land-Use Change, and Forestry (LULUCF) sector (i.e., the portion of harvested timber combusted to produce energy does not enter the HWP pools). Conversely, if timber is harvested and used as lumber in a house, it may be many decades or even centuries before the lumber decays and carbon is released to the atmosphere. If wood products are disposed of in SWDS, the carbon contained in the wood may be released many years or decades later or may be stored almost permanently in the SWDS. These latter fluxes, with the exception of CH_4 from wood in SWDS, which is included in the Waste sector, are also estimated in the LULUCF sector.

Net Change in Carbon Stocks within Forest Land of the United States

This section describes the general method for quantifying the net changes in carbon stocks in the five carbon storage pools and two harvested wood pools (a more detailed description of the methods and data is provided in Annex 3.13). The underlying methodology for determining carbon stock and stock change relies on data from the national forest inventory (NFI) conducted by the Forest Inventory and Analysis (FIA) program within the USDA Forest Service. The annual NFI is implemented across all U.S. forest lands within the conterminous 48 states, Alaska, Puerto Rico, and the U.S. Virgin Islands, and periodic inventories are available for Hawaii and some of the other U.S. Territories. The methods for estimation and monitoring are continuously improved and these improvements are reflected in the carbon estimates (Domke et al. 2022; Westfall et al. 2023). First, in the conterminous 48 states and coastal southeast and southcentral Alaska, the total carbon stocks are estimated for each carbon storage pool at the individual NFI plot, next the annual net changes in carbon stocks for each pool at the population level are estimated, and then the changes in stocks are summed for all pools to estimate total net flux at the population level (e.g., U.S. state). Changes in carbon stocks from disturbances, such natural disturbances (e.g., wildfires, insects/disease, wind) or harvesting, are included in the net changes (see Box 6-3 for more information). For instance, an inventory conducted after a fire implicitly includes only the carbon stocks remaining on the NFI plot. The IPCC (2006) recommends estimating changes in carbon stocks from forest lands according to several land-use types and conversions, specifically forest land remaining forest land and land converted to forest land, with the former being lands that have been forest lands for 20 years or longer and the latter being lands (i.e., croplands, grassland, wetlands, settlements and other lands) that have been converted to forest lands for less than 20 years.

The methods and data used to delineate forest carbon stock changes by these two categories continue to improve and in order to facilitate this delineation, a combination of estimation approaches was used to compile estimates in this *Inventory*. Methods for compiling carbon stocks and stock changes on forest land in interior Alaska are different from those used for estimation in the conterminous U.S. and coastal Alaska due to the recency of the operational FIA inventory in that region and differences in sampling protocols (see Annex 3.13 for more details). Finally, estimates of carbon stocks and stock changes on forest land in Hawaii and the U.S. Territories of American Samoa, Guam, Northern Mariana Islands, Puerto Rico, and the U.S. Virgin Islands (hereafter referred to as the U.S. Territories) are included for the first time in this *Inventory*. The FIA program has conducted annual inventories in parts of Puerto Rico (Mainland, Vieques, Culebra) and the U.S. Virgin Islands and periodic inventories in Hawaii, American Samoa, Guam, Northern Mariana Islands, and Puerto Rico (Mona Island). These inventories in combination with published estimates of carbon stocks, stock changes, and IPCC (2019) default estimates were used to compile estimates of carbon stocks and stock changes on forest land for these regions (see Annex 3.13 for more details).

Forest Area in the United States

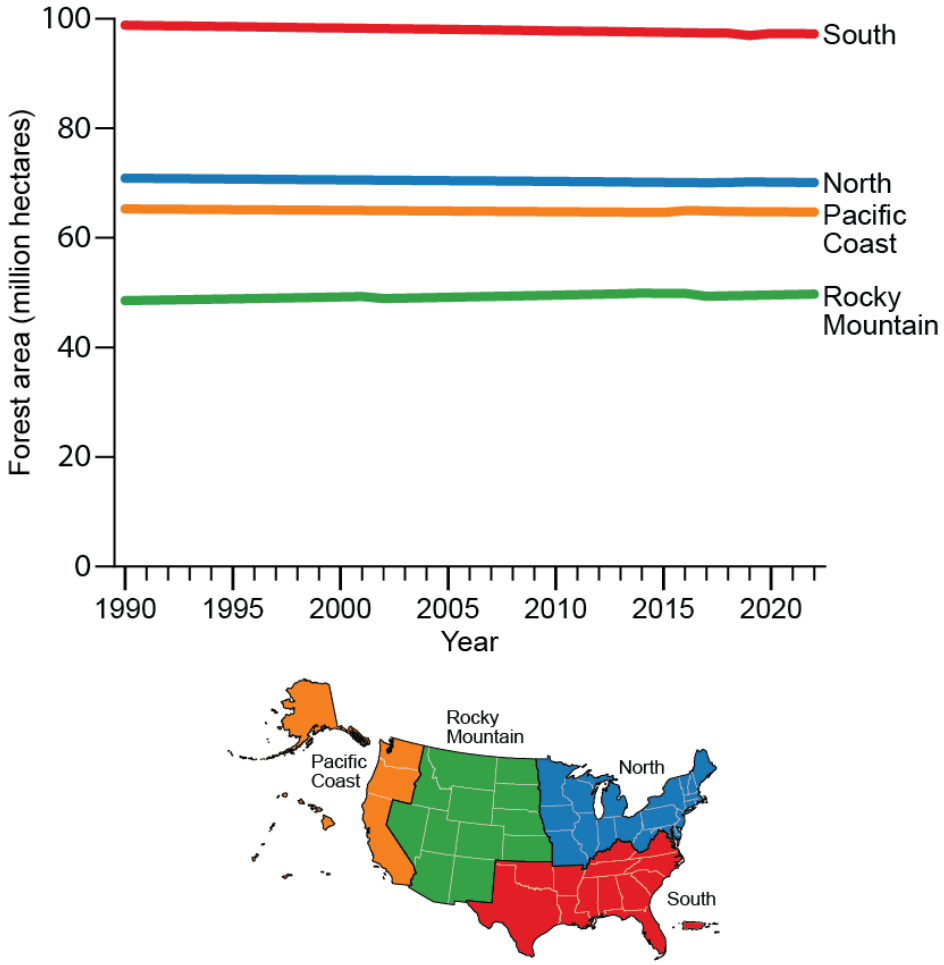
Approximately 32 percent of the managed U.S. land area is estimated to be forested based on the U.S. definition of forest land as provided in Section 6.1. All annual and periodic NFI plots included in the public FIA database as of September 2023 (which includes data collected through 2022 – note that the COVID 19 pandemic resulted in delays in data collection in many states) were used in this *Inventory*. The NFIs from the conterminous United States (USDA Forest Service 2023a, 2023b), Alaska, Hawaii, and the U.S. Territories comprise an estimated 282 million hectares of forest land that are considered managed and are included in the current *Inventory*. Some differences also exist in forest land area estimates from the latest update to the Resources Planning Act (RPA) Assessment (Oswalt et al. 2019) and the forest land area estimates included in this report, which are based on the annual and periodic NFI data through 2022 for all states (USDA Forest Service 2023b; Nelson et al. 2020). The methods for compiling area estimates for Hawaii and the U.S. Territories in this section are different from those in Section 6.1 because they do not rely on FIA data. Also, it is not possible to separate forest land remaining forest land from land converted to forest land in Wyoming because of the split annual cycle method used for population estimation (see Annex 3.13). This prevents harmonization of forest land in Wyoming with the NRI/NLCD method used in Section 6.1. Agroforestry systems that meet the definition of forest land are also not currently included in the current *Inventory* since they are not explicitly inventoried (i.e., classified as an agroforestry system) by either the FIA program or the Natural Resources Inventory (NRI) of the USDA Natural Resources Conservation Service (Perry et al. 2005).

An estimated 67 percent (208 million hectares) of U.S. forests in Alaska, Hawaii and the conterminous United States are classified as timberland, meaning they meet minimum levels of productivity and have not been removed from production. Approximately ten percent of Alaska forest land and 73 percent of forest land in the conterminous United States are classified as timberland. Of the remaining non-timberland in the conterminous United States, Alaska, and Hawaii, nearly 33 million hectares are reserved forest lands (withdrawn by law from management for production of wood products) and 102 million hectares are lower productivity forest lands (Oswalt et al. 2019). Historically, the timberlands in the conterminous United States have been more frequently or intensively surveyed than the forest lands removed from production because they do not meet the minimum level of productivity.

Since the late 1980s, gross forest land area in Alaska, Hawaii, and the conterminous United States has increased by about 13 million hectares (Oswalt et al. 2019). The southern region of the United States contains the most forest land (Figure 6-4). A substantial portion of this accrued forest land is from the conversion of abandoned croplands to forest (e.g., Woodall et al. 2015b). Estimated forest land area in the conterminous United States and Alaska represented in this *Inventory* is stable, but there are substantial conversions as described in 6.1 and each of the land conversion sections for each land-use category (e.g., land converted to cropland, land converted to grassland). The major influences on the net carbon flux from forest land across the 1990 to 2022 time series are management activities, natural disturbance, particularly wildfire, and the ongoing impacts of current and previous land-use conversions. These activities affect the net flux of carbon by altering the amount of carbon stored in forest ecosystems and also the area converted to forest land. For example, intensified management of forests that leads to an increased rate of growth of aboveground biomass (and possible changes to the other carbon storage pools) may increase the eventual biomass density of the forest, thereby increasing the uptake and storage of carbon in the aboveground biomass pool.[29] Though harvesting forests removes much of the carbon in aboveground biomass (and possibly changes carbon density in other pools), on average, the estimated volume of annual net growth in aboveground tree biomass in the conterminous United States is essentially twice the volume of annual removals on timberlands (Oswalt et al. 2019). The net effects of forest management and changes in forest land remaining forest land are captured in the estimates of carbon stocks and fluxes presented in this section.

[29] The term "biomass density" refers to the mass of live vegetation per unit area. It is usually measured on a dry-weight basis. Species-specific carbon fractions are used to convert dry biomass to carbon (Westfall et al. 2023).

Figure 6-4: Changes in Forest Area by Region for Forest Land Remaining Forest Land in the conterminous United States and Alaska (1990-2022)



Forest Carbon Stocks and Stock Change

In the forest land remaining forest land category, forest management practices, the regeneration of forest areas cleared more than 20 years prior to the reporting year, and timber harvesting have resulted in net removal (i.e., net sequestration or accumulation) of carbon each year from 1990 through 2022. The rate of forest clearing in the 17th century following European settlement had slowed by the late 19th century. Through the later part of the 20th century, many areas of previously forested land in the United States were allowed to revert to forests or were actively reforested. The impacts of these land-use changes still influence carbon fluxes from these forest lands. More recently, the 1970s and 1980s saw a resurgence of federally sponsored forest management programs (e.g., the Forestry Incentive Program) and soil conservation programs (e.g., the Conservation Reserve Program), which have focused on tree planting, improving timber management activities, combating soil erosion, and converting marginal cropland to forests. In addition to forest regeneration and management, forest harvests and natural disturbance have also affected net carbon fluxes. Because most of the timber harvested from U.S. forest land is used in wood products, and many discarded wood products are disposed of in SWDS rather than by incineration, substantial quantities of carbon in harvested wood are transferred to these long-term storage pools rather than being released rapidly to the atmosphere (Skog 2008). By maintaining current harvesting practices and regeneration activities on forest lands, along with continued input of harvested wood into the HWP pool, carbon stocks in the forest land remaining forest land category are likely to continue to increase in the near term, though

possibly at a slower rate. Changes in carbon stocks in the forest ecosystem and harvested wood pools associated with forest land remaining forest land were estimated to result in net removal of 787.0 MMT CO_2 Eq. (214.6 MMT carbon) in 2022 (Table 6-8, Table 6-9, Table A-203, Table A-204 and state-level estimates in Table A-207). The estimated net uptake of carbon in the Forest Ecosystem was 694.3 MMT CO_2 Eq. (189.3 MMT carbon) in 2022 (Table 6-8 and Table 6-9). The majority of this uptake in 2022, 491.7 MMT CO_2 Eq. (134.1 MMT carbon), was from aboveground biomass. Overall, estimates of average carbon density in forest ecosystems (including all pools) increased consistently over the time series with an average of approximately 208 MT carbon ha^{-1} from 1990 to 2022. This was calculated by dividing the forest ecosystem carbon stock estimates by the forest land area estimates for every year (see Table 6-10 and Table A-206) and then calculating the mean across the entire time series, i.e., 1990 through 2022. The increasing forest ecosystem carbon density, when combined with relatively stable forest area, results in net carbon accumulation over time. However, due to an aging forest land base, increases in the frequency and severity of disturbances in forests in some regions, among other drivers of change, forest carbon density is increasing at a slower rate resulting in an overall decline in the sink strength of forest land remaining forest land in the United States. Aboveground live biomass is responsible for the majority of net carbon uptake among all forest ecosystem pools (Figure 6-5). These increases may be influenced in some regions by reductions in carbon density or forest land area due to natural disturbances (e.g., wildfire, weather, insects/disease), particularly in Alaska. The inclusion of all managed forest land in Alaska has increased the interannual variability in carbon stock change estimates over the time series, and much of this variability can be attributed to severe fire years (e.g., 2022). The distribution of carbon in forest ecosystems in Alaska is substantially different from forests in the conterminous United States. In Alaska, more than nine percent of forest ecosystem carbon is stored in the litter carbon pool whereas in the conterminous United States, less than seven percent of the total ecosystem carbon stocks are in the litter pool. Much of the litter material in forest ecosystems is combusted during fire (IPCC 2006) leading to substantial carbon losses in this pool during severe fire years (Figure 6-5, Table A-206).

The estimated net accumulation of carbon in the HWP pool, i.e., the balance of additions from the transfer of harvested wood from the forest ecosystem and losses from the current decay of wood harvested in the past, was 92.8 MMT CO_2 Eq. (25.3 MMT carbon) in 2022 (Table 6-8, Table 6-9, Table A-203, and Table A-204). The majority of this uptake, 63.9 MMT CO_2 Eq. (17.4 MMT carbon), was from solid wood and paper in SWDS. Products in use accounted for an estimated 28.8 MMT CO_2 Eq. (7.9 MMT carbon) in 2022.

Table 6-8: Net CO_2 Flux from Forest Ecosystem Pools in Forest Land Remaining Forest Land and Harvested Wood Pools (MMT CO_2 Eq.)

Carbon Pool	1990	2005	2018	2019	2020	2021	2022
Forest Ecosystem	**(851.0)**	**(770.0)**	**(779.6)**	**(726.2)**	**(765.2)**	**(749.5)**	**(694.3)**
Aboveground Biomass	(600.9)	(550.8)	(536.7)	(516.3)	(522.8)	(513.0)	(491.7)
Belowground Biomass	(116.8)	(107.5)	(105.4)	(102.3)	(102.2)	(100.9)	(96.9)
Dead Wood	(132.0)	(131.2)	(138.0)	(133.4)	(136.2)	(135.3)	(131.4)
Litter	(2.4)	20.5	(1.5)	26.5	(3.4)	(0.1)	26.4
Soil (Mineral)	2.0	(0.8)	1.3	(1.3)	(1.3)	(0.9)	(1.2)
Soil (Organic)	(1.6)	(1.0)	(0.1)	(0.1)	(0.1)	(0.1)	(0.1)
Drained Organic Soil[a]	0.8	0.8	0.8	0.8	0.8	0.8	0.8
Harvested Wood	**(123.8)**	**(106.0)**	**(93.9)**	**(86.9)**	**(96.8)**	**(94.7)**	**(92.8)**
Products in Use	(54.8)	(42.6)	(28.8)	(22.6)	(32.3)	(30.4)	(28.8)
SWDS	(69.0)	(63.4)	(65.1)	(64.3)	(64.5)	(64.3)	(63.9)
Total Net Flux	**(974.8)**	**(876.0)**	**(873.5)**	**(813.2)**	**(862.0)**	**(844.2)**	**(787.0)**

[a] These estimates include carbon stock changes from drained organic soils from both forest land remaining forest land and land converted to forest land. See the section below on CO_2, CH_4, and N_2O emissions from drained organic soils for the methodology used to estimate the CO_2 emissions from drained organic soils. Also, Table 6-28 and Table 6-29 for non-CO_2 emissions from drainage of organic soils from both forest land remaining forest land and land converted to forest land.

Notes: Managed forest land area for Hawaii and the U.S. Territories was compiled using FIA data in this section which is different from how area estimates for those lands were compiled in Section 6.1. This results in small differences (less than 0.5 million hectares) in the forest land area estimates in this section and Section 6.1. Also, it is not possible to separate forest land remaining forest land from land converted to forest land in Wyoming because of the split annual cycle method used for population estimation, this prevents harmonization of forest land in Wyoming with the NRI/NLCD method used in Section 6.1. See Annex 3.13, Table A-206 for annual differences between the forest area reported in Section 6.1 and Section 6.2. The forest ecosystem carbon stock changes do not include trees on non-forest land (e.g., agroforestry systems and settlement areas—see Section 6.10 for estimates of carbon stock change from settlement trees). Forest ecosystem carbon stocks on managed forest land in interior Alaska, Hawaii, and the U.S. Territories were compiled using the gain-loss method as described in Annex 3.13. Parentheses indicate net carbon uptake (i.e., a net removal of carbon from the atmosphere). Total net flux is an estimate of the actual net flux between the total forest carbon pool and the atmosphere. Harvested wood estimates are based on results from annual surveys (see Annex 3.13, Table A-199) and models. Totals may not sum due to independent rounding.

Table 6-9: Net Carbon Flux from Forest Ecosystem Pools in Forest Land Remaining Forest Land and Harvested Wood Pools (MMT C)

Carbon Pool	1990	2005	2018	2019	2020	2021	2022
Forest Ecosystem	**(232.1)**	**(210.0)**	**(212.6)**	**(198.1)**	**(208.7)**	**(204.4)**	**(189.3)**
Aboveground Biomass	(163.9)	(150.2)	(146.4)	(140.8)	(142.6)	(139.9)	(134.1)
Belowground Biomass	(31.9)	(29.3)	(28.8)	(27.9)	(27.9)	(27.5)	(26.4)
Dead Wood	(36.0)	(35.8)	(37.6)	(36.4)	(37.1)	(36.9)	(35.8)
Litter	(0.7)	5.6	(0.4)	7.2	(0.9)	(0.0)	7.2
Soil (Mineral)	0.5	(0.2)	0.4	(0.4)	(0.3)	(0.2)	(0.3)
Soil (Organic)	(0.4)	(0.3)	(0.0)	(0.0)	(0.0)	(0.0)	(0.0)
Drained Organic Soil[a]	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Harvested Wood	**(33.8)**	**(28.9)**	**(25.6)**	**(23.7)**	**(26.4)**	**(25.8)**	**(25.3)**
Products in Use	(14.9)	(11.6)	(7.8)	(6.2)	(8.8)	(8.3)	(7.9)
SWDS	(18.8)	(17.3)	(17.8)	(17.5)	(17.6)	(17.5)	(17.4)
Total Net Flux	**(265.8)**	**(238.9)**	**(238.2)**	**(221.8)**	**(235.1)**	**(230.2)**	**(214.6)**

[a] These estimates include carbon stock changes from drained organic soils from both forest land remaining forest land and land converted to forest land. See the section below on CO_2, CH_4, and N_2O Emissions from Drained Organic Soils for the methodology used to estimate the carbon flux from drained organic soils. Also, see Table 6-28 and Table 6-29 for greenhouse gas emissions from non-CO_2 gases changes from drainage of organic soils from forest land remaining forest land and land converted to forest land.

Notes: Managed forest land area for Hawaii and the U.S. Territories was compiled using FIA data in this section which is different from how area estimates for those lands were compiled in Section 6.1 so there are small differences in the forest land area estimates in this Section and Section 6.1. Also, it is not possible to separate forest land remaining forest land from land converted to forest land in Wyoming because of the split annual cycle method used for population estimation, this prevents harmonization of forest land in Wyoming with the NRI/NLCD method used in Section 6.1). See Annex 3.13, Table A-203 for annual differences between the forest area reported in Section 6.1 and Section 6.2. The forest ecosystem carbon stock changes do not include trees on non-forest land (e.g., agroforestry systems and settlement areas—see Section 6.10 for estimates of carbon stock change from settlement trees). Forest ecosystem carbon stocks on managed forest land in Alaska, Hawaii, and the U.S. Territories were compiled using the gain-loss method as described in Annex 3.13. Parentheses indicate net carbon uptake (i.e., a net removal of carbon from the atmosphere). Total net flux is an estimate of the actual net flux between the total forest carbon pool and the atmosphere. Harvested wood estimates are based on results from annual surveys and models. Totals may not sum due to independent rounding.

Stock estimates for forest ecosystem and harvested wood carbon storage pools are presented in Table 6-10. Together, the estimated aboveground biomass and soil carbon pools account for a large proportion of total forest ecosystem carbon stocks. Forest land area estimates are also provided in Table 6-10, but these do not precisely match those in Section 6.1 for forest land remaining forest land. This is because the forest land area estimates in Table 6-10 include estimates of managed forest land in Hawaii and the U.S. Territories compiled using FIA estimates in this section while the area estimates for managed forest land in Hawaii and the U.S. Territories in Section 6.1 were compiled using different methods. Differences also exist because forest land area estimates are based on the latest NFI data through 2022, and woodland areas previously included as forest land have been separated and included in the grassland categories in this *Inventory*.[30]

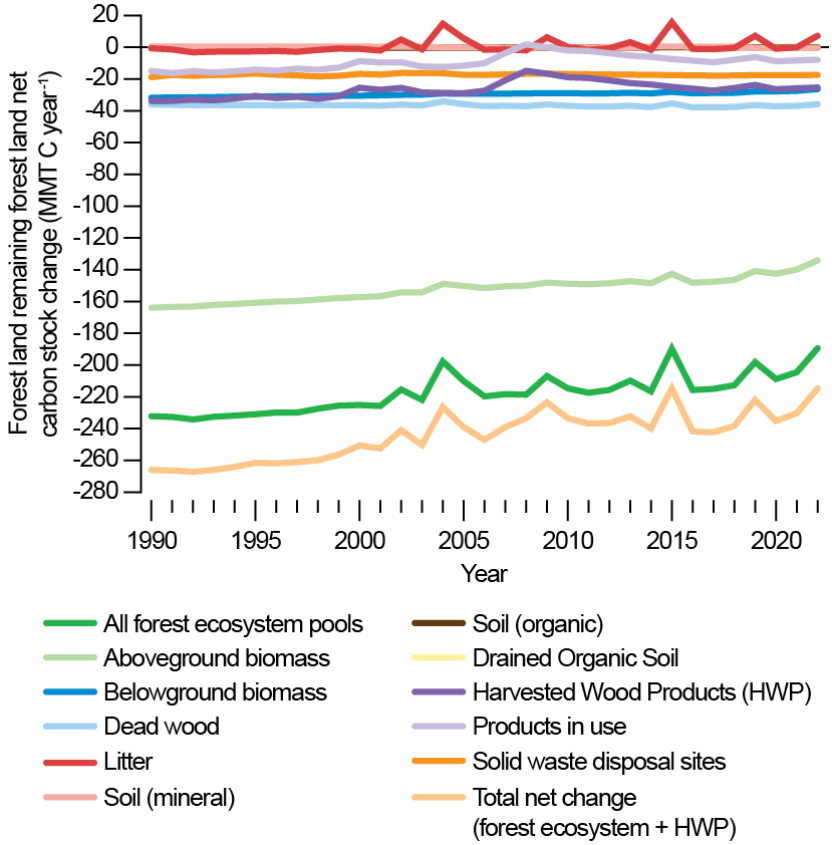
Table 6-10: Forest Area (1,000 ha) and Carbon Stocks in Forest Land Remaining Forest Land and Harvested Wood Pools (MMT C)

	1990	2005	2019	2020	2021	2022	2023
Forest Area (1,000 ha)	***283,500***	***282,521***	***281,137***	***281,779***	***281,780***	***281,752***	***281,725***
Carbon Pools (MMT C)							
Forest Ecosystem	**55,142**	**58,536**	**61,519**	**61,717**	**61,926**	**62,130**	**62,320**
Aboveground Biomass	12,739	15,122	17,199	17,340	17,483	17,622	17,757
Belowground Biomass	2,255	2,718	3,124	3,151	3,179	3,207	3,233
Dead Wood	1,977	2,521	3,038	3,074	3,111	3,148	3,184
Litter	3,789	3,794	3,775	3,767	3,768	3,768	3,761
Soil (Mineral)	28,407	28,401	28,400	28,400	28,401	28,401	28,401
Soil (Organic)	5,976	5,981	5,983	5,983	5,983	5,983	5,983
Harvested Wood	**1,895**	**2,353**	**2,671**	**2,694**	**2,721**	**2,747**	**2,772**
Products in Use	1,249	1,447	1,523	1,530	1,538	1,547	1,555
SWDS	646	906	1,147	1,165	1,182	1,200	1,217
Total C Stock	**57,037**	**60,890**	**64,189**	**64,411**	**64,647**	**64,877**	**65,092**

Notes: Managed forest land area for Hawaii and the U.S. Territories was compiled using FIA data in this section which is different from how area estimates for those lands were compiled in Section 6.1 so there are small differences in the forest land area estimates in this section and Section 6.1. Also, it is not possible to separate forest land remaining forest land from land converted to forest land in Wyoming because of the split annual cycle method used for population estimation, this prevents harmonization of forest land in Wyoming with the NRI/NLCD method used in Section 6.1 Representation of the U.S. Land Base (CRT Category 4.1). See Annex 3.13, Table A-213 for annual differences between the forest area reported in Section 6.1 and Section 6.2. The forest ecosystem carbon stocks do not include trees on non-forest land (e.g., agroforestry systems and settlement areas—see Section 6.10 for estimates of carbon stock change from settlement trees). Forest ecosystem carbon stocks on managed forest land in Alaska, Hawaii, and the U.S. Territories were compiled using the gain-loss method as described in Annex 3.13. Harvested wood product stocks include exports, even if the logs are processed in other countries, and exclude imports. Harvested wood estimates are based on results from annual surveys and models. Totals may not sum due to independent rounding. Population estimates compiled using FIA data are assumed to represent stocks as of January 1 of the inventory year. Flux is the net annual change in stock. Thus, an estimate of flux for 2022 requires estimates of carbon stocks for 2022 and 2023.

[30] See Annex 3.13, Table A-203 for annual differences between the forest area reported in Section 6.1 Representation of the U.S. Land Base and Section 6.2 Forest Land Remaining Forest Land.

Figure 6-5: Estimated Net Annual Changes in Carbon Stocks for All Carbon Pools in Forest Land Remaining Forest Land in the Conterminous United States and Alaska (1990-2022)



Box 6-3: CO_2 Emissions from Forest Fires

As stated previously, the forest inventory approach implicitly includes all carbon losses due to disturbances such as forest fires, because only carbon remaining in the forest is estimated. Net carbon stock change is estimated by subtracting consecutive carbon stock estimates. A forest fire disturbance removes carbon from the forest. The inventory data from the NFI on which net carbon stock estimates are based already reflect this carbon loss. Therefore, estimates of net annual changes in carbon stocks for U.S. forest land already includes CO_2 emissions from forest fires occurring in the conterminous states (48 states), Hawaii, Puerto Rico, and Guam as well as the portion of managed forest lands in Alaska. Because it is of interest to quantify the magnitude of CO_2 emissions from fire disturbance, these separate estimates are highlighted here. Note that these CO_2 estimates are based on the same methodology as applied for the non-CO_2 greenhouse gas emissions from forest fires that are also quantified in a separate section below as required by IPCC Guidance and the UNFCCC.

Emissions estimates are developed using IPCC (2019) methodology and based on U.S.-specific data and models to quantify the primary fire-specific components: area burned; availability and combustibility of fuel; fire severity (or consumption); and CO_2 and non-CO_2 emissions. Estimated CO_2 emissions for fires on forest lands in the United States for 2022 are 129.2 MMT CO_2 per year (Table 6-11). This estimate is an embedded component of the net annual forest carbon stock change estimates provided previously (i.e., Table 6-9), but this separate approach to estimating CO_2 emissions is necessary in order to associate these emissions with fire. See the discussion in Annex 3.13 for more details on this methodology. Note that in Alaska, a portion of the forest lands are considered unmanaged, therefore the estimates for Alaska provided in Table 6-11 include only managed forest land within the state, which is consistent with carbon stock change estimates provided above.

Table 6-11: Estimates of CO_2 (MMT per Year) Emissions[a] from Forest Fires in the Conterminous 48 States, Hawaii, Puerto Rico, Guam, and Alaska

	1990	2005	2018	2019	2020	2021	2022
CO_2 emitted from fires on forest land in the Conterminous 48 States, Hawaii, Puerto Rico, and Guam (MMT yr^{-1})	11.9	28.6	77.5	19.1	124.0	156.7	71.8
CO_2 emitted from fires on managed forest land in Alaska (MM Tyr^{-1})	43.2	113.5	7.1	34	0.4	6.8	57.4
Total CO_2 emitted (MMTyr^{-1})	**55.1**	**142.2**	**84.6**	**53**	**124.4**	**163.5**	**129.2**

[a] These emissions have already been included in the estimates of net annual changes in carbon stocks, which include the amount sequestered minus any emissions, including the assumption that combusted wood may continue to decay through time.

Note: Totals may not sum due to independent rounding.

Methodology and Time-Series Consistency

The methodology described herein is consistent with the *2006 IPCC Guidelines for National Inventories*. Forest ecosystem carbon stocks and net annual carbon stock change were determined according to the stock-difference method for the conterminous United States and coastal southeast and southcentral Alaska, which involved applying carbon estimation factors to annual forest inventories across time to obtain carbon stocks and then subtracting between the years to obtain the stock change. The gain-loss method was used to estimate carbon stocks and net annual carbon stock changes in interior Alaska, Hawaii, and the U.S. Territories. The approaches for estimating carbon stocks and stock changes on forest land remaining forest land are described in Annex 3.13. All annual and periodic NFI plots available in the public FIA database (USDA Forest Service 2023b) were used in the current *Inventory*. Additionally, NFI plots established and measured in 2014 as part of a pilot inventory in interior Alaska were also included in this *Inventory* as were plots established and measured since 2015 as part of the operational NFI in interior Alaska. Some of the data from the pilot and operational NFI in interior Alaska are not yet available in the public FIA database. Only plots which meet the definition of forest land (see Section 6.1) are measured in the NFI; as part of the pre-field process in the FIA program, all plots or portions of plots (i.e., conditions) are classified into a land-use category. This land use information on each forest and non-forest plot was used to estimate forest land area and land converted to and from forest land over the time series. The estimates in this section of the report are based on land use information from the NFI and they may differ from the other land-use categories where area estimates reported in the Land Representation were not updated (see Section 6.1). Further, managed forest land area estimates for Hawaii and the U.S. Territories were compiled using FIA data in this section which is different from how estimates for these lands were compiled in Section 6.1 (see Annex 3.13 for details on differences).

To implement the stock-difference approach, forest land conditions in the conterminous United States and coastal Alaska were observed on NFI plots at time t_0 and at a subsequent time $t_1=t_0+s$, where s is the time step (time measured in years) and is indexed by discrete (e.g., 5 year) forest age classes. The inventory from t_0 to t_1 was then projected to 2022. This projection approach requires simulating changes in the age-class distribution resulting from forest aging and disturbance events and then applying carbon density estimates for each age class to obtain population estimates for the nation. In cases where there are t_1 estimates in the last year (e.g., 2022) of the NFI no projections are necessary for those plots.

To implement the gain-loss approach in interior Alaska, forest land conditions in Alaska were observed on NFI plots from 2014 to 2022. Plot-level data from the NFI were harmonized with auxiliary data describing climate, forest structure, disturbance, and other site-specific conditions to develop non-parametric models to predict carbon stocks by forest ecosystem carbon pool as well as fluxes over the entire inventory period, 1990 to 2022. First, carbon stocks for each forest ecosystem carbon pool were predicted for the year 2016 for all NFI plot locations

(each plot representing 12,015 ha). Next, the chronosequence of sampled NFI plots and auxiliary information (e.g., climate, forest structure, disturbance, and other site-specific data) were used to predict annual gains and losses for each forest ecosystem carbon pool. The annual gains and losses were then combined with the stock estimates and disturbance information to compile plot- and population-level carbon stocks and fluxes for each year from 1990 to 2022.

To implement the gain-loss approach in Hawaii and the U.S. Territories, a combination of Tier 1 and Tier 2 methods were applied. All forest land conditions were observed on annual and periodic NFI plots from 2001 to 2019 (see Annex 3.13 for specific inventories included for each Island). Plot-level data from the NFI were harmonized with data describing ecological zone (FAO 2010), soil attributes (Johnson and Kern 2003; Deenik and McClellan, 2007, IPCC 2019), and dead wood and litter carbon stocks (Oswalt et al. 2008; IPCC 2019). Only estimates of carbon stocks in live trees were consistently available in the NFI for Hawaii and the U.S. Territories for each inventory. These estimates were used to obtain average annual carbon stock change estimates for above and belowground live trees which were applied to each forest plot to capture growth, harvest removals, and mortality. The carbon stocks and annual stock change estimates were compared with country-specific estimates (Oswalt et al. 2008; Selmants et al. 2017), and IPCC (2019) default estimates to ensure they were consistent with other sources. There were limited data available on disturbances and management activities on NFI plots over the times series so Tier 1 methods were applied for dead wood and litter. It was assumed that the average transfer rate into dead wood and litter pools is equivalent to the average transfer rate out of the dead organic matter pool so there are no net carbon stock changes included for these pools in the time series (IPCC 2006). Similarly, given data limitations on forest soils and changes on NFI plots over the time series, a Tier 1 approach was also used for soil carbon with country-specific estimates (Johnson and Kern 2003) and IPCC (2019) defaults used to estimate soil carbon stocks with no net carbon stock change reported.

To estimate carbon stock changes in harvested wood, estimates were based on factors such as the allocation of wood to various primary and end-use products as well as half-life (the time at which half of the amount placed in use will have been discarded from use) and expected disposition (e.g., product pool, SWDS, combustion). An overview of the different methodologies and data sources used to estimate the carbon in forest ecosystems within the conterminous United States and Alaska and harvested wood products for all of the United States is provided below. See Annex 3.13 for details and additional information related to the methods and data.

Methodological recalculations were applied to the entire time series to ensure time-series consistency from 1990 through 2022. Details on the emission/removal trends and methodologies through time are described in more detail in the Introduction and Methodology sections.

Forest Ecosystem Carbon from Forest Inventory

The United States applied the compilation approach described in Woodall et al. (2015a) for the current *Inventory* which removes the older periodic inventory data, which may be inconsistent with annual inventory data, from the estimation procedures. This approach enables the attribution of forest carbon accumulation by forest growth, land-use change, and natural disturbances such as fire. Development will continue on a system that attributes changes in forest carbon to disturbances and delineates land converted to forest land from forest land remaining forest land. As part of this development, carbon pool science will continue and will be expanded to improve the estimates of carbon stock transfers from forest land to other land uses and include techniques to better identify land-use change (see the Planned Improvements section below).

Unfortunately, the annual FIA inventory system does not extend into the 1970s, necessitating the adoption of a system to estimate carbon stocks prior to the establishment of the annual forest inventory. The estimation of carbon stocks prior to the annual national forest inventory consisted of a modeling framework comprised of a forest dynamics module (age transition matrices) and a land use dynamics module (land area transition matrices). The forest dynamics module assesses forest uptake, forest aging, and disturbance effects (e.g., disturbances such as wind, fire, and floods identified by foresters on inventory plots). The land use dynamics module assesses carbon stock transfers associated with afforestation and deforestation (Woodall et al. 2015b). Both modules are developed from land use area statistics and carbon stock change or carbon stock transfer by age class. The

required inputs are estimated from more than 625,000 forest and non-forest observations recorded in the FIA national database (U.S. Forest Service 2023a, b, c). Model predictions prior to the annual inventory period are constructed from the estimation system using the annual estimates. The estimation system is driven by the annual forest inventory system conducted by the FIA program (Frayer and Furnival 1999; Bechtold and Patterson 2005; Westfall et al. 2022; USDA Forest Service 2023d, 2023a). The FIA program relies on a rotating panel statistical design with a sampling intensity of one 674.5 m^2 ground plot per 2,403 ha of land and water area. A five or seven-panel design, with 20 percent or 14.3 percent of the field plots typically measured each year within a state, is used in the eastern United States and a ten-panel design, with typically ten percent of the field plots measured each year within a state, is used in the western United States. The interpenetrating hexagonal design across the U.S. landscape enables the sampling of plots at various intensities in a spatially and temporally unbiased manner. Typically, tree and site attributes are measured with higher sample intensity while other ecosystem attributes such as downed dead wood are sampled during summer months at lower intensities. The first step in incorporating FIA data into the estimation system is to identify annual and periodic inventory datasets by state and U.S. Territory. Inventories include data collected on permanent inventory plots on forest lands and were organized as separate datasets, each representing a complete inventory, or survey, of an individual state at a specified time. Many of the annual inventories reported for states are represented as "moving window" averages, which mean that a portion—but not all—of the previous year's inventory is updated each year (USDA Forest Service 2023d). Forest carbon estimates are organized according to these state surveys, and the frequency of surveys varies by state.

Using this FIA data, separate estimates were prepared for the five carbon storage pools identified by IPCC (2006) as described above. All estimates for the conterminous United States and Alaska were based on data collected from the extensive array of permanent, annual forest inventory plots and associated models (e.g., live tree belowground biomass) in the United States (USDA Forest Service 2023b, 2023c). Carbon conversion factors were applied at the disaggregated level of each inventory plot and then appropriately expanded to population estimates. Only live (and in some cases) standing dead wood estimates are available in the annual and periodic FIA inventories in Hawaii and the U.S. Territories. For this reason, a combination of approaches was used to obtain estimates for all carbon pools for the time series in these locations.

Carbon in Biomass

Live tree carbon pools include aboveground and belowground (coarse root) biomass of live trees with diameter at breast height (dbh) of at least 2.54 cm at 1.37 m above the litter. Separate estimates were made for above- and belowground biomass components. Over the last decade, the USDA Forest Service's FIA program and collaborators from universities and industry have been developing a new national methodology for the prediction of individual-tree volume, biomass, and carbon content. The resulting methodology is referred to as the National-Scale Volume and Biomass (NSVB) framework. The previous methodology used was the Component Ratio Method (CRM) framework (Woodall et al. 2010). While CRM was nationally consistent, tree biomass was still based on the volume predicted by regional models and tree carbon was assumed to be 50-percent of biomass, regardless of species. Hence, the need for NSVB, a nationally consistent methodology for compatible predictions of tree volume, biomass, and carbon content (Westfall et al. In press).

The NSVB covers timber tree species in the conterminous United States and coastal Alaska. All other trees (i.e., trees that are woodland species and trees within Pacific and Caribbean Islands) use regional models for volume and biomass, with updated carbon fractions (when available). While NSVB did not directly update models for trees that are considered woodland species or trees within the Pacific (USDA Forest Service 2022a, b) and Caribbean Islands (collectively referred to hereafter as "non-NSVB trees"), volume, biomass, and carbon estimates for these trees have also changed. For non-NSVB trees, the standardization of tree defects and how variables are reported (i.e., whether models for total-stem or merchantable-bole volumes are available) may be reflected as differences in volume estimates. Additionally, biomass estimates for non-NSVB trees are based on regional biomass models and no longer are adjusted as they were under the CRM. Finally, updates to carbon fractions (when available) and calculation of aboveground biomass are reflected in aboveground and belowground biomass carbon estimates (see Recalculations section and Annex 3.13 for more details).

Understory vegetation is a minor component of biomass, which is defined in the FIA program as all biomass of undergrowth plants in a forest, including woody shrubs and trees less than 2.54 cm dbh. For this *Inventory*, it was assumed that ten percent of total understory carbon mass is belowground (Smith et al. 2006). Estimates of carbon density were based on information in Birdsey (1996) and tree biomass estimates from the FIADB. Understory biomass represented over one percent of carbon in biomass, but its contribution rarely exceeded two percent of the total carbon stocks or stock changes across all forest ecosystem carbon pools each year.

Carbon in Dead Organic Matter

Dead organic matter is calculated as three separate pools—standing dead trees, downed dead wood, and litter—with carbon stocks estimated from sample data or from models as described below. The standing dead tree carbon pool includes aboveground and belowground (coarse root) biomass for trees of at least 2.54 cm dbh. Calculations followed the basic methods applied to live trees (Westfall et al. 2023) with additional modifications to account for decay and structural loss (Harmon et al. 2011). Downed dead wood estimates are based on measurement of a subset of FIA plots for downed dead wood (Domke et al. 2013; Woodall and Monleon 2008; Woodall et al. 2013). Downed dead wood is defined as pieces of dead wood greater than 7.5 cm diameter, at transect intersection, that are not attached to live or standing dead trees. This includes stumps and roots of harvested trees. To facilitate the downscaling of downed dead wood carbon estimates from the state-wide population estimates to individual plots, downed dead wood models specific to regions and forest types within each region are used. Litter carbon is the pool of organic carbon (also known as duff, humus, and fine woody debris) above the mineral soil and includes woody fragments with diameters of up to 7.5 cm. A subset of FIA plots are measured for litter carbon. A modeling approach, using litter carbon measurements from FIA plots (Domke et al. 2016), was used to estimate litter carbon for every FIA plot used in the estimation framework. These estimates are now available in the FIADB (USDA Forest Service 2023b).

Carbon in Forest Soil

Soil carbon is the largest terrestrial carbon sink with much of that carbon in forest ecosystems. The FIA program has been consistently measuring soil attributes as part of the annual inventory since 2001 and has amassed an extensive inventory of soil measurement data on forest land in the conterminous United States and coastal Alaska (O'Neill et al. 2005). Observations of mineral and organic soil carbon on forest land from the FIA program and the International Soil Carbon Monitoring Network were used to develop and implement a model framework that enabled the prediction of mineral and organic (i.e., undrained organic soils) soil carbon to a depth of 100 cm from empirical measurements collected on sample plots at a depth of 20 cm and included site-, stand-, and climate-specific variables that yield predictions of soil carbon stocks specific to forest land in the United States (Domke et al. 2017). These estimates are now available in the FIADB (USDA Forest Service 2023b). This approach allowed for separation of mineral and organic soils, the latter also referred to as Histosols, in the forest land remaining forest land category. Note that mineral and organic (i.e., undrained organic soils) soil carbon stock changes are reported to a depth of 100 cm for forest land remaining forest land to remain consistent with past reporting in this category, however for consistency across land-use categories, mineral (e.g., cropland, grassland, settlements) soil carbon is reported to a depth of 30 cm in Section 6.3 Land Converted to Forest Land. Estimates of carbon stock changes from organic soils shown in Table 6-8 and Table 6-9 include the emissions from drained organic forest soils, and the methods used to develop these estimates can be found in the Drained Organic Soils section below.

Harvested Wood Carbon

Estimates of the HWP contribution to forest carbon sinks and emissions (hereafter called "HWP contribution") were based on methods described in Skog (2008) using the WOODCARB II model. These methods are based on IPCC (2006) guidance for estimating the HWP contribution. IPCC (2006) provides methods that allow for reporting of the HWP contribution using one of several different methodological approaches: Production, stock change and atmospheric flow, as well as a default method that assumes there is no change in HWP carbon stocks (see Annex 3.13 for more details about each approach). The United States uses the production approach to report HWP

contribution. Under the production approach, carbon in exported wood was estimated as if it remains in the United States, and carbon in imported wood was not included in the estimates. Though reported, U.S. HWP estimates are based on the production approach, estimates resulting from use of the two alternative approaches, the stock change and atmospheric flow approaches, are also presented for comparison (see Annex 3.13). Annual estimates of change were calculated by tracking the annual estimated additions to and removals from the pool of products held in end uses (i.e., products in use such as housing or publications) and the pool of products held in SWDS. The carbon loss from harvest is reported in the forest ecosystem component of the forest land remaining forest land and land converted to forest land sections and for informational purposes in the Energy sector, but the non-CO_2 emissions associated with biomass energy are included in the Energy sector emissions (see Chapter 3). EPA includes HWP within the forest chapter because forests are the source of wood that goes into the HWP estimates.

Solidwood products include lumber and panels. End-use categories for solidwood include single and multifamily housing, alteration and repair of housing, and other end uses. There is one product category and one end-use category for paper. Additions to and removals from pools were tracked beginning in 1900, with the exception of additions of softwood lumber to housing, which began in 1800. Solidwood and paper product production and trade data were taken from USDA Forest Service and USDC Bureau of the Census, among other sources (Hair and Ulrich 1963; Hair 1958; USDC Bureau of Census 1976; Ulrich 1985, 1989; Steer 1948; AF&PA 2006a, 2006b; Howard 2003, 2007; Howard and Jones 2016; Howard and Liang 2019; AF&PA 2021; AF&PA 2023; FAO 2023). Estimates for disposal of products reflects the change over time in the fraction of products discarded to SWDS (as opposed to burning or recycling) and the fraction of SWDS that were in sanitary landfills versus dumps.

There are five annual HWP variables that were used in varying combinations to estimate HWP contribution using any one of the three main approaches listed above. These are:

(1A) annual change of carbon in wood and paper products in use in the United States,

(1B) annual change of carbon in wood and paper products in SWDS in the United States,

(2A) annual change of carbon in wood and paper products in use in the United States and other countries where the wood came from trees harvested in the United States,

(2B) annual change of carbon in wood and paper products in SWDS in the United States and other countries where the wood came from trees harvested in the United States,

(3) Carbon in imports of wood, pulp, and paper to the United States,

(4) Carbon in exports of wood, pulp and paper from the United States, and

(5) Carbon in annual harvest of wood from forests in the United States.

The sum of variables 2A and 2B yielded the estimate for HWP contribution under the production estimation approach. A key assumption for estimating these variables that adds uncertainty in the estimates was that products exported from the United States and held in pools in other countries have the same half-lives for products in use, the same percentage of discarded products going to SWDS, and the same decay rates in SWDS as they would in the United States.

Uncertainty

A quantitative uncertainty analysis placed bounds on the flux estimates for forest ecosystems through a combination of sample-based and model-based approaches to uncertainty estimation for forest ecosystem CO_2 flux using IPCC Approach 1 (Table 6-12 and Table A-214 for state-level uncertainties). A Monte Carlo stochastic simulation of the methods described above, and probabilistic sampling of carbon conversion factors, were used to determine the HWP uncertainty using IPCC Approach 2. See Annex 3.13 for additional information. The 2022 net annual change for forest carbon stocks was estimated to be between –866.5 and –708.3 MMT CO_2 Eq. around a central estimate of –787.0 MMT CO_2 Eq. at a 95 percent confidence level. This includes a range of –769.6 to –618.9 MMT CO_2 Eq. around a central estimate of –694.3 MMT CO_2 Eq. for forest ecosystems and –118.0 to -70.0 MMT

CO_2 Eq. around a central estimate of -92.8 MMT CO_2 Eq. for HWP.

Table 6-12: Quantitative Uncertainty Estimates for Net CO_2 Flux from Forest Land Remaining Forest Land: Changes in Forest Carbon Stocks (MMT CO_2 Eq. and Percent)

Source	Gas	2022 Flux Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Flux Estimate (MMT CO_2 Eq.)		Uncertainty Range Relative to Flux Estimate (%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Forest Ecosystem C Pools[a]	CO_2	(694.3)	(769.6)	(618.9)	-10.9%	+10.9%
Harvested Wood Products[b]	CO_2	(92.8)	(118.0)	(70.0)	-27.2%	+24.6%
Total Forest	**CO_2**	**(787.0)**	**(866.5)**	**(708.3)**	**-10.1%**	**+10.0%**

[a] Range of flux estimates predicted through a combination of sample-based and model-based uncertainty for a 95 percent confidence interval, IPCC Approach 1.

[b] Range of flux estimates predicted by Monte Carlo stochastic simulation for a 95 percent confidence interval, IPCC Approach 2.

Notes: Parentheses indicate negative values or net uptake. Totals may not sum due to independent rounding.

QA/QC and Verification

The FIA program has conducted consistent forest surveys based on extensive statistically-based sampling of most of the forest land in the conterminous U.S., dating back to 1952. The FIA program includes numerous quality assurance and quality control (QA/QC) procedures, including calibration among field crews, duplicate surveys of some plots, and systematic checking of recorded data. Because of the statistically-based sampling, the large number of survey plots, and the quality of the data, the survey databases developed by the FIA program form a strong foundation for carbon stock estimates. Field sampling protocols, summary data, and detailed inventory databases are archived and are publicly available (USDA Forest Service 2023d).

General quality control procedures were used in performing calculations to estimate carbon stocks based on survey data. For example, the carbon datasets, which include inventory variables such as areas and volumes, were compared to standard inventory summaries such as the forest resource statistics of Oswalt et al. (2019) or selected population estimates generated from the FIA database, which are available at an FIA internet site (USDA Forest Service 2023b). Agreement between the carbon datasets and the original inventories is important to verify accuracy of the data used.

Additional verification analyses are currently underway to compare forest carbon stock change estimates developed using the NSVB model to estimates stemming from other forest biomass models as well as remote sensing imagery.

Estimates of the HWP variables and the HWP contribution under the production estimation approach use data from USDC Bureau of the Census and USDA Forest Service surveys of production and trade, among other sources (Hair and Ulrich 1963; Hair 1958; USDC Bureau of Census 1976; Ulrich 1985, 1989; Steer 1948; AF&PA 2006a, 2006b; Howard 2003, 2007; Howard and Jones 2016; Howard and Liang 2019; AF&PA 2021; AF&PA 2023; FAO 2023). Factors to convert wood and paper to units of carbon are based on estimates by industry and U.S. Forest Service published sources (see Annex 3.13). The WOODCARB II model uses estimation methods suggested by IPCC (2006). Estimates of annual carbon change in solidwood and paper products in use were calibrated to meet two independent criteria. The first criterion is that the WOODCARB II model estimate of carbon in houses standing in 2001 needs to match an independent estimate of carbon in housing based on U.S. Census and USDA Forest Service survey data. Meeting the first criterion resulted in an estimated half-life of about 80 years for single family housing built in the 1920s, which is confirmed by other U.S. Census data on housing. The second criterion is that the WOODCARB II model estimate of wood and paper being discarded to SWDS needs to match EPA estimates of discards used in the Waste sector each year over the period 1990 to 2000 (EPA 2006). These criteria help reduce uncertainty in estimates of annual change in carbon in products in use in the United States and, to a lesser degree,

reduce uncertainty in estimates of annual change in carbon in products made from wood harvested in the United States. In addition, WOODCARB II landfill decay rates have been validated by ensuring that estimates of CH_4 emissions from landfills based on EPA (2006) data are reasonable in comparison to CH_4 estimates based on WOODCARB II landfill decay rates.

Recalculations Discussion

There were several methodological improvements implemented in the current *Inventory* which have resulted in substantial changes when compared to the previous (1990 through 2021) *Inventory*.

First, there were new FIA data included for several states, in some cases, multiple years of new data in this *Inventory* resulting from delays that occurred due to the global pandemic. Delays still exist in some states so it is possible that multiple years of data may be available in the years ahead leading to small changes in forest ecosystem carbon stocks and stock changes throughout the time series. These changes are most notable in the conterminous United States (Table 6-14) and coastal southeast and southcentral Alaska (Table 6-15). In coastal Alaska, remeasurement data from the FIA program facilitated the use of the compilation system used in most of the conterminous United States, improving consistency and facilitating the disaggregation of forest land conversions in this region for the first time. This transition in compilation methodology resulted in a 10.6 percent increase in forest land area (449,287 ha) in coastal Alaska which contributed, in part, to increases in forest ecosystem carbon stocks across all pools (Table 6-15).

This *Inventory* also implemented new methods for estimating standing live and dead aboveground biomass carbon in the FIA program (Westfall et al. 2023). These new methods, leveraging the newly developed national-scale volume and biomass framework (NSVB), represent nearly a decade of research and development in the FIA program. The new methods: 1) greatly simplify predictions of aboveground biomass because only five model specifications are used nationally instead of dozens of species- and species-group specific models used in each region and/or state, 2) eliminate administrative boundaries (e.g., regions or states) in favor of ecologically-based regions (i.e., ecodivisons) to capture variation in tree size and volume (or biomass) within species or species groups, 3) models are based on tree measurements from in-situ data which also facilitates more accurate quantification of model uncertainty, 4) result in consistent model behavior for all tree species and sizes, and 5) use species-specific carbon fractions for biomass to carbon conversions compared to the previous method which assumed a default 50 percent biomass to carbon fraction.

The implementation of the NSVB models resulted in an increase in estimates of aboveground biomass carbon stocks on forest land in the United States of approximately 11 percent (1,761.9 MMT C) in the current *Inventory* for the year 2022 relative to the previous *Inventory* estimate for the year 2022 (Table 6-13) and accounted for 34 percent of the total increase in estimates of forest carbon stocks in this *Inventory* relative to the previous *Inventory* for the same year (Table 6-13). These increases can largely be attributed to more accurate characterization of top and limb biomass in the new models (Westfall et al. 2023). This also led to small increases in estimates of belowground biomass carbon stocks since that model is based on a ratio of aboveground biomass. There were also increases of more than 11 percent (321 MMT C) in estimates of dead wood carbon stocks due to the implementation of the new NSVB models in the FIA program for standing dead trees (Table 6-13), which accounted for 6.2 percent of the increases in estimates of forest ecosystem carbon stocks in this *Inventory* relative to the previous *Inventory* for the same year.

The litter and soil model framework used in this *Inventory* and implemented across the entire time series was formally adopted in the FIA program this year and predictions compiled using this framework are now available in the public FIA database (USDA Forest Service 2023b). As part of the formal adoption of these methods in the FIA program, all variables and associated datasets used in the models were evaluated. New climate normals for the time period 1991 to 2020 were included in both the litter and soil models using PRISM data for the conterminous United States and climate normals for 1981 to 2010 (the only period available) were included for the first time in coastal Alaska. Collectively, these updates and improvements resulted in carbon stock estimates that were 10.1 percent larger (3,150.7 MMT C) in this *Inventory* relative to the previous *Inventory* for mineral and organic soil in the United States and overall accounted for approximately 48 percent of the total increases in forest carbon stock

in the current *Inventory* for the year 2022 when compared to the previous *Inventory* for the same year (Table 6-13, Table 6-14). In coastal Alaska, there were comparable increases in predictions in the *Inventory* relative to previous *Inventories*. These increases can be attributed to increases in estimates of forest land area in coastal Alaska as well as the incorporation of climate data in the litter and soil models. Estimates of litter carbon stocks also decreased slightly on forest land remaining forest land relative to the previous Inventory (Table 6-13) due to the implementation of the NSVB models where the litter model relies on estimates of aboveground biomass as a model parameter. Finally, new data on wildfire in Interior Alaska in the latest *Inventory* also contributed to updated estimates in the time series for this area of forest land where there were decreases in the estimates of all but the organic soil carbon pools (Table 6-16). Collectively these updates and improvements resulted in a 2.3 percent decrease (119.1 MMT C) in estimates of litter carbon stocks on forest land in the United States

Managed forest land in Hawaii and several U.S. Territories[31] were included for the first time in the current *Inventory* which resulted in an increase in managed forest land area of approximate 1.3 M ha and associated increases in carbon stocks of 286 MMT C for the year 2023 in this *Inventory*. While the inclusion of these forest land areas represents a relatively small increase in forest area and forest ecosystem carbon stocks overall, their inclusion represents an important improvement toward completeness in this *Inventory*.

Table 6-13: Recalculations of Forest Area (1,000 ha) and Carbon Stocks in Forest Land Remaining Forest Land and Harvested Wood Pools (MMT C)

	2022 Estimate, Previous *Inventory*	2022 Estimate, Current *Inventory*	2023 Estimate, Current *Inventory*
Forest Area (1000 ha)	***279,800***	***281,752***	***281,725***
Carbon Pools (MMT C)			
Forest	**56,951**	**62,130**	**62,320**
Aboveground Biomass	15,861	17,622	17,757
Belowground Biomass	3,143	3,207	3,233
Dead Wood	2,827	3,148	3,184
Litter	3,888	3,768	3,761
Soil (Mineral)	25,916	28,401	28,401
Soil (Organic)	5,317	5,983	5,983
Harvested Wood	**2,749**	**2,747**	**2,772**
Products in Use	1,549	1,547	1,555
SWDS	1,200	1,200	1,217
Total Stock	**59,701**	**64,877**	**65,092**

Note: Totals may not sum due to independent rounding.

Table 6-14: Recalculations of Forest Area (1,000 ha) and Carbon Stocks in Forest Land Remaining Forest Land (MMT C) in the Conterminous United States

	2022 Estimate, Previous *Inventory*	2022 Estimate, Current *Inventory*	2023 Estimate, Current *Inventory*
Forest Area (1000 ha)	***249,821***	***250,036***	***249,999***
Carbon Pools (MMT C)			
Forest	**46,575**	**51,195**	**51,391**
Aboveground Biomass	14,947	16,641	16,773
Belowground Biomass	2,959	3,006	3,032
Dead Wood	2,558	2,883	2,920
Litter	2,474	2,383	2,384
Soil (Mineral)	23,086	25,467	25,467
Soil (Organic)	550	815	815

[31] American Samoa, Guam, Norther Mariana Islands, U.S. Virgin Islands, and Puerto Rico

Note: Totals may not sum due to independent rounding.

Table 6-15: Recalculations of Forest Area (1,000 ha) and Carbon Stocks in Forest Land Remaining Forest Land (MMT C) in Coastal Southeast and Southcentral Alaska

	2022 Estimate, Previous *Inventory*	2022 Estimate, Current *Inventory*	2023 Estimate, Current *Inventory*
Forest Area (1000 ha)	***4,222***	***4,671***	***4,681***
Carbon Pools (MMT C)			
Forest	**1,235**	**1,458**	**1,460**
Aboveground Biomass	362	421	423
Belowground Biomass	76	85	85
Dead Wood	94	107	107
Litter	129	130	130
Soil (Mineral)	411	470	470
Soil (Organic)	163	245	245

Note: Totals may not sum due to independent rounding.

Table 6-16: Recalculations of Forest Area (1,000 ha) and Carbon Stocks in Forest Land Remaining Forest Land (MMT C) in Interior Alaska

	2022 Estimate, Previous *Inventory*	2022 Estimate, Current *Inventory*	2023 Estimate, Current *Inventory*
Forest Area (1000 ha)	***25,758***	***25,758***	***25,758***
Carbon Pools (MMT C)			
Forest	**9,142**	**9,192**	**9,183**
Aboveground Biomass	551	485	484
Belowground Biomass	107	92	92
Dead Wood	176	154	153
Litter	1,285	1,248	1,240
Soil (Mineral)	2,419	2,308	2,308
Soil (Organic)	4,604	4,905	4,905

Note: Totals may not sum due to independent rounding.

Table 6-17: Recalculations of Forest Area (1,000 ha) and Carbon Stocks in Forest Land Remaining Forest Land (MMT C) in Hawaii and United States Territories

	2022 Estimate, Previous *Inventory*	2022 Estimate, Current *Inventory*	2023 Estimate, Current *Inventory*
Forest Area (1000 ha)	***NE***	***1,287***	***1,287***
Carbon Pools (MMT C)			
Forest	**NE**	**285**	**286**
Aboveground Biomass	NE	76	77
Belowground Biomass	NE	23	24
Dead Wood	NE	4	4
Litter	NE	7	7
Soil (Mineral)	NE	156	156
Soil (Organic)	NE	19	19

NE (Not Estimated)

Note: Totals may not sum due to independent rounding.

The new FIA data and methodological improvements described throughout this text and specifically in this section on recalculations of estimates of forest ecosystem carbon stocks extend to forest ecosystem carbon stock changes in the current *Inventory*. In total, estimates for the forest land remaining forest land sink increased 21.4 percent (sink estimates increased by 40.8 MMT C). On average across the time-series, these recalculations resulted in a

21.7 percent increase in estimates of the forest sink across the time series (sink estimates increased on average, 43.4 MMT C over the time series) relative to the previous *Inventory* (Table 6-18).

Changes in estimates of forest ecosystem carbon stock changes accounted for most of the increases between this *Inventory* and the previous *Inventory* (Table 6-18) and of those, new data and improvements in methods in the conterminous United States accounted for 97 percent (-41.8 MMT C) increases in estimates of forest ecosystem carbon stock changes in the current Inventory relative to the same year in the previous Inventory (Table 6-19). Estimates of carbon stock changes in the aboveground biomass pool increased by 25.2 percent in the current Inventory relative to the same year in the previous Inventory and accounted for 65.2 percent (-27.2 MMT C) of the increase in estimates from this *Inventory* (Table 6-19). These changes can be directly attributed to the implementation of the NSVB models in the FIA program. These increases extend to the belowground biomass pool where the increases in estimates of aboveground biomass resulted in increases in the estimates of belowground biomass by 23.8 percent (-5.1 MMT C). These increases accounted for 12.2 percent of the total increase in carbon stock changes in the forest ecosystem pools in this *Inventory*. There were also substantial increases in dead wood carbon stock changes which can also be attributed to the implementation of the NSVB models for standing dead trees (Westfall et al. In press). There was a 34.4 percent increase (-9.5 MMT C) in estimates of dead wood carbon stock changes between this Inventory and the same year in the previous Inventory. This increase in the estimates of dead wood accounts for 22.8 percent of the total increases in estimates of forest ecosystem carbon stock changes in this Inventory relative to the same year in the previous *Inventory* (Table 6-19).

There were also small differences in the estimates of carbon stock changes for the litter and the soil carbon pools in the conterminous United States, coastal and Interior Alaska (Table 6-19, Table 6-20, Table 6-21). These changes were all relatively small when compared to changes in live and standing dead biomass.

The inclusion of forest land in Hawaii and several U.S. Territories[32] also contributed to increases in the estimates of carbon stock changes in the current Inventory. Collectively, these areas contributed -1.3 MMT C to the forest land remaining forest land carbon sink in the year 2022 in the current *Inventory* (Table 6-22).

Finally, new data included in the HWP time series resulted in a minor decrease (< 1 percent) in carbon stocks in the HWP pools (Table 6-13) and an associated decrease of 7.9 percent (2.2 MMT C) in estimates of carbon stock changes (Table 6-18). These decreases are the result of decreases in estimates of carbon stock changes for products in use (19.4 percent) in the current *Inventory* relative to the same year in the previous *Inventory* (Table 6-18). With the easing of the global pandemic and the return of consumers to the marketplace, there was a rebound in the purchase and accumulation of solid wood products. Alternatively, paper products in use have been declining in recent years, which could be the result of greater digitization across society. These trends are expected to continue in 2023.

Table 6-18: Recalculations of Net Carbon Flux from Forest Ecosystem Pools in Forest Land Remaining Forest Land and Harvested Wood Pools (MMT C)

Carbon Pool (MMT C)	2021 Estimate, Previous *Inventory*	2021 Estimate, Current *Inventory*	2022 Estimate, Current *Inventory*
Forest	**(161.6)**	**(204.4)**	**(189.3)**
Aboveground Biomass	(111.6)	(139.9)	(134.1)
Belowground Biomass	(22.1)	(27.5)	(26.4)
Dead Wood	(27.6)	(36.9)	(35.8)
Litter	0.5	(0.0)	7.2
Soil (Mineral)	(1.1)	(0.2)	(0.3)
Soil (Organic)	0.0	(0.0)	(0.0)
Drained organic soil	0.2	0.2	0.2
Harvested Wood	**(28.0)**	**(25.8)**	**(25.3)**
Products in Use	(10.3)	(8.3)	(7.9)

[32] American Samoa, Guam, Norther Mariana Islands, U.S. Virgin Islands, and Puerto Rico

SWDS	(17.7)	(17.5)	(17.4)
Total Net Flux	**(189.6)**	**(230.2)**	**(214.6)**

Note: Totals may not sum due to independent rounding. Parentheses indicate net sequestration.

Table 6-19: Recalculations of Net Carbon Flux from Forest Ecosystem Pools in Forest Land Remaining Forest Land (MMT C) in the Conterminous United States

Carbon Pool (MMT C)	2021 Estimate, Previous *Inventory*	2021 Estimate, Current *Inventory*	2022 Estimate, Current *Inventory*
Forest	**(158.5)**	**(200.3)**	**(195.9)**
Aboveground Biomass	(108.1)	(135.3)	(132.1)
Belowground Biomass	(21.3)	(26.4)	(25.8)
Dead Wood	(27.7)	(37.2)	(36.8)
Litter	(0.5)	(1.0)	(0.8)
Soil (Mineral)	(1.1)	(0.2)	(0.3)
Soil (Organic)	0.0	(0.1)	(0.1)

Note: Totals may not sum due to independent rounding. Parentheses indicate net sequestration.

Table 6-20: Recalculations of Net Carbon Flux from Forest Ecosystem Pools in Forest Land Remaining Forest Land (MMT C) in Coastal Alaska

Carbon Pool (MMT C)	2021 Estimate, Previous *Inventory*	2021 Estimate, Current *Inventory*	2022 Estimate, Current *Inventory*
Forest	**(2.0)**	**(1.9)**	**(1.9)**
Aboveground Biomass	(1.3)	(1.4)	(1.4)
Belowground Biomass	(0.3)	(0.3)	(0.3)
Dead Wood	(0.3)	(0.1)	(0.1)
Litter	0.0	(0.1)	(0.1)
Soil (Mineral)	0.0	0.0	0.0
Soil (Organic)	0.0	0.0	0.0

Note: Totals may not sum due to independent rounding. Parentheses indicate net sequestration.

Table 6-21: Recalculations of Net Carbon Flux from Forest Ecosystem Pools in Forest Land Remaining Forest Land (MMT C) in Interior Alaska

Carbon Pool (MMT C)	2021 Estimate, Previous *Inventory*	2021 Estimate, Current *Inventory*	2022 Estimate, Current *Inventory*
Forest	**(1.2)**	**(1.1)**	**9.6**
Aboveground Biomass	(2.1)	(2.1)	0.4
Belowground Biomass	(0.5)	(0.5)	0.0
Dead Wood	0.4	0.4	1.1
Litter	1.0	1.0	8.0
Soil (Mineral)	0.0	0.0	0.0
Soil (Organic)	0.0	0.0	0.0

Note: Totals may not sum due to independent rounding. Parentheses indicate net sequestration.

Table 6-22: Recalculations of Net Carbon Flux from Forest Ecosystem Pools in Forest Land Remaining Forest Land (MMT C) in Hawaii and United States Territories

Carbon Pool (MMT C)	2021 Estimate, Previous *Inventory*	2021 Estimate, Current *Inventory*	2022 Estimate, Current *Inventory*
Forest	**NE**	**(1.4)**	**(1.3)**
Aboveground Biomass	NE	(1.0)	(1.0)
Belowground Biomass	NE	(0.3)	(0.3)
Dead Wood	NE	(0.0)	0.0

Litter	NE	0.0	(0.0)
Soil (Mineral)	NE	(0.0)	0.0
Soil (Organic)	NE	0.0	0.0

NE (Not Estimated)

Note: Totals may not sum due to independent rounding. Parentheses indicate net sequestration.

Planned Improvements

Reliable estimates of forest carbon stocks and changes across the diverse ecosystems of the United States require a high level of investment in both annual monitoring and associated analytical techniques. Development of improved monitoring/reporting techniques is a continuous process that occurs simultaneously with annual *Inventory* submissions. Planned improvements can be broadly assigned to the following categories: development of a robust estimation and reporting system, individual carbon pool estimation, coordination with other land-use categories, and periodic and annual inventory data incorporation.

While this *Inventory* submission includes carbon change by forest land remaining forest land and land converted to forest land and carbon stock changes for all IPCC pools in these two categories, there are many improvements that are still necessary. The estimation approach used for the conterminous United States in the current *Inventory* for the forest land category operates at the state scale, whereas previously the western United States and southeast and southcentral coastal Alaska operated at a regional scale. While this is an improvement over previous Inventories and led to improved estimation and separation of land-use categories in the current *Inventory*, including coastal Alaska, research is underway to leverage all FIA data (periodic and annual inventories) and auxiliary information (i.e., remotely sensed information) to operate at finer spatial and temporal scales. As in past submissions, emissions and removals associated with natural (e.g., wildfire, insects, and disease) and human (e.g., harvesting) disturbances are implicitly included in the report given the design of the annual NFI, but not explicitly estimated. In addition to integrating auxiliary information into the estimation framework and leveraging all NFI plot measurements, alternative estimators are also being evaluated which will eliminate latency in population estimates from the NFI, improve annual estimation and characterization of interannual variability, facilitate attribution of fluxes to particular activities, and allow for streamlined harmonization of NFI data with auxiliary data products. This will also facilitate separation of prescribed and wildfire emissions in future reports. The transparency and repeatability of estimation and reporting systems will be improved through the dissemination of open-source code (e.g., R programming language) in concert with the public availability of the periodic and annual NFI (USDA Forest Service 2023b). Also, several FIA database processes are being institutionalized to increase efficiency and QA/QC in reporting and further improve transparency, completeness, consistency, accuracy, and availability of data used in reporting. Finally, a combination of approaches was used to estimate uncertainty associated with carbon stock changes in the forest land remaining forest land category in this report. There is research underway investigating more robust approaches to estimate total uncertainty (Clough et al. 2016), which will be considered in future *Inventory* reports.

The modeling framework used to estimate downed dead wood within the dead wood carbon pool (Smith et al. 2022) will be updated similar to the litter (Domke et al. 2016) and soil carbon pools (Domke et al. 2017). With the implementation of the new models for volume, biomass, and carbon estimation for live and standing dead trees, the methods for litter and soil carbon estimation used in this *Inventory* and recent *Inventories* have been adopted in the FIA program so there is now alignment and consistency between litter and soil carbon estimates in this *Inventory* and the FIA database. Finally, components of other pools, such as carbon in belowground biomass (Russell et al. 2015) and understory vegetation (Russell et al. 2014; Johnson et al. 2017), are being explored but may require additional investment in field inventories before improvements can be realized in the *Inventory* report.

The foundation of forest carbon estimation and reporting is the annual NFI. The ongoing annual surveys by the FIA program are expected to improve the accuracy and precision of forest carbon estimates as new state surveys become available (USDA Forest Service 2023b). With the exception of Wyoming (which will have sufficient remeasurements in the years ahead), all other states in the conterminous United States and coastal Alaska now

have sufficient annual NFI data to consistently estimate carbon stocks and stock changes for the future using the state-level compilation system. The FIA program continues to install permanent plots in interior Alaska as part of the operational NFI, and as more plots are added to the NFI, they will be used to improve estimates for all managed forest land in Alaska. Estimates of carbon stocks and stock changes for Hawaii and the U.S. Territories were included in this *Inventory* using Tier 1 and Tier 2 methods. The methods used to include all managed forest land in the conterminous United States will be used in future Inventories for Hawaii and U.S. Territories as additional forest carbon data become available (only a small number of plots from Hawaii are currently available from the annualized sampling design). To that end, research is underway to incorporate all NFI information (both annual and periodic data) and the dense time series of remotely sensed data in multiple inferential frameworks for estimating greenhouse gas emissions and removals as well as change (i.e., disturbance or land-use changes) detection and attribution across the entire reporting period and all managed forest land in the United States. Leveraging this auxiliary information will aid the efforts to improve estimates for interior Alaska, Hawaii, and the U.S. Territories, as well as the entire inventory system. In addition to fully inventorying all managed forest land in the United States, the more intensive sampling (i.e., more samples) of fine woody debris, litter, and SOC on a subset of FIA plots continues and will substantially improve spatial and temporal resolution of carbon pools (Westfall et al. 2013) as this information becomes available. Increased sample intensity of some carbon pools and using annualized sampling data as it becomes available for those states currently not reporting are planned for future submissions. The NFI sampling frame extends beyond the forest land-use category (e.g., woodlands, which fall into the grasslands land-use category, and urban areas, which fall into the settlements land-use category) with inventory-relevant information for trees outside of forest land. These data will be utilized as they become available in the NFI.

Non-CO_2 Emissions from Forest Fires

Emissions of non-CO_2 gases from forest fires were estimated using U.S.-specific data and models for annual area of forest burned, fuel, consumption, and emission consistent with IPCC (2019). In 2022, emissions from this source were estimated to be 9.1 MMT CO_2 Eq. of CH_4 and 5.7 MMT CO_2 Eq. of N_2O (Table 6-23; kt units provided in Table 6-24). The estimates of non-CO_2 emissions from forest fires include the conterminous 48 states, Hawaii, Puerto Rico, Guam and managed forest land in Alaska (Ogle et al. 2018) because the fire data in use with the current methods identifies fires on these areas within the interval 1990 through 2022.

Table 6-23: Non-CO_2 Emissions from Forest Fires (MMT CO_2 Eq.)[a]

Gas	1990	2005	2018	2019	2020	2021	2022
CH_4	3.4	9.2	6.0	3.4	9.8	12.7	9.1
N_2O	2.4	6.3	3.7	2.3	5.5	7.2	5.7
Total	**5.8**	**15.4**	**9.7**	**5.7**	**15.3**	**19.9**	**14.8**

[a] These estimates include non-CO_2 emissions from forest fires on forest land remaining forest land and land converted to forest land.

Note: Totals may not sum due to independent rounding.

Table 6-24: Non-CO_2 Emissions from Forest Fires (kt)[a]

Gas	1990	2005	2018	2019	2020	2021	2022
CH_4	122	328	213	120	349	452	327
N_2O	9	24	14	9	21	27	21
CO	3179	8447	4648	3054	7266	9598	7593
NO_x	49	124	93	51	123	160	121

[a] These estimates include non-CO_2 emissions from forest fires on forest land remaining forest land and land converted to forest land.

Methodology and Time-Series Consistency

Non-CO_2 emissions from forest fires—primarily CH_4 and N_2O emissions—were calculated consistent with IPCC (2019) methodology, which represent updates of the IPCC (2006) guidance on reporting fire emissions. For the conterminous states and Alaska, estimates were developed with U.S.-specific data and models on area burned, fuel, consumption, and emissions as provided through the Wildland Fire Emissions Inventory System calculator (WFEIS, French et al. 2011, 2014). However, these fire emissions models did not extend to include Hawaii, Puerto Rico, or Guam, so forest fire estimates for these areas relied on Tier 1 emissions factors (IPCC 2019). Spatial definitions of wildland burned areas were the starting point for all estimates, from WFEIS or Tier 1. The three burned area datasets in use are the Monitoring Trends in Burn Severity (MTBS, Eidenshink et al. 2007), MODIS burned area mapping (MODIS MCD64A1 V6.1, Giglio et al. 2018), and Wildland Fire Interagency Geospatial Service (WFIGS) fire perimeters (WFIGS 2023). The MTBS data available for this report (MTBS 2023) included fires from 1990 through 2021 for all states and Puerto Rico (the exception was Alaska 2021 where emissions calculations were not available). The MODIS-based records include 2001 through 2022 for the 48 conterminous states plus Alaska. The WFIGS-based records for 2020 through 2022 included all states plus Puerto Rico and Guam. Note that N_2O emissions are not included in WFEIS calculations; the emissions provided here are based on the average N_2O to CO_2 ratio of 0.000166 (Larkin et al. 2014; IPCC 2019). See the emissions from forest fires section in Annex 3.13 for further details on all fire-related emissions calculations for forests. Consistent use of available data sources, data processing, and calculation methods were applied to the entire time series to ensure time-series consistency from 1990 through 2022.

Uncertainty

Uncertainty estimates for non-CO_2 emissions from forest fires are based on a Monte Carlo (IPCC Approach 2) approach to propagate variability among the alternate WFEIS annual estimates per state. Uncertainty in parts of the WFEIS system are not currently quantified. Among potential sources for future analysis are burned areas from MTBS, WFIGS, or MODIS, the fuels models or the Consume model (Prichard et al. 2014). See Annex 3.13 for the quantities and assumptions employed to define and propagate uncertainty. The results of the Approach 2 quantitative uncertainty analysis are summarized in Table 6-25.

Table 6-25: Quantitative Uncertainty Estimates of Non-CO_2 Emissions from Forest Fires (MMT CO_2 Eq. and Percent)[a]

Source	Gas	2022 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[b] (MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Non-CO_2 Emissions from Forest Fires	CH_4	9.1	6.2	12.1	-32%	+32%
Non-CO_2 Emissions from Forest Fires	N_2O	5.7	3.6	7.8	-36%	+37%

[a] These estimates include non-CO_2 emissions from forest fires on forest land remaining forest land and land converted to forest land.

[b] Range of flux estimates predicted by Monte Carlo stochastic simulation for a 95 percent confidence interval.

QA/QC and Verification

Tier 1 and Tier 2 QA/QC activities were conducted consistent with the U.S. QA/QC plan. Source-specific quality control measures for estimating non-CO_2 emissions from forest fires included checking input data, documentation, and calculations to ensure data were properly handled through the inventory process and results were consistent with values expected from those calculations. The QA/QC procedures did not reveal any inaccuracies or incorrect input values.

Recalculations Discussion

The methods used in the current (1990 through 2022) *Inventory* to compile estimates of non-CO_2 emissions from forest fires represent a slight change relative to the previous (1990 through 2021) *Inventory*. The basic components of calculating forest fire emissions (IPCC 2019) remain unchanged, but the WFEIS-based estimates now include MTBS, WFIGS, and MODIS based burns (depending on year). The MTBS and WFIGS based estimates are now calculated per burn event (i.e., separately for each forest fire), which improves precision for scaling or allocating emissions such as to managed versus unmanaged lands in Alaska.

An additional source of change leading to recalculations are recent and ongoing updates to the MTBS fire records (i.e., including both most-recent as well as possible updates to past years' fires). The WFEIS calculations now use version 6.1 of the MODIS burned area model and updated versions of the Fuel Characteristic Classification System (FCCS) fuel layer and the Consume model (see WFEIS 2023) for additional details on updates. The addition of forest fire emissions for Hawaii, Puerto Rico, and Guam had little effect on the magnitude of overall emissions.

Estimates of non-CO_2 emissions from forest fires (e.g., Table 6-24) are lower for most years over the time series 1990-2021 in comparison with the previous Inventory (EPA 2023), with an average decrease of 12 percent across all years. For, 2021 the estimate decreased from 24.4 to 19.9 MMT CO_2 Eq. (an 18.7 percent decrease). Changes over the time series are expected because the entire interval is recalculated each year in response to modifications in the fire datasets that can affect all years. For example, MTBS updates burn perimeters for all years as data resolution changes. This year, the WFEIS calculator updated a fuel dataset as well as the Consume model (noted above). The addition of estimates for Hawaii, Puerto Rico, and Guam had negligible effect on the estimates.

Planned Improvements

Continuing improvements are planned for developing better fire and site-specific estimates for forest fires, for example, improving on the Tier-1 factors currently employed for Hawaii, Puerto Rico, and Guam. Additional focus will be on addressing three aspects of reporting: best use of WFEIS, better resolution of uncertainty as discussed above, and identification of burned areas that are not currently captured by the burn records in use.

N_2O Emissions from N Additions to Forest Soils

Of the synthetic nitrogen (N) fertilizers applied to soils in the United States, no more than one percent is applied to forest soils. Application rates are similar to those occurring on cropland soils, but in any given year, only a small proportion of total forested land receives N fertilizer. This is because forests are typically fertilized only twice during their approximately 40-year growth cycle (once at planting and once midway through their life cycle). While the rate of N fertilizer application for the area of forests that receives N fertilizer in any given year is relatively high, the annual application rate is quite low over the entire area of forest land.

N additions to soils result in direct and indirect N_2O emissions. Direct emissions occur on-site due to the N additions. Indirect emissions result from fertilizer N that is transformed and transported to another location through volatilization in the form of ammonia (NH_3) and nitrogen oxide (NO_x), in addition to leaching and runoff of nitrates (NO_3), and later converted into N_2O at off-site locations. The indirect emissions are assigned to forest land because the management activity leading to the emissions occurred in forest land.

Direct soil N_2O emissions from forest land remaining forest land and land converted to forest land[33] in 2022 were 0.3 MMT CO_2 Eq. (1.2 kt), and the indirect emissions were 0.1 MMT CO_2 Eq. (0.4 kt). Total emissions for 2022 were 0.4 MMT CO_2 Eq. (1.5 kt) and have increased by 455 percent from 1990 to 2022. Total forest soil N_2O emissions are summarized in Table 6-26.

[33] The N_2O emissions from land converted to forest land are included with forest land remaining forest land because it is not currently possible to separate the activity data by land use conversion category.

Table 6-26: N_2O Fluxes from Soils in Forest Land Remaining Forest Land and Land Converted to Forest Land (MMT CO_2 Eq. and kt N_2O)

	1990	2005	2018	2019	2020	2021	2022
Direct N_2O Fluxes from Soils							
MMT CO_2 Eq.	0.1	0.3	0.3	0.3	0.3	0.3	0.3
kt N_2O	0.2	1.2	1.2	1.2	1.2	1.2	1.2
Indirect N_2O Fluxes from Soils							
MMT CO_2 Eq.	+	0.1	0.1	0.1	0.1	0.1	0.1
kt N_2O	0.1	0.4	0.4	0.4	0.4	0.4	0.4
Total (MMT CO_2 Eq.)	**0.1**	**0.4**	**0.4**	**0.4**	**0.4**	**0.4**	**0.4**
Total (kt N_2O)	**0.3**	**1.5**	**1.5**	**1.5**	**1.5**	**1.5**	**1.5**

+ Does not exceed 0.05 MMT CO_2 Eq. or 0.05 kt.

Note: Totals may not sum due to independent rounding. The N_2O emissions from land converted to forest land are included with forest land remaining forest land because it is not currently possible to separate the activity data by land use conversion category.

Methodology and Time-Series Consistency

The IPCC Tier 1 approach is used to estimate N_2O from soils within forest land remaining forest land and land converted to forest land. According to U.S. Forest Service statistics for 1996 (USDA Forest Service 2001), approximately 75 percent of trees planted are for timber, and about 60 percent of national total harvested forest area is in the southeastern United States. Although southeastern pine plantations represent the majority of fertilized forests in the United States, this Inventory also incorporated N fertilizer application to commercial Douglas-fir stands in western Oregon and Washington. For the Southeast, estimates of direct N_2O emissions from fertilizer applications to forests are based on the area of pine plantations receiving fertilizer in the southeastern United States and estimated application rates (Albaugh et al. 2007; Fox et al. 2007). Fertilizer application is rare for hardwoods and therefore not included in the inventory (Binkley et al. 1995). For each year, the area of pine receiving N fertilizer is multiplied by the weighted average of the reported range of N fertilization rates (121 lbs. N per acre). Area data for pine plantations receiving fertilizer in the Southeast are not available for 2005 through 2022, so data from 2004 are used for these years. For commercial forests in Oregon and Washington, only fertilizer applied to Douglas-fir is addressed in the inventory because the vast majority (approximately 95 percent) of the total fertilizer applied to forests in this region is applied to Douglas-fir stands (Briggs 2007). Estimates of total Douglas-fir area and the portion of fertilized area are multiplied to obtain annual area estimates of fertilized Douglas-fir stands. Similar to the Southeast, data are not available for 2005 through 2022, so data from 2004 are used for these years. The annual area estimates are multiplied by the typical rate used in this region (200 lbs. N per acre) to estimate total N applied (Briggs 2007), and the total N applied to forests is multiplied by the IPCC (2006) default emission factor of one percent to estimate direct N_2O emissions.

For indirect emissions, the volatilization and leaching/runoff N fractions for forest land are calculated using the IPCC default factors of 10 percent and 30 percent, respectively. The amount of N volatilized is multiplied by the IPCC default factor of one percent for the portion of volatilized N that is converted to N_2O off-site. The amount of N leached/runoff is multiplied by the IPCC default factor of 0.075 percent for the portion of leached/runoff N that is converted to N_2O off-site. The resulting estimates are summed to obtain total indirect emissions.

The same method is applied in all years of this *Inventory* to ensure time-series consistency from 1990 through 2022.

Uncertainty

The amount of N_2O emitted from forests depends not only on N inputs and fertilized area, but also on a large number of variables, including organic carbon availability, oxygen gas partial pressure, soil moisture content, pH, temperature, and tree planting/harvesting cycles. The effect of the combined interaction of these variables on N_2O flux is complex and highly uncertain. IPCC (2006) does not incorporate any of these variables into the default

methodology, except variation in estimated fertilizer application rates and estimated areas of forested land receiving nitrogen fertilizer. All forest soils are treated equivalently under this methodology. Furthermore, only applications of synthetic nitrogen fertilizers to forest are captured in this *Inventory*, so applications of organic nitrogen fertilizers are not estimated. However, the total quantity of organic nitrogen inputs to soils in the United States is included in the *Inventory* within the agricultural soil management source category (Section 5.4) and settlements remaining settlements (Section 6.10).

Uncertainties exist in the fertilization rates, annual area of forest lands receiving fertilizer, and the emission factors. Fertilization rates are assigned a default level[34] of uncertainty at ±50 percent, and area receiving fertilizer is assigned a ±20 percent according to expert knowledge (Binkley 2004). IPCC (2006) provided estimates for the uncertainty associated with direct and indirect N_2O emission factor for synthetic N fertilizer application to soils.

Uncertainty is quantified using simple error propagation methods (IPCC 2006). The results of the quantitative uncertainty analysis are summarized in Table 6-27. Direct N_2O fluxes from soils in 2022 are estimated to be between 0.1 and 1.0 MMT CO_2 Eq. at a 95 percent confidence level. This indicates a range of 59 percent below and 211 percent above the emission estimate of 0.3 MMT CO_2 Eq. for 2022. Indirect N_2O emissions in 2022 are 0.1 MMT CO_2 Eq. and have a range are between 0.01 and 0.3 MMT CO_2 Eq., which is 86 percent below to 238 percent above the emission estimate for 2022.

Table 6-27: Quantitative Uncertainty Estimates of N_2O Fluxes from Soils in Forest Land Remaining Forest Land and Land Converted to Forest Land (MMT CO_2 Eq. and Percent)

Source	Gas	2022 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate (MMT CO_2 Eq.)		Uncertainty Range Relative to Emission Estimate (%)	
Forest Land Remaining Forest Land			**Lower Bound**	**Upper Bound**	**Lower Bound**	**Upper Bound**
Direct N_2O Fluxes from Soils	N_2O	0.3	0.1	1.0	-59%	+211%
Indirect N_2O Fluxes from Soils	N_2O	0.1	+	0.3	-86%	+238%

+ Does not exceed 0.05 MMT CO_2 Eq.

Note: Totals may not sum due to independent rounding.

QA/QC and Verification

The spreadsheet containing fertilizer applied to forests and calculations for N_2O and uncertainty ranges are checked and verified based on the sources of these data consistent with the U.S. *Inventory* QA/QC plan, which is in accordance with Volume 1, Chapter 6 of the *2006 IPCC Guidelines* (see Annex 8 for more details).

Recalculations Discussion

No recalculations were performed for the current *Inventory*.

CO_2, CH_4, and N_2O Emissions from Drained Organic Soils[35]

Drained organic soils on forest land are identified separately from other forest soils largely because mineralization of the exposed or partially dried organic material results in continuous CO_2 and N_2O emissions (IPCC 2006). In addition, the *2013 Supplement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories: Wetlands*

[34] Uncertainty is unknown for the fertilization rates so a conservative value of ±50 percent is used in the analysis.

[35] Estimates of CO_2 emissions from drained organic soils are described in this section but reported in Table 6-8 and Table 6-9 for both Forest land remaining forest land and land converted to forest land in order to allow for reporting of all carbon stock changes on forest lands in a complete and comprehensive manner.

(IPCC 2014) calls for estimating CH_4 emissions from these drained organic soils and the ditch networks used to drain them.

Organic soils are identified on the basis of thickness of organic horizon and percent organic matter content. All organic soils are assumed to have originally been wet, and drained organic soils are further characterized by drainage or the process of artificially lowering the soil water table, which exposes the organic material to drying and the associated emissions described in this section. The land base considered here is drained inland organic soils that are coincident with forest area as identified by the NFI of the USDA Forest Service (USDA Forest Service 2022b).

The estimated area of drained organic soils on forest land is 70,849 ha and did not change over the time series based on the data used to compile the estimates in the current *Inventory*. These estimates are based on permanent plot locations of the NFI (USDA Forest Service 2022b) coincident with mapped organic soil locations (STATSGO2 2016), which identifies forest land on organic soils. Forest sites that are drained are not explicitly identified in the data, but for this estimate, planted forest stands on sites identified as mesic or xeric (which are identified in USDA Forest Service 2022c, d) are labeled "drained organic soil" sites.

Land use, region, and climate are broad determinants of emissions as are more site-specific factors such as nutrient status, drainage level, exposure, or disturbance. Current data are limited in spatial precision and thus lack site specific details. At the same time, corresponding emissions factor data specific to U.S. forests are similarly lacking. Tier 1 estimates are provided here following IPCC (2014). Total annual non-CO_2 emissions on forest land with drained organic soils in 2022 are estimated as 0.1 MMT CO_2 Eq. per year (Table 6-28; kt units provided in Table 6-29).

The Tier 1 methodology provides methods to estimate emissions of CO_2 from three pathways: direct emissions primarily from mineralization; indirect, or off-site, emissions associated with dissolved organic carbon releasing CO_2 from drainage waters; and emissions from (peat) fires on organic soils. Data about forest fires specifically located on drained organic soils are not currently available; as a result, no corresponding estimate is provided here. Non-CO_2 emissions provided here include CH_4 and N_2O. Methane emissions generally associated with anoxic conditions do occur from the drained land surface, but the majority of these emissions originate from ditches constructed to facilitate drainage at these sites. Emission of N_2O can be significant from these drained organic soils in contrast to the very low emissions from wet organic soils.

Table 6-28: Non-CO_2 Emissions from Drained Organic Forest Soils[a,b] (MMT CO_2 Eq.)

Source	1990	2005	2018	2019	2020	2021	2022
CH_4	+	+	+	+	+	+	+
N_2O	0.1	0.1	0.1	0.1	0. 1	0.1	0.1
Total	**0.1**	**0.1**	**0.1**	**0.1**	**0.1**	**0.1**	**0.1**

+ Does not exceed 0.05 MMT CO_2 Eq.

[a] This table includes estimates from forest land remaining forest land and land converted to forest land.

[b] Estimates of CO_2 emissions from drained organic soils are described in this section but reported in Table 6-8 and Table 6-9 for both forest land remaining forest land and land converted to forest land in order to allow for reporting of all carbon stock changes on forest lands in a complete and comprehensive manner.

Note: Totals may not sum due to independent rounding.

Table 6-29: Non-CO_2 Emissions from Drained Organic Forest Soils[a,b] (kt)

Source	1990	2005	2018	2019	2020	2021	2022
CH_4	1	1	1	1	1	1	1
N_2O	+	+	+	+	+	+	+

+ Does not exceed 0.5 kt.

[a] This table includes estimates from forest land remaining forest land and land converted to forest land.

[b] Estimates of CO_2 emissions from drained organic soils are described in this section but reported in Table 6-8 and Table 6-9 for both forest land remaining forest land and land converted to forest land in order to allow for reporting of all carbon stock changes on forest lands in a complete and comprehensive manner.

Methodology and Time-Series Consistency

The Tier 1 methods for estimating CO_2, CH_4 and N_2O emissions from drained inland organic soils on forest lands follow IPCC (2006), with extensive updates and additional material presented in the *2013 Supplement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories: Wetlands* (IPCC 2014). With the exception of quantifying area of forest on drained organic soils, which is user-supplied, all quantities necessary for Tier 1 estimates are provided in Chapter 2, Drained Inland Organic Soils of IPCC (2014).

Estimated area of drained organic soils on forest land is 70,849 ha based on analysis of the permanent NFI of the USDA Forest Service and did not change over the time series. The most recent plot data per state within the inventories were used in a spatial overlay with the STATSGO2 (2016) soils data, and forest plots coincident with the soil order histosol were selected as having organic soils. Information specific to identifying "drained organic" are not in the inventory data so an indirect approach was employed here. Specifically, artificially regenerated forest stands (inventory field STDORGCD=1) on mesic or xeric sites (inventory field 11≤PHYSCLCD≤29) are labeled "drained organic soil" sites. From this selection, forest area and sampling error for forest on drained organic sites are based on the population estimates developed within the inventory data for each state (USDA Forest Service 2022d). Eight states, all temperate forests (including pine forest in northern Florida, which largely display characteristics of temperate forests), were identified as having drained organic soils (Table 6-30).

Table 6-30: States identified as having Drained Organic Soils, Area of Forest on Drained Organic Soils, and Sampling Error

State	Forest on Drained Organic Soil (1,000 ha)	Sampling Error (68.3% as ± Percentage of Estimate)
Florida	2.4	79
Georgia	3.7	71
Michigan	18.7	34
Minnesota	30.2	19
North Carolina	1.3	99
Virginia	2.3	102
Washington	2.1	101
Wisconsin	10.1	30
Total	**70.8**	**14**

Note: Totals may not sum due to independent rounding.

The Tier 1 methodology provides methods to estimate emissions for three pathways of carbon emission as CO_2. Note that subsequent mention of equations and tables in the remainder of this section refer to Chapter 2 of IPCC (2014). The first pathway–direct CO_2 emissions–is calculated according to Equation 2.3 and Table 2.1 as the product of forest area and emission factor for temperate drained forest land. The second pathway—indirect, or off-site, emissions—is associated with dissolved organic carbon (DOC) releasing CO_2 from drainage waters according to Equation 2.4 and Table 2.2, which represent a default composite of the three pathways for this flux: (1) the flux of DOC from natural (undrained) organic soil; (2) the proportional increase in DOC flux from drained organic soils relative to undrained sites; and (3) the conversion factor for the part of DOC converted to CO_2 after export from a site. The third pathway—emissions from (peat) fires on organic soils—assumes that the drained organic soils burn in a fire, but not any wet organic soils. However, this *Inventory* currently does not include emissions for this pathway because data on the combined fire and drained organic soils information are not available at this time; this may become available in the future with additional analysis.

Non-CO_2 emissions, according to the Tier 1 method, include methane (CH_4), nitrous oxide (N_2O), and carbon monoxide (CO). Emissions associated with peat fires include factors for CH_4 and CO in addition to CO_2, but fire estimates are assumed to be zero for the current *Inventory*, as discussed above. Methane emissions generally associated with anoxic conditions do occur from the drained land surface, but the majority of these emissions originate from ditches constructed to facilitate drainage at these sites. From this, two separate emission factors are used, one for emissions from the area of drained soils and a second for emissions from drainage ditch waterways. Calculations are conducted according to Equation 2.6 and Tables 2.3 and 2.4, which includes the default fraction of the total area of drained organic soil which is occupied by ditches. Emissions of N_2O can be significant from these drained soils in contrast to the very low emissions from wet organic soils. Calculations are conducted according to Equation 2.7 and Table 2.5, which provide the estimate as kg N per year.

Methodological calculations were applied to the entire set of estimates for 1990 through 2022. Year-specific data are not available. Estimates are based on a single year and applied as the annual estimates over the interval.

Uncertainty

Uncertainties are based on the sampling error associated with forest area of drained organic soils and the uncertainties provided in the Chapter 2 (IPCC 2014) emissions factors (Table 6-31). The estimates and resulting quantities representing uncertainty are based on the IPCC Approach 1–error propagation. However, probabilistic sampling of the distributions defined for each emission factor produced a histogram result that contained a mean and 95 percent confidence interval. The primary reason for this approach was to develop a numerical representation of uncertainty with the potential for combining with other forest components. The methods and parameters applied here are identical to previous inventories, but input values were resampled for this *Inventory*, which results in minor changes in the number of significant digits in the resulting estimates, relative to past values. The total non-CO_2 emissions in 2022 from drained organic soils on forest land remaining forest land and land converted to forest land were estimated to be between zero and 0.150 MMT CO_2 Eq. around a central estimate of 0.068 MMT CO_2 Eq. at a 95 percent confidence level.

Table 6-31: Quantitative Uncertainty Estimates for Non-CO_2 Emissions on Drained Organic Forest Soils (MMT CO_2 Eq. and Percent)[a]

Source	2022 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate (MMT CO_2 Eq.)		Uncertainty Range Relative to Emission Estimate (%)	
		Lower Bound	Upper Bound	Lower Bound	Upper Bound
CH_4	+	+	+	-69%	+82%
N_2O	0.1	+	0.1	-118%	+132%
Total	**0.1**	**+**	**0.2**	**-107%**	**+121%**

+ Does not exceed 0.05 MMT CO_2 Eq.

[a] Range of flux estimates predicted through a combination of sample-based and IPCC defaults for a 95 percent confidence interval, IPCC Approach 1.

Note: Totals may not sum due to independent rounding.

QA/QC and Verification

IPCC (2014) guidance cautions of a possibility of double counting some of these emissions. Specifically, the off-site emissions of dissolved organic carbon from drainage waters may be double counted if soil carbon stock and change is based on sampling and this carbon is captured in that sampling. Double counting in this case is unlikely since plots identified as drained were treated separately in this chapter. Additionally, some of the non-CO_2 emissions may be included in either the wetlands or sections on N_2O emissions from managed soils. These paths to double counting emissions are unlikely here because these issues are taken into consideration when developing the estimates and this chapter is the only section directly including such emissions on forest land.

Recalculations Discussion

No recalculations were performed for the current *Inventory*.

Planned Improvements

Additional data will be compiled to update estimates of forest areas on drained organic soils as new reports and geospatial products become available. For example, current and recent past estimates are based on drained organic soils identified in a limited number of the conterminous states; if forests on drained organic soils are identified in additional areas including Alaska, Hawaii, Puerto Rico, or Guam, they will be included in future *Inventories*.

6.3 Land Converted to Forest Land (CRT Category 4A2)

The carbon stock change estimates for land converted to forest land that are provided in this Inventory include all forest land in an inventory year that had been in another land use(s) during the previous 20 years.[36] For example, cropland or grassland converted to forest land during the past 20 years would be reported in this category. Converted lands are in this category for 20 years as recommended in the *2006 IPCC Guidelines* (IPCC 2006), after which they are classified as forest land remaining forest land. Estimates of carbon stock changes from all pools (i.e., aboveground and belowground biomass, dead wood, litter and soils), as recommended by IPCC (2006), are included in the land converted to forest land category of this *Inventory*.

Area of Land Converted to Forest in the United States[37]

Land conversion to and from forests has occurred regularly throughout United States history. The 1970s and 1980s saw a resurgence of federally sponsored forest management programs (e.g., the Forestry Incentive Program) and soil conservation programs (e.g., the Conservation Reserve Program), which have focused on tree planting, improving timber management activities, combating soil erosion, and converting marginal cropland to forests. Recent analyses suggest that net accumulation of forest area continues in areas of the United States, in particular the northeastern United States (Woodall et al. 2015b). Specifically, the annual conversion of land from other land-use categories (i.e., cropland, grassland, wetlands, settlements, and other lands) to forest land resulted in a fairly continuous net annual accretion of forest land area from over the time series at an average rate of 1.0 million ha year-1.

Over the 20-year conversion period used in the land converted to forest land category, the conversion of grassland to forest land resulted in the largest source of carbon transfer and uptake, accounting for approximately 38

[36] The annual NFI data used to compile estimates of carbon transfer and uptake in this section are based on 5- to 10-yr remeasurements so the exact conversion period was limited to the remeasured data over the time series.

[37] The estimates reported in this section only include the 48 conterminous states in the United States. Land use conversions to forest land in Alaska are currently included in the Forest Land Remaining Forest Land section because currently there is insufficient data to separate the changes and estimates for Hawaii were not included because there is insufficient NFI data to support inclusion at this time. Also, it is not possible to separate forest land remaining forest land from land converted to forest land in Wyoming because of the split annual cycle method used for population estimation, this prevents harmonization of forest land in Wyoming with the NRI/NLCD method used in Section 6.1. See Annex 3.13, Table A-203 for annual differences between the forest area reported in Section 6.1 and Section 6.3.

percent of the uptake annually. Estimated carbon uptake has remained relatively stable over the time series across all conversion categories (see Table 6-24). The net flux of carbon from all forest pool stock changes in 2022 was -100.3 MMT CO_2 Eq. (-27.4 MMT C) (see Table 6-24 and Table 6-25).

Mineral soil carbon stocks increased slightly over the time series for land converted to forest land. The small gains are associated with cropland converted to forest land, settlements converted to forest land, and other land converted to forest land. Much of this conversion is from soils that are more intensively used under annual crop production or settlement management, or are conversions from other land, which has little to no soil carbon. In contrast, grassland converted to forest land leads to a loss of soil carbon across the time series, which negates some of the gain in soil carbon with the other land-use conversions. Managed pasture to forest land is the most common conversion. This conversion leads to a loss of soil carbon because pastures are mostly improved in the United States with fertilization and/or irrigation, which enhances carbon input to soils relative to typical forest management activities.

Table 6-32: Net CO_2 Flux from Forest Carbon Pools in Land Converted to Forest Land by Land Use Change Category (MMT CO_2 Eq.)

Land Use/Carbon Pool	1990	2005	2018	2019	2020	2021	2022
Cropland Converted to Forest Land	**(17.6)**	**(17.5)**	**(17.3)**	**(17.3)**	**(17.2)**	**(17.2)**	**(17.2)**
Aboveground Biomass	(10.2)	(10.1)	(10.0)	(10.0)	(10.0)	(10.0)	(10.0)
Belowground Biomass	(1.7)	(1.7)	(1.7)	(1.7)	(1.7)	(1.7)	(1.7)
Dead Wood	(2.2)	(2.2)	(2.2)	(2.2)	(2.2)	(2.2)	(2.2)
Litter	(3.3)	(3.2)	(3.2)	(3.2)	(3.2)	(3.2)	(3.2)
Mineral Soil	(0.2)	(0.2)	(0.2)	(0.1)	(0.1)	(0.1)	(0.1)
Grassland Converted to Forest Land	**(36.7)**	**(36.9)**	**(37.2)**	**(37.2)**	**(37.2)**	**(37.2)**	**(37.2)**
Aboveground Biomass	(22.5)	(22.7)	(22.8)	(22.8)	(22.8)	(22.8)	(22.8)
Belowground Biomass	(2.7)	(2.7)	(2.7)	(2.7)	(2.7)	(2.7)	(2.7)
Dead Wood	(4.0)	(4.1)	(4.1)	(4.1)	(4.1)	(4.1)	(4.1)
Litter	(7.6)	(7.7)	(7.7)	(7.7)	(7.7)	(7.7)	(7.7)
Mineral Soil	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Other Land Converted to Forest Land	**(5.2)**	**(5.3)**	**(5.5)**	**(5.5)**	**(5.5)**	**(5.5)**	**(5.5)**
Aboveground Biomass	(2.2)	(2.2)	(2.3)	(2.3)	(2.3)	(2.3)	(2.3)
Belowground Biomass	(0.3)	(0.4)	(0.4)	(0.4)	(0.4)	(0.4)	(0.4)
Dead Wood	(0.7)	(0.8)	(0.8)	(0.8)	(0.8)	(0.8)	(0.8)
Litter	(1.2)	(1.2)	(1.2)	(1.2)	(1.2)	(1.2)	(1.2)
Mineral Soil	(0.7)	(0.8)	(1.0)	(0.9)	(0.9)	(0.9)	(0.9)
Settlements Converted to Forest Land	**(31.9)**	**(31.6)**	**(31.4)**	**(31.4)**	**(31.4)**	**(31.4)**	**(31.4)**
Aboveground Biomass	(19.8)	(19.6)	(19.5)	(19.4)	(19.4)	(19.4)	(19.4)
Belowground Biomass	(3.4)	(3.3)	(3.3)	(3.3)	(3.3)	(3.3)	(3.3)
Dead Wood	(3.8)	(3.8)	(3.8)	(3.8)	(3.8)	(3.8)	(3.8)
Litter	(4.9)	(4.8)	(4.8)	(4.8)	(4.8)	(4.8)	(4.8)
Mineral Soil	(0.0)	(0.03)	(0.1)	(0.1)	(0.1)	(0.1)	(0.1)
Wetlands Converted to Forest Land	**(8.8)**	**(8.9)**	**(8.9)**	**(8.9)**	**(8.9)**	**(8.9)**	**(8.9)**
Aboveground Biomass	(4.9)	(5.0)	(5.0)	(5.0)	(5.0)	(5.0)	(5.0)
Belowground Biomass	(0.9)	(0.9)	(0.9)	(0.9)	(0.9)	(0.9)	(0.9)
Dead Wood	(1.2)	(1.2)	(1.2)	(1.2)	(1.2)	(1.2)	(1.2)
Litter	(1.8)	(1.8)	(1.8)	(1.8)	(1.8)	(1.8)	(1.8)
Mineral Soil	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Total Aboveground Biomass Flux	**(59.7)**	**(59.6)**	**(59.6)**	**(59.6)**	**(59.6)**	**(59.6)**	**(59.6)**
Total Belowground Biomass Flux	**(9.0)**	**(9.0)**	**(9.0)**	**(9.0)**	**(9.0)**	**(9.0)**	**(9.0)**
Total Dead Wood Flux	**(12.0)**	**(12.0)**	**(12.1)**	**(12.1)**	**(12.1)**	**(12.1)**	**(12.1)**
Total Litter Flux	**(18.8)**	**(18.8)**	**(18.8)**	**(18.8)**	**(18.8)**	**(18.8)**	**(18.8)**
Total Mineral Soil Flux	**(0.8)**	**(0.8)**	**(1.0)**	**(0.9)**	**(0.9)**	**(0.9)**	**(0.9)**

Total Flux	**(100.2)**	**(100.2)**	**(100.4)**	**(100.3)**	**(100.3)**	**(100.3)**	**(100.3)**

Notes: Totals may not sum due to independent rounding. Parentheses indicate net uptake. Forest ecosystem carbon stock changes from land conversion in interior Alaska, Hawaii, and the U.S. Territories are currently included in the forest land remaining forest land section because there is insufficient data to separate the changes at this time. It is not possible to separate forest land remaining forest land from land converted to forest land in Wyoming because of the split annual cycle method used for population estimation, this prevents harmonization of forest land in Wyoming with the NRI/NLCD method used in Section 6.1. See Annex 3.13, Table A-217 for annual differences between the forest area reported in Section 6.1 and Section 6.3. The forest ecosystem carbon stock changes from land conversion do not include trees on non-forest land (e.g., agroforestry systems and settlement areas—see 6.10 for estimates of carbon stock change from settlement trees). It is not possible to separate emissions from drained organic soils between forest land remaining forest land and land converted to forest land so estimates for all organic soils are included in Table 6-8 of the Forest Land Remaining Forest Land section of the *Inventory*.

Table 6-33: Net Carbon Flux from Forest Carbon Pools in Land Converted to Forest Land by Land Use Change Category (MMT C)

Land Use/Carbon Pool	1990	2005	2018	2019	2020	2021	2022
Cropland Converted to Forest Land	**(4.8)**	**(4.8)**	**(4.7)**	**(4.7)**	**(4.7)**	**(4.7)**	**(4.7)**
Aboveground Biomass	(2.8)	(2.8)	(2.7)	(2.7)	(2.7)	(2.7)	(2.7)
Belowground Biomass	(0.5)	(0.5)	(0.5)	(0.5)	(0.5)	(0.5)	(0.5)
Dead Wood	(0.6)	(0.6)	(0.6)	(0.6)	(0.6)	(0.6)	(0.6)
Litter	(0.9)	(0.9)	(0.9)	(0.9)	(0.9)	(0.9)	(0.9)
Mineral Soil	(0.1)	(0.1)	(0.0)	(0.0)	(0.0)	(0.0)	(0.0)
Grassland Converted to Forest Land	**(10.0)**	**(10.1)**	**(10.2)**	**(10.2)**	**(10.2)**	**(10.2)**	**(10.1)**
Aboveground Biomass	(6.1)	(6.2)	(6.2)	(6.2)	(6.2)	(6.2)	(6.2)
Belowground Biomass	(0.7)	(0.7)	(0.7)	(0.7)	(0.7)	(0.7)	(0.7)
Dead Wood	(1.1)	(1.1)	(1.1)	(1.1)	(1.1)	(1.1)	(1.1)
Litter	(2.1)	(2.1)	(2.1)	(2.1)	(2.1)	(2.1)	(2.1)
Mineral Soil	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Other Land Converted to Forest Land	**(1.4)**	**(1.4)**	**(1.5)**	**(1.5)**	**(1.5)**	**(1.5)**	**(1.5)**
Aboveground Biomass	(0.6)	(0.6)	(0.6)	(0.6)	(0.6)	(0.6)	(0.6)
Belowground Biomass	(0.1)	(0.1)	(0.1)	(0.1)	(0.1)	(0.1)	(0.1)
Dead Wood	(0.2)	(0.2)	(0.2)	(0.2)	(0.2)	(0.2)	(0.2)
Litter	(0.3)	(0.3)	(0.3)	(0.3)	(0.3)	(0.3)	(0.3)
Mineral Soil	(0.2)	(0.2)	(0.3)	(0.2)	(0.3)	(0.3)	(0.3)
Settlements Converted to Forest Land	**(8.7)**	**(8.6)**	**(8.6)**	**(8.6)**	**(8.6)**	**(8.6)**	**(8.6)**
Aboveground Biomass	(5.4)	(5.4)	(5.3)	(5.3)	(5.3)	(5.3)	(5.3)
Belowground Biomass	(0.9)	(0.9)	(0.9)	(0.9)	(0.9)	(0.9)	(0.9)
Dead Wood	(1.0)	(1.0)	(1.0)	(1.0)	(1.0)	(1.0)	(1.0)
Litter	(1.3)	(1.3)	(1.3)	(1.3)	(1.3)	(1.3)	(1.3)
Mineral Soil	(0.0)	(0.0)	(0.0)	(0.0)	(0.0)	(0.0)	(0.0)
Wetlands Converted to Forest Land	**(2.4)**	**(2.4)**	**(2.4)**	**(2.4)**	**(2.4)**	**(2.4)**	**(2.4)**
Aboveground Biomass	(1.3)	(1.4)	(1.4)	(1.4)	(1.4)	(1.4)	(1.4)
Belowground Biomass	(0.2)	(0.2)	(0.2)	(0.2)	(0.2)	(0.2)	(0.2)
Dead Wood	(0.3)	(0.3)	(0.3)	(0.3)	(0.3)	(0.3)	(0.3)
Litter	(0.5)	(0.5)	(0.5)	(0.5)	(0.5)	(0.5)	(0.5)
Mineral Soil	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Total Aboveground Biomass Flux	**(16.3)**	**(16.3)**	**(16.3)**	**(16.3)**	**(16.3)**	**(16.3)**	**(16.3)**
Total Belowground Biomass Flux	**(2.5)**	**(2.5)**	**(2.5)**	**(2.4)**	**(2.4)**	**(2.4)**	**(2.4)**
Total Dead Wood Flux	**(3.3)**	**(3.3)**	**(3.3)**	**(3.3)**	**(3.3)**	**(3.3)**	**(3.3)**
Total Litter Flux	**(5.1)**	**(5.1)**	**(5.1)**	**(5.1)**	**(5.1)**	**(5.1)**	**(5.1)**
Total Mineral Soil Flux	**(0.2)**	**(0.2)**	**(0.3)**	**(0.2)**	**(0.2)**	**(0.3)**	**(0.2)**
Total Flux	**(27.3)**	**(27.3)**	**(27.4)**	**(27.4)**	**(27.4)**	**(27.4)**	**(27.4)**

+ Absolute value does not exceed 0.05 MMT C.

Notes: Totals may not sum due to independent rounding. Parentheses indicate net uptake. Forest ecosystem carbon stock changes from land conversion in interior Alaska, Hawaii, and the U.S. Territories are currently included in the forest land remaining forest land section because there is not sufficient data to separate the changes at this time. It is not possible to separate forest land remaining forest land from land converted to forest land in Wyoming because of the split annual cycle method used for population estimation, this prevents harmonization of forest land in Wyoming with the NRI/NLCD method used in Section 6.1. See Annex 3.13, Table A-217 for annual differences between the forest area reported in Section 6.1 and Section 6.3. The forest ecosystem carbon stock changes from land conversion do not include trees on non-forest land (e.g., agroforestry systems and settlement areas—see Section 6.10 for estimates of carbon stock change from settlement trees). It is not possible to separate emissions from drained organic soils between forest land remaining forest land and land converted to forest land so estimates for organic soils are included in Table 6-9 and Table 6-10 of the Forest Land Remaining Forest Land section of the *Inventory*.

Methodology and Time-Series Consistency

The following section includes a description of the methodology used to estimate stock changes in all forest carbon pools for land converted to forest land. National Forest Inventory data and IPCC (2006) defaults for reference carbon stocks were used to compile separate estimates for the five carbon storage pools. Estimates for aboveground and belowground biomass, dead wood and litter were based on data collected from the extensive array of permanent, annual NFI plots and associated models (e.g., live tree belowground biomass estimates) in the United States (USDA Forest Service 2023b, 2023c). Carbon conversion factors were applied at the individual plot and then appropriately expanded to state population estimates, which are summed to provide the national estimate. To ensure consistency in the land converted to forest land category where carbon stock transfers occur between land-use categories, all soil estimates are based on methods from Ogle et al. (2003, 2006) and IPCC (2006).

The methods used for estimating carbon stocks and stock changes in the land converted to forest land are consistent with those used for forest land remaining forest land. For land-use conversion, IPCC (2006) default biomass carbon stock values were applied in the year of conversion on individual plots to estimate the C stocks removed due to land-use conversion from croplands and grasslands. There is no biomass loss data or IPCC (2006) defaults to include transfers, losses, or gains of carbon in the year of the conversion for other land use (i.e., other lands, settlements, wetlands) conversions to forest land so these were incorporated for these conversion categories. All annual NFI plots included in the public FIA database as of September 2023 were used in this Inventory. Forest land conditions were observed on NFI plots at time t_0 and at a subsequent time $t_1=t_0+s$, where s is the time step (time measured in years) and is indexed by discrete (e.g., 5 year) forest age classes. The inventory from t_0 was then projected from t_1 to 2022. This projection approach requires simulating changes in the age-class distribution resulting from forest aging and disturbance events and then applying carbon density estimates for each age class to obtain population estimates for the nation.

Carbon in Biomass

Live tree carbon pools include aboveground and belowground (coarse root) biomass of live trees with diameter at breast height (dbh) of at least 2.54 cm at 1.37 m above the forest floor. Separate estimates were made for above and belowground biomass components. If inventory plots included data on individual trees, aboveground tree carbon was based on Westfall et al. (2023). The component ratio method (CRM) which is a function of volume, species, and diameter was used to compile estimates for woodland species where diameter measurements are taken at root collar and to compile belowground biomass carbon for all tree species (Woodall et al. (2011a). An additional component of foliage, which was not explicitly included in Woodall et al. (2011a), was added to each woodland tree following the same CRM method.

Understory vegetation is a minor component of biomass and is defined as all biomass of undergrowth plants in a forest, including woody shrubs and trees less than 2.54 cm dbh. For the current *Inventory*, it was assumed that 10 percent of total understory carbon mass is belowground (Smith et al. 2006). Estimates of carbon density were

based on information in Birdsey (1996) and biomass estimates from Jenkins et al. (2003). Understory biomass represented over one percent of carbon in biomass, but its contribution rarely exceeded 2 percent of the total.

Biomass losses associated with conversion from grassland and cropland to forest land were assumed to occur in the year of conversion. To account for these losses, IPCC (2006) defaults for aboveground and belowground biomass on grasslands and aboveground biomass on croplands were subtracted from sequestration in the year of the conversion. As previously discussed, for all other land use (i.e., other lands, settlements, wetlands) conversions to forest land no biomass loss data were available, and no IPCC (2006) defaults currently exist to include transfers, losses, or gains of carbon in the year of the conversion, so none were incorporated for these conversion categories. As defaults or country-specific data become available for these conversion categories, they will be incorporated.

Carbon in Dead Organic Matter

Dead organic matter was initially calculated as three separate pools—standing dead trees, downed dead wood, and litter—with carbon stocks estimated from sample data or from models. The standing dead tree carbon pool includes aboveground and belowground (coarse root) biomass for trees of at least 2.54 cm dbh. Calculations followed the basic method applied to live trees (Westfall et al. 2023, Woodall et al. 2011a) with additional modifications to account for decay and structural loss (Harmon et al. 2011). Downed dead wood estimates are based on measurement of a subset of FIA plots for downed dead wood (Domke et al. 2013; Woodall and Monleon 2008; Woodall et al. 2013). Downed dead wood is defined as pieces of dead wood greater than 7.5 cm diameter, at transect intersection, that are not attached to live or standing dead trees. This includes stumps and roots of harvested trees. To facilitate the downscaling of downed dead wood carbon estimates from the state-wide population estimates to individual plots, downed dead wood models specific to regions and forest types within each region are used. Litter carbon is the pool of organic carbon (also known as duff, humus, and fine woody debris) above the mineral soil and includes woody fragments with diameters of up to 7.5 cm. A subset of FIA plots are measured for litter carbon. A modeling approach, using litter carbon measurements from FIA plots (Domke et al. 2016) was used to estimate litter carbon for every FIA plot used in the estimation framework. Dead organic matter carbon stock estimates are included for all land-use conversions to forest land.

Mineral Soil Carbon Stock Changes

A Tier 2 method is applied to estimate mineral soil C stock changes for land converted to forest land (Ogle et al. 2003, 2006; IPCC 2006). For this method, land is stratified by climate, soil types, land use, and land management activity, and then assigned reference carbon levels and factors for the forest land and the previous land use. The difference between the stocks is reported as the stock change under the assumption that the change occurs over 20 years. Reference C stocks have been estimated from data in the National Soil Survey Characterization Database (USDA-NRCS 1997), and U.S.-specific stock change factors have been derived from published literature (Ogle et al. 2003, 2006). Land use and land-use change patterns are determined from a combination of the Forest Inventory and Analysis Dataset (FIA) and the 2017 National Resources Inventory (NRI) (USDA-NRCS 2020). The areas have been modified in the NRI survey through a process in which the Forest Inventory and Analysis (FIA) survey data and the National Land Cover Dataset (NLCD; Yang et al. 2018) are harmonized with the NRI data. This process ensures that the land use areas are consistent across all land-use categories (see Section 6.1 for more information). Note that soil C in this Inventory is reported to a depth of 100 cm in the forest land remaining forest land category (Domke et al. 2017) while other land-use categories report soil C to a depth of 30 cm. However, to ensure consistency in the land converted to forest land category where C stock transfers occur between land-use categories, soil C estimates were based on a 30 cm depth using methods from Ogle et al. (2003, 2006) and IPCC (2006). See Annex 3.12 for more information about this method.

In order to ensure time-series consistency, the same methods are applied from 1990 to 2020 so that changes reflect anthropogenic activity and not methodological adjustments. Mineral soil organic C stock changes from 2021 to 2022 are estimated using a linear extrapolation method described in Box 6-4 of the Methodology section in Cropland Remaining Cropland. The extrapolation is based on a linear regression model with moving-average

(ARMA) errors using the 1990 to 2020 emissions data and is a standard data splicing method for estimating emissions at the end of a time series if activity data are not available (IPCC 2006). The Tier 2 method described previously will be applied to recalculate the 2021 to 2022 emissions in a future *Inventory*.

Uncertainty

A quantitative uncertainty analysis placed bounds on the flux estimates for land converted to forest land through a combination of sample-based and model-based approaches to uncertainty for forest ecosystem CO_2 Eq. flux (IPCC Approach 1). Uncertainty estimates for forest pool carbon stock changes were developed using the same methodologies as described in the forest land remaining forest land section for aboveground and belowground biomass, dead wood, and litter. The exception was when IPCC default estimates were used for reference carbon stocks in certain conversion categories (i.e., cropland converted to forest land and grassland converted to forest land). In those cases, the uncertainties associated with the IPCC (2006) defaults were included in the uncertainty calculations. IPCC Approach 2 was used to propagate errors with estimation of mineral soils carbon stock changes for land-use conversions, and is described in the cropland remaining cropland section.

Uncertainty estimates are presented in Table 6-34 for each land conversion category and carbon pool. Uncertainty estimates were obtained using a combination of sample-based and model-based approaches for all non-soil carbon pools (IPCC Approach 1) and a Monte Carlo approach (IPCC Approach 2) was used for mineral soil. Uncertainty estimates were combined using the error propagation model (IPCC Approach 1). The combined uncertainty for all carbon stocks in land converted to forest land ranged from 11 percent below to 11 percent above the 2022 carbon stock change estimate of –100.3 MMT CO_2 Eq.

Table 6-34: Quantitative Uncertainty Estimates for Forest Carbon Pool Stock Changes (MMT CO_2 Eq. per Year) in 2022 from Land Converted to Forest Land by Land Use Change

Land Use/Carbon Pool	2022 Flux Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Flux Range[a] (MMT CO_2 Eq.)		(%)	
		Lower Bound	Upper Bound	Lower Bound	Upper Bound
Cropland Converted to Forest Land	(17.2)	(25.8)	(8.7)	-50%	50%
Aboveground Biomass	(10.0)	(18.4)	(1.7)	-83%	83%
Belowground Biomass	(1.7)	(2.7)	(0.7)	-61%	61%
Dead Wood	(2.2)	(3.4)	(1.0)	-56%	56%
Litter	(3.2)	(4.3)	(2.1)	-34%	34%
Non-federal Mineral Soils	(0.1)	(0.3)	0.0	-142%	142%
Federal Mineral Soils	(0.0)	(0.1)	0.1	-8,796%	8,796%
Grassland Converted to Forest Land	(37.2)	(39.6)	(34.8)	-6%	6%
Aboveground Biomass	(22.8)	(24.2)	(21.5)	-6%	6%
Belowground Biomass	(2.7)	(3.0)	(2.5)	-10%	10%
Dead Wood	(4.1)	(4.3)	(4.0)	-3%	3%
Litter	(7.7)	(8.3)	(7.2)	-7%	7%
Non-federal Mineral Soils	0.2	(0.1)	0.5	-142%	142%
Federal Mineral Soils	0.0	(0.1)	0.1	-1,310%	1,310%
Other Lands Converted to Forest Land	(5.5)	(7.8)	(3.2)	-42%	42%
Aboveground Biomass	(2.3)	(4.4)	(0.2)	-92%	92%
Belowground Biomass	(0.4)	(0.8)	0.1	-121%	121%
Dead Wood	(0.8)	(1.3)	(0.2)	-74%	74%
Litter	(1.2)	(1.8)	(0.6)	-53%	53%
Non-federal Mineral Soils	(0.9)	(1.4)	(0.5)	-49%	49%
Federal Mineral Soils	(0.0)	(0.2)	0.1	-666%	666%
Settlements Converted to Forest Land	(31.4)	(37.9)	(24.9)	-21%	21%
Aboveground Biomass	(19.4)	(25.6)	(13.3)	-32%	32%
Belowground Biomass	(3.3)	(4.6)	(2.0)	-40%	40%

Dead Wood	(3.8)	(4.9)	(2.6)	-31%	31%
Litter	(4.8)	(5.7)	(3.9)	-19%	19%
Non-federal Mineral Soils	(0.1)	(0.1)	(0.0)	-32%	32%
Federal Mineral Soils	(0.0)	(0.0)	0.0	-193%	193%
Wetlands Converted to Forest Land	(8.9)	(9.1)	(8.8)	-2%	2%
Aboveground Biomass	(5.0)	(5.2)	(4.9)	-3%	3%
Belowground Biomass	(0.9)	(0.9)	(0.9)	-3%	3%
Dead Wood	(1.2)	(1.3)	(1.2)	-4%	4%
Litter	(1.8)	(1.9)	(1.7)	-3%	3%
Non-federal Mineral Soils	0.0	0.0	0.0	0%	0%
Federal Mineral Soils	0.0	0.0	0.0	0%	0%
Total: Aboveground Biomass	(59.6)	(70.3)	(48.9)	-18%	18%
Total: Belowground Biomass	(9.0)	(10.7)	(7.2)	-19%	19%
Total: Dead Wood	(12.1)	(13.8)	(10.3)	-15%	15%
Total: Litter	(18.8)	(20.4)	(17.2)	-9%	8%
Total: Mineral Soils	(0.9)	(1.3)	(0.5)	-42%	42%
Total: Lands Converted to Forest Lands	**(100.3)**	**(111.4)**	**(89.2)**	**-11%**	**11%**

+ Absolute value does not exceed 0.05 MMT CO_2 Eq.

NA (Not Applicable)

[a] Range of flux estimate for 95 percent confidence interval.

Notes: Totals may not sum due to independent rounding. Parentheses indicate net uptake. It is not possible to separate emissions from drained organic soils between forest land remaining forest land and land converted to forest land so estimates for organic soils are included in Table 6-8 and Table 6-9 of the Forest Land Remaining Forest Land section of the *Inventory*.

QA/QC and Verification

See QA/QC and Verification sections under Forest Land Remaining Forest Land and for mineral soil estimates, Cropland Remaining Cropland.

Recalculations Discussion

The approach for estimating carbon stock changes in land converted to forest land is consistent with the methods used for forest land remaining forest Land and is described in Annex 3.13. The land converted to forest land estimates in this Inventory are based on the land-use change information in the annual NFI. All conversions are based on empirical estimates compiled using plot remeasurements from the NFI, IPCC (2006) default biomass carbon stocks removed from croplands and grasslands in the year of conversion on individual plots and the Tier 2 method for estimating mineral soil carbon stock changes (Ogle et al. 2003, 2006; IPCC 2006). All annual NFI plots included in the public FIA database as of September 2023 were used in this *Inventory*. This is the fourth year that remeasurement data from the annual NFI were available throughout the conterminous United States (with the exception of Wyoming) and coastal southeast and southcentral Alaska to estimate land-use conversion. The availability of remeasurement data from the annual NFI allowed for consistent plot-level estimation of carbon stocks and stock changes for forest land remaining forest land and the land converted to forest land categories. Estimates in the previous *Inventory* were based on state-level carbon density estimates and a combination of NRI data and NFI data in the eastern United States. The refined analysis in this *Inventory* resulted in changes in the land converted to forest land categories. Overall, the land converted to forest land carbon stock changes increased by approximately 2 percent in 2022 between the previous *Inventory* (1990 through 2021) and the current *Inventory* (Table 6-35). While the overall change is relatively small, changes by conversion categories were substantial between this *Inventory* and the previous *Inventory*. These changes can be attributed to six methodological improvements implemented this year. First, managed pastureland was previously classified as cropland and is now classified as grassland to align with NRI definitions and classifications. This resulted in a substantial structural decrease in the cropland converted to forest land category area and associated carbon stock changes and a substantial structural increase in the grassland converted to forest land area and associated carbon stock changes.

Second, in this *Inventory* all NFI plots with evidence of water are classified as wetlands to align with definitions and classifications in the NRI. In the previous *Inventory*, some NFI plots with evidence of water were classified as other land. This methodological improvement resulted in increases in the wetlands converted to forest land category and decreases in the other land converted to forest land category. Third, estimates of carbon stocks and stock changes on managed forest land in coastal Alaska are now compiled in the same ways as the conterminous United States allowing for estimates of land conversions. This led to small increases in the area and associated carbon stock change estimates in the land converted to forest land category. Fourth, the implementation of new methods for estimating aboveground biomass carbon in live and standing dead trees resulted in changes across all land use conversion categories in the aboveground and belowground biomass, dead wood, and litter pools. Fifth, new climate normals (1990 through 2020) were incorporated in the litter model resulting in additional changes in that pool. Finally, there were new NFI data incorporated into the latest *Inventory* which contributed to changes when compared with the previous *Inventory*.

Table 6-35: Recalculations of the Net Carbon Flux from Forest Carbon Pools in Land Converted to Forest Land by Land Use Change Category (MMT C)

Conversion category and Carbon pool (MMT C)	2021 Estimate, Previous *Inventory*	2021 Estimate, Current *Inventory*	2022 Estimate, Current *Inventory*
Cropland Converted to Forest Land	**(10.3)**	**(4.7)**	**(4.7)**
Aboveground Biomass	(6.0)	(2.7)	(2.7)
Belowground Biomass	(1.2)	(0.5)	(0.5)
Dead Wood	(1.3)	(0.6)	(0.6)
Litter	(1.8)	(0.9)	(0.9)
Mineral Soil	(0.1)	(0.0)	(0.0)
Grassland Converted to Forest Land	**(3.4)**	**(10.2)**	**(10.1)**
Aboveground Biomass	(1.7)	(6.2)	(6.2)
Belowground Biomass	(0.3)	(0.7)	(0.7)
Dead Wood	(0.3)	(1.1)	(1.1)
Litter	(1.1)	(2.1)	(2.1)
Mineral Soil	0.1	0.1	0.1
Other Land Converted to Forest Land	**(2.9)**	**(1.5)**	**(1.5)**
Aboveground Biomass	(1.3)	(0.6)	(0.6)
Belowground Biomass	(0.2)	(0.1)	(0.1)
Dead Wood	(0.4)	(0.2)	(0.2)
Litter	(0.7)	(0.3)	(0.3)
Mineral Soil	(0.3)	(0.3)	(0.3)
Settlements Converted to Forest Land	**(9.3)**	**(8.6)**	**(8.6)**
Aboveground Biomass	(5.7)	(5.3)	(5.3)
Belowground Biomass	(1.1)	(0.9)	(0.9)
Dead Wood	(1.1)	(1.0)	(1.0)
Litter	(1.5)	(1.3)	(1.3)
Mineral soil	(0.0)	(0.0)	(0.0)
Wetlands Converted to Forest Land	**(0.9)**	**(2.4)**	**(2.4)**
Aboveground Biomass	(0.4)	(1.4)	(1.4)
Belowground Biomass	(0.1)	(0.2)	(0.2)
Dead Wood	(0.1)	(0.3)	(0.3)
Litter	(0.4)	(0.5)	(0.5)
Mineral Soil	0.0	0.0	0.0
Total Aboveground Biomass Flux	**(15.0)**	**(16.3)**	**(16.3)**
Total Belowground Biomass Flux	**(2.8)**	**(2.4)**	**(2.4)**
Total Dead Wood Flux	**(3.2)**	**(3.3)**	**(3.3)**
Total Litter Flux	**(5.5)**	**(5.1)**	**(5.1)**
Total SOC (Mineral) Flux	**(0.3)**	**(0.3)**	**(0.2)**
Total Flux	**(26.8)**	**(27.4)**	**(27.4)**

Notes: Totals may not sum due to independent rounding. Parentheses indicate net sequestration.

Planned Improvements

There are many improvements necessary to improve the estimation of carbon stock changes associated with land-use conversion to forest land over the entire time series. First, soil carbon has historically been reported to a depth of 100 cm in the forest land remaining forest land category (Domke et al. 2017) while other land-use categories (e.g., grasslands and croplands) report soil carbon to a depth of 30 cm. To ensure greater consistency in the land converted to forest land category where carbon stock transfers occur between land-use categories, all mineral soil estimates in the land converted to forest land category in this Inventory are based on methods from Ogle et al. (2003, 2006) and IPCC (2006). Methods have recently been developed (Domke et al. 2017) to estimate soil carbon to depths of 20, 30, and 100 cm in the forest land category using in situ measurements from the FIA program within the USDA Forest Service and the International Soil Carbon Network. In subsequent Inventories, a common reporting depth will be defined for all land-use conversion categories and Domke et al. (2017) will be used in the forest land remaining forest land and land converted to forest land categories to ensure consistent reporting across all forest land. Second, due to the 5 to 10-year remeasurement periods within the FIA program and limited land-use change information available over the entire time series, estimates presented in this section may not reflect the entire 20-year conversion history. Third, since the sum of all land converted to forest land is used to adjust specific land-use conversions into forest land for the state-level estimates in the NRI and NLCD, there is the potential for differences in area estimates in states where specific land-use conversions into forest land do not exist in the FIA data. These difference in area estimates may result in differences between the summed estimates for mineral soil carbon stock changes across all states and the estimates reported in Table 6-31 through Table 6-34. Work is underway to integrate the dense time series of remotely sensed data into a new estimation system, which will facilitate land conversion estimation over the entire time series.

6.4 Cropland Remaining Cropland (CRT Category 4B1)

Carbon in cropland ecosystems occurs in biomass, dead organic matter, and soils. However, carbon storage in cropland biomass and dead organic matter is relatively ephemeral and does not need to be reported according to the IPCC (2006), with the exception of carbon stored in perennial woody crop biomass, such as citrus groves and apple orchards, in addition to the biomass, downed wood and dead organic matter in agroforestry systems. Within soils, carbon is found in organic and inorganic forms of carbon, but soil organic carbon is the main source and sink for atmospheric CO_2. IPCC (2006) recommends reporting changes in soil organic carbon stocks due to agricultural land use and management activities for mineral and organic soils.[38]

Well-drained mineral soils typically contain from 1 to 6 percent organic carbon by weight, whereas mineral soils with high water tables for substantial periods of a year may contain significantly more carbon (NRCS 1999). Conversion of mineral soils from their native state to agricultural land uses can cause up to half of the soil organic carbon to be lost to the atmosphere due to enhanced microbial decomposition. The rate and ultimate magnitude of carbon loss depends on subsequent management practices, climate and soil type (Ogle et al. 2005). Agricultural practices, such as clearing, drainage, tillage, planting, grazing, crop residue management, fertilization, application of biosolids (i.e., treated sewage sludge) and flooding, can modify both organic matter inputs and decomposition, and thereby result in a net carbon stock change (Paustian et al. 1997a; Lal 1998; Conant et al. 2001; Ogle et al. 2005; Griscom et al. 2017; Ogle et al. 2019). Eventually, the soil can reach a new equilibrium that reflects a balance

[38] Carbon dioxide emissions associated with liming and urea application are also estimated but are included in the Liming and Urea Fertilization sections of the Agriculture chapter of the *Inventory*.

between carbon inputs (e.g., decayed plant matter, roots, and organic amendments such as manure and crop residues) and carbon loss through microbial decomposition of organic matter (Paustian et al. 1997b).

Organic soils, also referred to as histosols, include all soils with more than 12 to 20 percent organic carbon by weight, depending on clay content (NRCS 1999; Brady and Weil 1999). The organic layer of these soils can be very deep (i.e., several meters), and form under inundated conditions that results in minimal decomposition of plant residues. When organic soils are prepared for crop production, they are drained and tilled, leading to aeration of the soil that accelerates both the decomposition rate and CO_2 emissions.[39] Due to the depth and richness of the organic layers, carbon loss from drained organic soils can continue over long periods of time, which varies depending on climate and composition (i.e., decomposability) of the organic matter (Armentano and Menges 1986). Due to deeper drainage and more intensive management practices, the use of organic soils for annual crop production leads to higher carbon loss rates than drainage of organic soils in grassland or forests (IPCC 2006).

Cropland remaining cropland includes all cropland in an inventory year that has been cropland for a continuous time period of at least 20 years. This determination is based on the United States Department of Agriculture (USDA) National Resources Inventory (NRI) for non-federal lands (USDA-NRCS 2020) and the National Land Cover Dataset for federal lands (Yang et al. 2018; Homer et al. 2007; Fry et al. 2011; Homer et al. 2015). Cropland includes all land that is used to produce food and fiber, forage that is harvested and used as feed (e.g., hay and silage), in addition to cropland that has been enrolled in the Conservation Reserve Program (CRP)[40] (i.e., considered set-aside cropland).

There are two discrepancies between the current land representation (see Section 6.1) and the area data that have been used in the *Inventory* for cropland remaining cropland. First, croplands in Alaska are not included in the *Inventory*, and second, some miscellaneous croplands that occur throughout the United States are also not included in the *Inventory* due to limited understanding of greenhouse gas emissions from these management systems (e.g., aquaculture). These differences lead to discrepancies between the managed area in cropland remaining cropland and the cropland area included in the *Inventory* analysis (Table 6-39). Improvements are underway to incorporate croplands in Alaska and miscellaneous croplands as part of future *Inventories* (see Planned Improvements section).

Land use and land management of mineral soils are the largest contributor to total net carbon stock change, especially in the early part of the time series (see Table 6-36 and Table 6-37). In 2022, mineral soils are estimated to sequester 62.0 MMT CO_2 Eq. (16.9 MMT C). This level of carbon storage in mineral soils represents a more than 58 percent increase since the initial reporting year of 1990. Carbon dioxide emissions from organic soils are 30.3 MMT CO_2 Eq. (8.3 MMT C) in 2022, which is an 11 percent decrease in losses of soil carbon compared to 1990. In total, United States agricultural soils in cropland remaining cropland sequestered approximately 31.7 MMT CO_2 Eq. (8.6 MMT C) in 2022.

Table 6-36: Net CO_2 Flux from Soil Carbon Stock Changes in Cropland Remaining Cropland (MMT CO_2 Eq.)

Soil Type	1990	2005	2018	2019	2020	2021	2022
Mineral Soils	(39.2)	(61.8)	(47.1)	(48.5)	(38.2)	(62.2)	(62.0)
Organic Soils	34.2	30.2	29.3	29.1	29.4	30.2	30.3

[39] N_2O emissions from drained organic soils are included in the Agricultural Soil Management section of the Agriculture chapter of the *Inventory*.

[40] The Conservation Reserve Program (CRP) is a land conservation program administered by the Farm Service Agency (FSA). In exchange for a yearly rental payment, farmers enrolled in the program agree to remove environmentally sensitive land from agricultural production and plant species that will improve environmental health and quality. Contracts for land enrolled in CRP are 10 to 15 years in length. The long-term goal of the program is to re-establish valuable land cover to help improve water quality, prevent soil erosion, and reduce loss of wildlife habitat.

Total Net Flux	**(5.0)**	**(31.6)**	**(17.8)**	**(19.4)**	**(8.8)**	**(32.0)**	**(31.7)**

Notes: Totals may not sum due to independent rounding. Parentheses indicate net sequestration.

Table 6-37: Net CO_2 Flux from Soil Carbon Stock Changes in Cropland Remaining Cropland (MMT C)

Soil Type	1990	2005	2018	2019	2020	2021	2022
Mineral Soils	(10.7)	(16.9)	(12.9)	(13.2)	(10.4)	(17.0)	(16.9)
Organic Soils	9.3	8.2	8.0	7.9	8.0	8.2	8.3
Total Net Flux	**(1.4)**	**(8.6)**	**(4.9)**	**(5.3)**	**(2.4)**	**(8.7)**	**(8.6)**

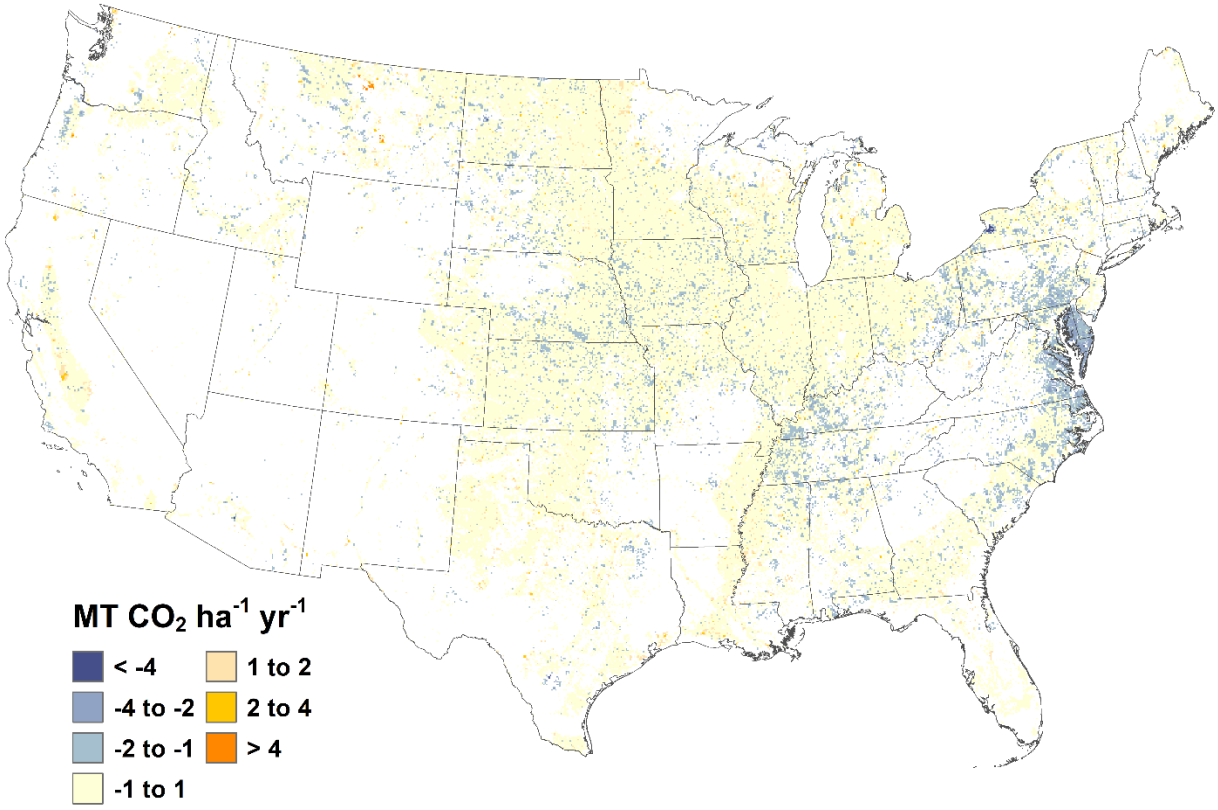
Notes: Totals may not sum due to independent rounding. Parentheses indicate net sequestration.

Soil organic carbon stocks increase in cropland remaining cropland largely due to conservation tillage (i.e., reduced- and no-till practices), land set-aside from production in the Conservation Reserve Program, annual crop production with hay or pasture in rotations, and manure amendments (Ogle et al. 2023). The mineral soil carbon stock changes between 1990 and 2022 range from 38.2 to 69.6 MMT CO_2 Eq. per year, with a mean of 55.9 MMT CO_2 Eq. Soil organic carbon losses from drainage of organic soils are relatively stable across the time series with a mean emission of 30.2 MMT CO_2 Eq. per year.

The spatial variability in the 2020 annual soil organic carbon stock changes[41] are displayed in Figure 6-6 and Figure 6-7 for mineral and organic soils, respectively. Isolated areas with high rates of carbon accumulation occur throughout the agricultural land base in the United States, but there are more concentrated areas, such as the Maryland, Delaware, and Virginia where there have been relatively high adoption rates of cover crop management. The regions with the highest rates of emissions from drainage of organic soils occur in the Southeastern Coastal Region (particularly Florida and Louisiana), Northeast and upper Midwest surrounding the Great Lakes, and isolated areas along the Pacific Coast (particularly California), which coincides with the largest concentrations of organic soils in the United States that are used for agricultural production.

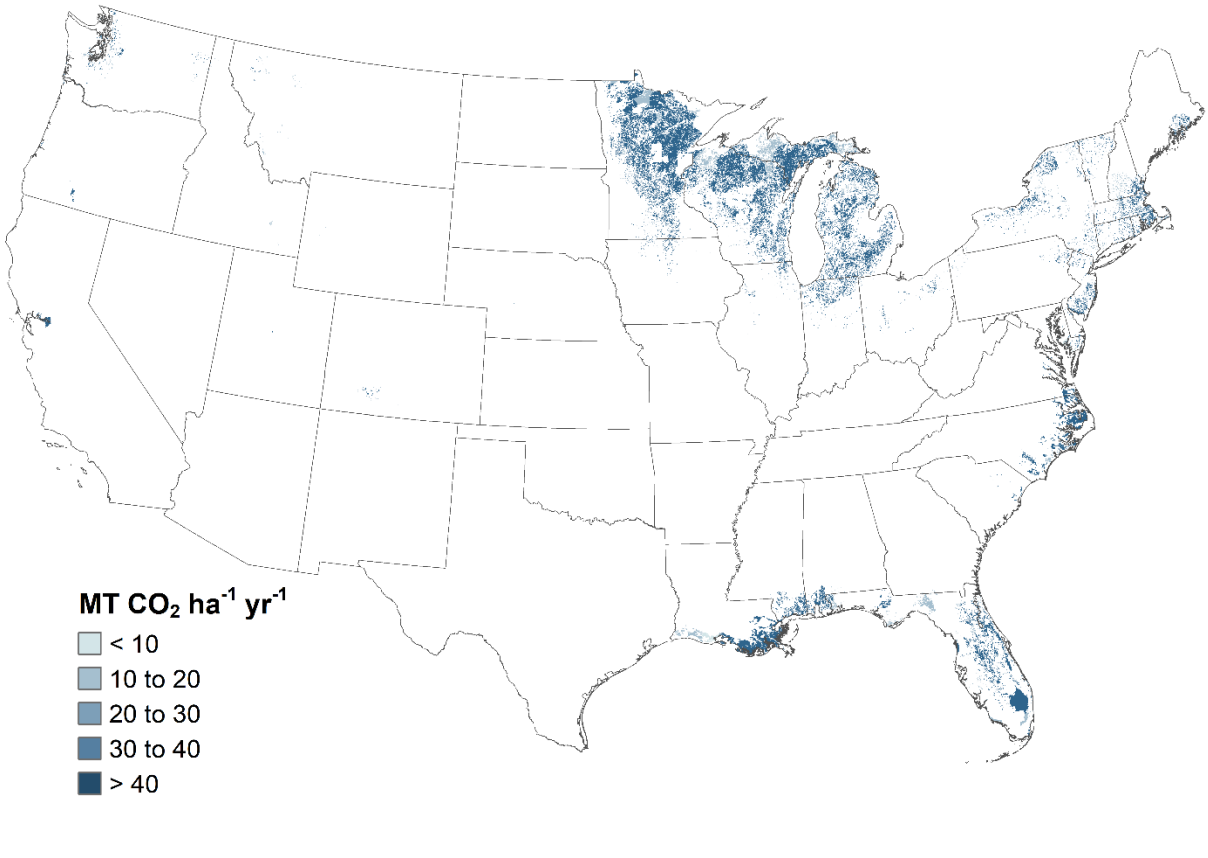
[41] Only national-scale emissions are estimated for 2021 to 2022 in this *Inventory* using the surrogate data method, and therefore the fine-scale emission patterns in this map are based on *Inventory* data from 2020.

Figure 6-6: Total Net Annual Soil Carbon Stock Changes for Mineral Soils under Agricultural Management within States, 2020, Cropland Remaining Cropland



Note: Only national-scale soil organic carbon stock changes are estimated for 2021 to 2022 in the current *Inventory* using a surrogate data method, and therefore the fine-scale emission patterns in this map are based on *Inventory* data from 2020. Negative values represent a net increase in soil organic carbon stocks, and positive values represent a net decrease in soil organic carbon stocks.

Figure 6-7: Total Net Annual Soil Carbon Stock Changes for Organic Soils under Agricultural Management within States, 2020, Cropland Remaining Cropland



Note: Only national-scale soil organic carbon stock changes are estimated for 2021 to 2022 in the current *Inventory* using a surrogate data method, and therefore the fine-scale emission patterns in this map are based on *Inventory* data from 2020.

Methodology and Time-Series Consistency

The following section includes a description of the methodology used to estimate changes in soil organic carbon stocks for cropland remaining cropland, including (1) agricultural land use and management activities on mineral soils; and (2) agricultural land use and management activities on organic soils. Carbon dioxide emissions and removals[42] due to changes in mineral soil organic carbon stocks are estimated using a Tier 3 method for the majority of annual crops (Ogle et al. 2010, 2023). A Tier 2 IPCC method is used for the remaining crops not included in the Tier 3 method (see list of crops in the Mineral Soil Carbon Stock Changes section below) (Ogle et al. 2003, 2006). In addition, a Tier 2 method is used for very gravelly, cobbly, or shaley soils (i.e., classified as soils that have greater than 35 percent of soil volume comprised of gravel, cobbles, or shale, regardless of crop). Emissions from organic soils are estimated using a Tier 2 IPCC method. While a combination of Tier 2 and 3 methods are used to estimate carbon stock changes across most of the time series, a surrogate data method has been applied to

[42] Removals occur through uptake of CO_2 into crop and forage biomass that is later incorporated into soil carbon pools.

estimate stock changes in the last two years of the *Inventory*. Stock change estimates based on surrogate data will be recalculated in a future *Inventory* report using the Tier 2 and 3 methods when data become available.

Soil organic carbon stock changes on non-federal lands are estimated for cropland remaining cropland (as well as agricultural land falling into the IPCC categories land converted to cropland, grassland remaining grassland, and land converted to grassland) according to land-use histories recorded in the USDA NRI survey through 2017 (USDA-NRCS 2020), and the cropping histories were extended through 2020 using the USDA-NASS Crop Data Layer Product (CDL) (USDA-NASS 2021). The areas have been modified in the original NRI survey through a process in which the Forest Inventory and Analysis (FIA) survey data and the National Land Cover Dataset (Yang et al. 2018) are harmonized with the NRI data. This process ensures that the land-use areas are consistent across all land- use categories (see Section 6.1 for more information).

The NRI is a statistically-based sample and includes approximately 604,000 survey locations in agricultural land for the conterminous United States and Hawaii. There are 364,333 survey locations that are included in the Tier 3 method, and another 239,757 locations included in the Tier 2 method. Each survey location is associated with a weight that allows scaling of carbon stock changes from NRI survey locations to the entire country (i.e., each weight represents the amount of area that is expected to have the same land use/management history as the sample point).

Land use and some management information (e.g., crop type, soil attributes, and irrigation) are collected for each NRI point on a 5-year cycle beginning from 1982 through 1997. For cropland, data has been collected for 4 out of 5 years during each survey cycle (i.e., 1979 through 1982, 1984 through 1987, 1989 through 1992, and 1994 through 1997). In 1998, the NRI program began collecting annual data, and the annual data are currently available through 2017 (USDA-NRCS 2020). For 2018 to 2020, the time series is extended with the crop data provided in USDA-NASS CDL (USDA-NASS 2021), by overlaying NRI survey locations on the CDL in a geographic information system and extracting the crop types to extend the cropping histories. NRI survey locations are classified as cropland remaining cropland in a given year between 1990 and 2020 if the land use has been cropland for a continuous time period of at least 20 years. The NRI survey locations are classified according to land use histories starting in 1979, and consequently the classifications are based on less than 20 years from 1990 to 1998. This may have led to an overestimation of cropland remaining cropland in the early part of the time series to the extent that some areas are converted to cropland between 1971 and 1978.

Soil Carbon Stock Changes for Mineral Soils

An IPCC Tier 3 model-based approach (Ogle et al. 2010) is applied to estimate organic carbon stock changes for mineral soils on the majority of land that is used to produce annual crops and forage crops that are harvested and used as feed (e.g., hay and silage) in the United States. These crops include alfalfa hay, barley, corn, cotton, dry beans, grass hay, grass-clover hay, lentils, oats, onions, peanuts, peas, potatoes, rice, sorghum, soybeans, sugar beets, sunflowers, tobacco, tomatoes, and wheat, but is not applied to estimate organic carbon stock changes from other crops or rotations with other crops. The model-based approach uses the DayCent ecosystem model (Parton et al. 1998; Del Grosso et al. 2001, 2011) to estimate soil organic carbon stock changes, soil nitrous oxide (N_2O) emissions from agricultural soil management, and methane (CH_4) emissions from rice cultivation. Carbon and nitrogen dynamics are linked in plant-soil systems through the biogeochemical processes of microbial decomposition and plant production (McGill and Cole 1981). Coupling the two source categories (i.e., agricultural soil carbon and N_2O) in a single inventory analysis ensures that there is a consistent treatment of the processes and interactions between carbon and nitrogen cycling in soils.

The remaining crops on mineral soils are estimated using an IPCC Tier 2 method (Ogle et al. 2003), including some vegetables, perennial/horticultural crops, and crops that are rotated with these crops. The Tier 2 method is also used for very gravelly, cobbly, or shaley soils (greater than 35 percent by volume), and soil organic carbon stock changes on federal croplands. Mineral soil organic carbon stocks are estimated using a Tier 2 method for these areas because the DayCent model, which is used for the Tier 3 method, has not been fully tested for estimating carbon stock changes associated with these crops and rotations, as well as cobbly, gravelly, or shaley soils. In addition, there is insufficient information to simulate croplands on federal lands using DayCent.

A surrogate data method is used to estimate soil organic carbon stock changes from 2021 to 2022 at the national scale for land areas included in the Tier 2 and Tier 3 methods. Specifically, linear regression models with autoregressive moving-average (ARMA) errors (Brockwell and Davis 2016) are used to estimate the relationship between surrogate data and the 1990 to 2020 stock change data that are derived using the Tier 2 and 3 methods. Surrogate data for these regression models include corn and soybean yields from USDA-NASS statistics,[43] and weather data from the PRISM Climate Group (PRISM 2022). See Box 6-4 for more information about the surrogate data method. Stock change estimates for 2021 to 2022 will be recalculated in future Inventories with an updated time series of activity data.

Box 6-4: Surrogate Data Method

Time series extension is needed because there are typically gaps at the end of the time series. This is mainly because the NRI, which provides critical data for estimating greenhouse gas emissions and removals, does not release new activity data every year.

A surrogate data method has been used to impute missing emissions at the end of the time series for soil organic carbon stock changes in cropland remaining cropland, land converted to cropland, grassland remaining grassland, and land converted to grassland. A linear regression model with autoregressive moving-average (ARMA) errors (Brockwell and Davis 2016) is used to estimate the relationship between the surrogate data and the modeled 1990 to 2020 emissions data that has been compiled using the inventory methods described in this section. The model to extend the time series is given by

$$Y = X\beta + \varepsilon,$$

where Y is the response variable (e.g., soil organic carbon), Xβ contains specific surrogate data depending on the response variable, and ε is the remaining unexplained error. Models with a variety of surrogate data were tested, including commodity statistics, weather data, or other relevant information. Parameters are estimated from the emissions data for 1990 to 2020 using standard statistical techniques, and these estimates are used to predict the missing emissions data for 2021 to 2022.

A critical issue with the application of splicing methods is to adequately account for the additional uncertainty introduced by predicting emissions rather than compiling the full inventory. Consequently, uncertainty will increase for years with imputed estimates based on the splicing methods, compared to those years in which the full inventory is compiled. This added uncertainty is quantified within the model framework using a Monte Carlo approach. The approach requires estimating parameters for results in each iteration of the Monte Carlo analysis for the full inventory (i.e., the surrogate data model is refit with the emissions estimated in each Monte Carlo iteration from the full inventory analysis with data from 1990 to 2020), estimating emissions from each model and deriving confidence intervals combining uncertainty across all iterations. This approach propagates uncertainties through the calculations from the original inventory and the surrogate data method. Furthermore, the 95 percent confidence intervals are estimated using the 3 sigma rules assuming a unimodal density (Pukelsheim 1994).

Tier 3 Approach. Mineral soil organic carbon stocks and stock changes are estimated to a 30 cm depth using the DayCent ecosystem model (Parton et al. 1998; Del Grosso et al. 2001, 2011), which simulates cycling of carbon, nitrogen, and other nutrients in cropland, grassland, forest, and savanna ecosystems. The DayCent model utilizes the soil carbon modeling framework developed in the Century model (Parton et al. 1987, 1988, 1994; Metherell et al. 1993), but has been refined to simulate dynamics at a daily time-step. Input data on land use and management are specified at a daily resolution and include land-use type, crop/forage type, and management activities (e.g.,

[43] See https://quickstats.nass.usda.gov/.

planting, harvesting, fertilization, manure amendments, tillage, irrigation, cover crops, and grazing; more information is provided below). The model simulates net primary productivity (NPP) using the NASA-CASA production algorithm MODIS Enhanced Vegetation Index (EVI) products, MOD13Q1 and MYD13Q1, for most croplands[44] (Potter et al. 1993, 2007). The model simulates soil temperature and water dynamics, using daily weather data from a 4-kilometer gridded product developed by the PRISM Climate Group (2022), and soil attributes from the Soil Survey Geographic Database (SSURGO) (Soil Survey Staff 2020). This method is more accurate than the Tier 1 and 2 approaches provided by the IPCC (2006) because the simulation model treats changes as continuous over time as opposed to the simplified discrete changes represented in the default method (see Box 6-5 for additional information).

Box 6-5: Tier 3 Approach for Soil Carbon Stocks Compared to Tier 1 or 2 Approaches

A Tier 3 model-based approach is used to estimate soil organic carbon stock changes for the majority of agricultural land with mineral soils. This approach results in a more complete and accurate estimation of soil organic carbon stock changes and entails several fundamental differences from the IPCC Tier 1 or 2 methods, as described below.

1) The IPCC Tier 1 and 2 methods are simplified approaches for estimating soil organic carbon stock changes and classify land areas into discrete categories based on highly aggregated information about climate (six regions), soil (seven types), and management (eleven management systems) in the United States. In contrast, the Tier 3 model incorporates the same variables (i.e., climate, soils, and management systems) with considerably more detail both temporally and spatially, and captures multi-dimensional interactions through the more complex model structure.

2) The IPCC Tier 1 and 2 methods have a coarser spatial resolution in which data are aggregated to soil types in climate regions, of which there about 30 combinations in the United States. In contrast, the Tier 3 model simulates soil carbon dynamics at about 364,000 individual NRI survey locations in crop fields and grazing lands.

The IPCC Tier 1 and 2 methods use a simplified approach for estimating changes in carbon stocks that assumes a step-change from one equilibrium level of the carbon stock to another equilibrium level. In contrast, the Tier 3 approach simulates a continuum of carbon stock changes that may reach a new equilibrium over an extended period of time depending on the environmental conditions (i.e., a new equilibrium often requires hundreds to thousands of years to reach). More specifically, the DayCent model, which is used in the United States Inventory, simulates soil carbon dynamics (and CO_2 emissions and uptake) on a daily time step based on carbon emissions and removals from plant production and decomposition processes. These changes in soil organic carbon stocks are influenced by multiple factors that affect primary production and decomposition, including changes in land use and management, weather variability and secondary feedbacks between management activities, climate, and soils.

Historical land-use patterns and irrigation histories are simulated with DayCent based on the 2017 USDA NRI survey (USDA-NRCS 2020). Additional sources of activity data are used to supplement the activity data from the NRI. The USDA-NRCS Conservation Effects and Assessment Project (CEAP) provides data on a variety of cropland management activities, and is used to inform the inventory analysis about tillage practices, mineral fertilization, manure amendments, cover crop management, as well as planting and harvest dates (USDA-NRCS 2022; USDA-

[44] NPP is estimated with the NASA-CASA algorithm for most of the cropland that is used to produce major commodity crops in the central United States from 2000 to 2020. Other regions and years prior to 2000 are simulated with a method that incorporates water, temperature and moisture stress on crop production (see Metherell et al. 1993), but does not incorporate the additional information about crop condition provided with remote sensing data.

NRCS 2018; USDA-NRCS 2012). CEAP data are collected at a subset of NRI survey locations, and currently provide management information from approximately 2002 to 2006 and 2013 to 2016. These data are combined with other datasets in an imputation analysis. This imputation analysis is comprised of three steps: a) determine the trends in management activity across the time series by combining information from several datasets (discussed below); b) use Gradient Boosting (Friedman 2001) to determine the likely management practice at a given NRI survey location; and c) assign management practices from the CEAP survey to the specific NRI locations using a predictive mean matching method for certain variables that are adapted to reflect the trending information (Little 1988; van Buuren 2012). Gradient boosting is a machine learning technique used in regression and classification tasks, among others. It combines predictions from multiple weak prediction models and outperforms many complicated machine learning algorithms. It makes the best predictions at specific NRI survey locations or at state or region level models. The predictive mean matching method identifies the most similar management activity recorded in the CEAP surveys that match the prediction from the gradient boosting algorithm. The matching ensures that imputed management activities are realistic for each NRI survey location, and not odd or physically unrealizable results that could be generated by the gradient boosting. There are six complete imputations of the management activity data using these methods.

To determine trends in mineral fertilization and manure amendments, CEAP data are combined with information on fertilizer use and rates by crop type for different regions of the United States from the USDA Economic Research Service. The data collection program was known as the Cropping Practices Surveys through 1995 (USDA-ERS 1997), and is now part of data collection known as the Agricultural Resource Management Surveys (ARMS) (USDA-ERS 2020). Additional data on fertilization practices are compiled through other sources particularly the National Agricultural Statistics Service (USDA-NASS 1992, 1999, 2004). To determine the trends in tillage management, CEAP data are combined with Conservation Technology Information Center data between 1989 and 2004 (CTIC 2004) and OpTIS Data Product[45] for 2008 to 2020 (Hagen et al. 2020). The CTIC data are adjusted for long-term adoption of no-till agriculture (Towery 2001). For cover crops, CEAP data are combined with information from USDA Census of Agriculture (USDA-NASS 2012, 2017) and the OpTIS data (Hagen et al. 2020). It is assumed that cover crop management was minimal prior to 1990 and the rates increased linearly over the decade to the levels of cover crop management in the CEAP survey.

Uncertainty in the carbon stock estimates from DayCent associated with management activity includes input uncertainty due to missing management data in the NRI survey, which is imputed from other sources as discussed above; model uncertainty due to incomplete specification of carbon and nitrogen dynamics in the DayCent model algorithms and associated parameterization; and sampling uncertainty associated with the statistical design of the NRI survey. Uncertainty is estimated with two variance components (Ogle et al. 2010). The first variance component quantifies the uncertainty in management activity data, model structure and parameterization. To assess this uncertainty, carbon and nitrogen dynamics at each NRI survey location are simulated six times using the imputation product and other model driver data. Uncertainty in parameterization and model algorithms are determined using a structural uncertainty estimator derived from fitting a linear mixed-effect model (Ogle et al. 2007, 2010, 2023). The data are combined in a Monte Carlo stochastic simulation with 1,000 iterations for 1990 through 2020. For each iteration, there is a random selection of management data from the imputation product (select one of the six imputations), and random selection of parameter values and random effects for the linear mixed-effect model (i.e., structural uncertainty estimator). The second variance component quantifies uncertainty in scaling from the NRI survey to the entire land base, and is computed with the NRI replicate weights using a standard variance estimator for a two-stage sample design (Särndal et al. 1992). The two variance components are combined using simple error propagation methods provided by the IPCC (2006), i.e., by taking the square root of the sum of the squares of the standard deviations of the uncertain quantities. Carbon stocks and 95 percent confidence intervals are estimated for each year between 1990 and 2020 using the DayCent model. Further elaboration on the methodology and data used to estimate carbon stock changes from mineral soils are described in Annex 3.12.

[45] OpTIS data on tillage and cover crop practices provided by Regrow Agriculture, Inc.

In order to ensure time-series consistency, the Tier 3 method is applied from 1990 to 2020 so that changes reflect anthropogenic activity and not methodological adjustments. In addition, soil organic carbon stock changes from 2021 to 2022 are approximated with a linear extrapolation of emission patterns from 1990 to 2020. The extrapolation is based on a linear regression model with moving-average (ARMA) errors (see Box 6-4). Linear extrapolation is a standard data splicing method for approximating emissions at the end of a time series (IPCC 2006). The time series of activity data will be updated in a future inventory, and emissions from 2021 to 2022 will be recalculated.

Tier 2 Approach. In the IPCC Tier 2 method, data on climate, soil types, land use, and land management activity are used to classify land area and apply appropriate factors to estimate soil organic carbon stock changes to a 30 cm depth (Ogle et al. 2003, 2006). The primary source of activity data for land use, crop and irrigation histories is the 2017 NRI survey (USDA-NRCS 2020). Each NRI survey location is classified by soil type, climate region, and management condition using data from other sources. Survey locations on federal lands are included in the NRI, but land use and cropping history are not compiled for these locations in the survey program (i.e., NRI is restricted to data collection on non-federal lands). Therefore, land-use patterns for the NRI survey locations on federal lands are based on the National Land Cover Database (NLCD) (Yang et al. 2018; Fry et al. 2011; Homer et al. 2007; Homer et al. 2015).

Additional management activities needed for the Tier 2 method are based on the imputation product described for the Tier 3 approach, including tillage practices, mineral fertilization, and manure amendments that are assigned to NRI survey locations. Activity data used exclusively in the Tier 2 method are wetland restoration for Conservation Reserve Program land from Euliss and Gleason (2002). Climate zones in the United States are determined from the IPCC climate map (IPCC 2006), and then assigned to NRI survey locations.

Reference carbon stocks are estimated using the National Soil Survey Characterization Database (NRCS 1997) with cultivated cropland as the reference condition, rather than native vegetation as used in IPCC (2006). Soil measurements under agricultural management are much more common and easily identified in the National Soil Survey Characterization Database (NRCS 1997) than are soils under a native condition, and therefore cultivated cropland provides a more robust sample for estimating the reference condition. Country-specific carbon stock change factors are derived from published literature to determine the impact of management practices on soil organic carbon storage (Ogle et al. 2003, 2006). The factors represent changes in tillage, cropping rotations, intensification, and land-use change between cultivated and uncultivated conditions. However, country-specific factors associated with organic matter amendments are not estimated due to an insufficient number of studies in the United States to analyze the impacts of this practice. Instead, factors from IPCC (2006) are used to estimate the effect of those activities.

Uncertainty in soil carbon stock changes is estimated with two variance components (Ogle et al., 2010). The first variance component quantifies the uncertainty in management activity data and carbon stock change factors. To assess this uncertainty, changes in soil organic carbon stocks for mineral soils are estimated 1,000 times for 1990 through 2020 using a Monte Carlo stochastic simulation approach and probability distribution functions for the country-specific stock change factors, reference carbon stocks, and land use activity data (Ogle et al. 2003; Ogle et al. 2006). The second variance component quantifies uncertainty in scaling from the NRI survey to the entire land base, and is computed with the NRI replicate weights using a standard variance estimator for a two-stage sample design (Särndal et al. 1992). The two variance components are combined using simple error propagation methods provided by the IPCC (2006), i.e., by taking the square root of the sum of the squares of the standard deviations of the uncertain quantities. Further elaboration on the methodology and data used to estimate stock changes from mineral soils are described in Annex 3.12.

In order to ensure time-series consistency, the Tier 2 method is applied from 1990 to 2020 so that changes reflect anthropogenic activity and not methodological adjustments. In addition, soil organic carbon stock changes for the remainder of the time series are approximated with a linear extrapolation of emission patterns from 1990 to 2020. The extrapolation is based on a linear regression model with moving-average (ARMA) errors (see Box 6-4). Linear extrapolation is a standard data splicing method for approximating emissions at the end of a time series (IPCC

2006). As with the Tier 3 method, time series of activity data will be updated in a future inventory, and emissions from 2021 to 2022 will be recalculated (see Planned Improvements section).

Soil Carbon Stock Changes for Organic Soils

Annual carbon emissions from drained organic soils in cropland remaining cropland are estimated using the Tier 2 method provided in IPCC (2006), with country-specific carbon loss rates (Ogle et al. 2003) rather than default IPCC rates. As with mineral soils, uncertainty is estimated with two variance components (Ogle et al., 2010). The first variance component quantifies the uncertainty in management activity data and emission factors. A Monte Carlo stochastic simulation with 1,000 iterations is used to quantify this uncertainty with probability distribution functions for the country-specific organic soil emission factors and land use activity data. The second variance component quantifies uncertainty in scaling from the NRI survey to the entire land base, and is computed with the NRI replicate weights using a standard variance estimator for a two-stage sample design (Särndal et al. 1992). The two variance components are combined using simple error propagation methods provided by the IPCC (2006), i.e., by taking the square root of the sum of the squares of the standard deviations of the uncertain quantities. Further elaboration on the methodology and data used to estimate stock changes from organic soils are described in Annex 3.12.

In order to ensure time-series consistency, the same Tier 2 method is applied from 1990 to 2020 so that changes reflect anthropogenic activity and not methodological adjustments. In addition, soil organic carbon stock changes for the remainder of the time series are approximated with a linear extrapolation of emission patterns from 1990 to 2020. The extrapolation is based on a linear regression model with moving-average (ARMA) errors (see Box 6-4). Linear extrapolation is a standard data splicing method for approximating emissions at the end of a time series (IPCC 2006). Estimates for 2021 to 2022 will be recalculated in a future inventory when new activity data are incorporated into the analysis.

Uncertainty

Uncertainty is quantified for changes in soil organic carbon stocks associated with cropland remaining cropland (including both mineral and organic soils). Uncertainty estimates are presented in Table 6-38 for each subsource (mineral and organic soil carbon stocks) and the methods that are used in the *Inventory* analyses (i.e., Tier 2 and Tier 3). Uncertainty for the Tier 2 and 3 approaches is derived from two variance components (Ogle et al. 2010). For the first component, a Monte Carlo approach is used to address uncertainties in management activity data as well as model parameterization and structure or emissions factors for the Tier 3 and Tier 2 methods, respectively (Ogle et al. 2010, 2023). The second variance component is quantifying uncertainty in scaling from the NRI survey to the entire land base, and is computed using a standard variance estimator for a two-stage sample design (Särndal et al. 1992). The two variance components are combined using simple error propagation methods provided by the IPCC (2006), i.e., by taking the square root of the sum of the squares of the standard deviations of the uncertain quantities (see Annex 3.12 for further discussion). For 2021 to 2022, additional uncertainty is propagated through a Monte Carlo analysis that is associated with the surrogate data method (see Box 6-3). Soil organic carbon stock changes from the Tier 2 and 3 approaches are combined using the simple error propagation method provided by the IPCC (2006). The combined uncertainty is calculated by taking the square root of the sum of the squares of the standard deviations of the uncertain quantities.

The combined uncertainty for soil organic carbon stocks in cropland remaining cropland ranges from 212 percent below to 212 percent above the 2022 stock change estimate of -31.7 MMT CO_2 Eq. The large relative uncertainty around the 2022 stock change estimate is mostly due to variation in soil organic carbon stock changes that is not explained by the surrogate data method, leading to high prediction error.

Table 6-38: Approach 2 Quantitative Uncertainty Estimates for Soil Carbon Stock Changes occurring within Cropland Remaining Cropland (MMT CO_2 Eq. and Percent)

Source	2022 Flux Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Flux Estimate[a] (MMT CO_2 Eq.)		(%)	
		Lower Bound	Upper Bound	Lower Bound	Upper Bound
Mineral Soil C Stocks: Cropland Remaining Cropland, Tier 3 Inventory Methodology	(58.8)	(123.6)	5.9	-110%	+110%
Mineral Soil C Stocks: Cropland Remaining Cropland, Tier 2 Inventory Methodology	(3.2)	(8.4)	2.0	-162%	+162%
Organic Soil C Stocks: Cropland Remaining Cropland, Tier 2 Inventory Methodology	30.3	12.7	47.9	-58%	+58%
Combined Uncertainty for Flux associated with Agricultural Soil Carbon Stock Change in Cropland Remaining Cropland	**(31.7)**	**(99.0)**	**35.6**	**-212%**	**+212%**

[a] Range of C stock change estimates is a 95 percent confidence interval.
Notes: Totals may not sum due to independent rounding. Parentheses indicate net sequestration.

Uncertainty is also associated with lack of reporting of agricultural woody biomass and dead organic matter carbon stock changes. However, woody biomass carbon stock changes are likely minor in perennial crops, with relatively small amounts of woody crops such as orchards and nut plantations. There will be removal and replanting of tree crops each year, but the net effect on biomass carbon stock changes is probably minor because the overall area and tree density is relatively constant across time series. In contrast, agroforestry practices, such as shelterbelts, riparian forests and intercropping with trees, may have more significant changes over the *Inventory* time series, compared to perennial woody crops, at least in some regions of the United States, but there are currently no datasets to evaluate the trends. Changes in litter carbon stocks are also assumed to be negligible in croplands over annual time frames, although there are certainly significant changes at sub-annual time scales across seasons. This trend may change in the future, particularly if crop residue becomes a viable feedstock for bioenergy production.

QA/QC and Verification

Quality control measures included checking input data, model scripts, and results to ensure data are properly handled throughout the inventory process consistent with the U.S. *Inventory* QA/QC plan, which is in accordance with Volume 1, Chapter 6 of the *2006 IPCC Guidelines* (see Annex 8 for more details). Inventory reporting forms and text are reviewed and revised as needed to correct transcription errors. In addition, results from the DayCent model are compared to field measurements and soil monitoring sites associated with the NRI (Spencer et al. 2011), and a statistical relationship has been developed to assess uncertainties in the predictive capability of the model (Ogle et al. 2007). The comparisons include 69 long-term experiment sites and 145 NRI soil monitoring network sites, with 1406 observations across all of the sites (see Annex 3.12 for more information). Quality control uncovered several errors in the Tier 2 method following the initial analysis, such as no estimation for some NRI survey locations (i.e., federal lands and Hawaii), double counting some NRI survey locations with aggregation to the national scale, and errors in the estimation of the two variance components associated with the uncertainty analysis. The errors have been corrected following the diagnosis of the quality control issues.

Recalculations Discussion

Several improvements have been implemented in this *Inventory* leading to the need for recalculations. These improvements included a) incorporating new USDA-NRCS NRI data through 2017; b) extending the time series for crop histories through 2020 using USDA-NASS CDL data; c) incorporating USDA-NRCS CEAP survey data for 2013 to 2016; d) incorporating cover crop and tillage management information from the OpTIS remote-sensing data product from 2008 to 2020; e) modifying the statistical imputation method for the management activity data associated with about tillage practices, mineral fertilization, manure amendments, cover crop management, and

planting and harvest dates using gradient boosting instead of an artificial neural network; f) updating time series of synthetic nitrogen fertilizer sales data, PRP nitrogen and manure nitrogen available for application to soils; g) constraining synthetic nitrogen fertilization and manure nitrogen applications in the Tier 3 method at the state scale rather than the national scale; h) re-calibrating the soil carbon module in the DayCent model using Bayesian methods; and i) expanding the crops in the Tier 3 method to include dry beans, lentils, onions, peas and tomatoes, which shifted some NRI survey locations from the Tier 2 to the Tier 3 method. The combined impact from these improvements resulted in an average annual increase in soil C stocks of 4.2 MMT CO_2 Eq., or 26 percent, from 1990 to 2021 relative to the previous *Inventory*.

Planned Improvements

A key improvement is conducting an analysis of carbon stock changes in Alaska for cropland. The improvement will be conducted using the Tier 2 method for mineral and organic soils that is described earlier in this section. The analysis will initially focus on land-use change, which typically has a larger impact on soil organic carbon stock changes than management practices, but will be further refined over time to incorporate management data. The improvement will resolve most of the differences between the managed land base for cropland remaining cropland and amount of area currently included in cropland remaining cropland (see Table 6-39).

Table 6-39: Comparison of Managed Land Area in Cropland Remaining Cropland and Area in the Current Cropland Remaining Cropland Inventory (Thousand Hectares)

	Area (Thousand Hectares)		
Year	Managed Land	*Inventory*	Difference
1990	162,273	162,247	26
1991	161,840	161,814	26
1992	161,343	161,317	26
1993	159,577	159,551	26
1994	157,890	157,864	26
1995	157,277	157,251	26
1996	156,639	156,613	26
1997	156,018	155,992	26
1998	152,335	152,309	26
1999	151,432	151,406	26
2000	151,257	151,231	26
2001	150,734	150,708	26
2002	150,426	150,400	26
2003	151,055	151,029	26
2004	150,787	150,761	26
2005	150,417	150,391	26
2006	149,908	149,882	26
2007	150,117	150,091	26
2008	149,718	149,692	26
2009	149,660	149,634	26
2010	149,222	149,196	26
2011	148,626	148,600	26
2012	148,297	148,271	26
2013	148,660	148,633	26
2014	149,141	149,115	26
2015	148,525	148,499	26
2016	148,436	148,410	26

2017	148,331	148,305	26
2018	149,720	149,694	26
2019	149,503	149,477	26
2020	149,822	149,796	26
2021	150,591	*	*
2022	151,276	*	*

Activity data on land use have not been incorporated into the *Inventory* after 2020, designated with asterisks (*).

There are several other planned improvements underway related to the plant production module in DayCent. Crop parameters associated with temperature effects on plant production will be further improved in DayCent with additional model calibration. Senescence events following grain filling in crops, such as wheat, are being modified based on recent model algorithm development, and will be incorporated. There will also be further testing and parameterization of the DayCent model to reduce uncertainty, particularly the submodules that are used to approximate the cycling of nitrogen through the plant-soil system, which will also have impacts on carbon cycling in the model simulations.

Improvements are underway to simulate crop residue burning in the DayCent model based on the amount of crop residues burned according to the data that are used in the field burning of agricultural residues source category (see Section 5.7). This improvement will more accurately represent the carbon inputs to the soil that are associated with residue burning. In addition, a review of available data on biosolids (i.e., treated sewage sludge) application will be undertaken to improve the distribution of biosolids application on croplands, grasslands and settlements.

Another improvement is to estimate biomass carbon stock changes in agroforestry systems and perennial tree crops. Methods combining survey data and remote sensing imagery are under development to determine the extent of land with agroforestry and perennial tree crops. In addition, a meta-analysis is being conducted to derive country-specific factors for biomass C stock changes in agroforestry systems. Although the influence of perennial tree crop biomass is expected to be minor, carbon stock changes may be significantly impacted by the effect of agroforestry practices.

Many of these improvements are expected to be completed for the next (1990 through 2023) *Inventory* (i.e., 2025 submission), pending prioritization of resources.

6.5 Land Converted to Cropland (CRT Category 4B2)

Land converted to cropland includes all current cropland in an inventory year that had been in another land use(s) during the previous 20 years (IPCC 2006), and used to produce food or fiber, or forage that is harvested and used as feed (e.g., hay and silage). For example, grassland or forest land converted to cropland during the past 20 years would be reported in this category. Recently converted lands are retained in this category for 20 years as recommended by IPCC (2006).

Land use change can lead to large losses of carbon to the atmosphere, particularly conversions from forest land (Houghton et al. 1983; Houghton and Nassikas 2017). Moreover, conversion of forest to another land use (i.e., deforestation) is one of the largest anthropogenic sources of emissions to the atmosphere globally, although this source may be declining (Tubiello et al. 2015).

The *2006 IPCC Guidelines* recommend reporting changes in biomass, dead organic matter and soil organic carbon stocks with land use change. All soil organic carbon stock changes are estimated and reported for land converted to cropland, but reporting of carbon stock changes for aboveground and belowground biomass, dead wood, and litter pools is limited to forest land converted to cropland and grassland converted to cropland for woodland conversions (i.e., woodland conversion to cropland).[46]

Grassland converted to cropland is the largest source of emissions from 1990 to 2000, while forest land converted to cropland is the largest source of emissions from 2001 to 2022. This shift is largely due to reduced losses of carbon from mineral soils after 2001. The high losses of carbon from forest land converted to cropland is due to reductions in biomass and dead organic matter carbon following conversion from forests (Table 6-40 and Table 6-41). The net change in total carbon stocks for 2022 led to CO_2 emissions to the atmosphere of 35.1 MMT CO_2 Eq. (9.6 MMT C), including 12.1 MMT CO_2 Eq. (3.3 MMT C) from aboveground biomass carbon losses, 2.0 MMT CO_2 Eq. (0.6 MMT C) from belowground biomass carbon losses, 2.3 MMT CO_2 Eq. (0.6 MMT C) from dead wood carbon losses, 3.4 MMT CO_2 Eq. (0.9 MMT C) from litter carbon losses, 12.6 MMT CO_2 Eq. (3.4 MMT C) from mineral soils and 2.7 MMT CO_2 Eq. (0.7 MMT C) from drainage and cultivation of organic soils. The overall net loss of carbon has declined by 23 percent from 1990 to 2022.

Table 6-40: Net CO_2 Flux from Soil, Dead Organic Matter and Biomass Carbon Stock Changes in Land Converted to Cropland by Land-Use Change Category (MMT CO_2 Eq.)

	1990	2005	2018	2019	2020	2021	2022
Grassland Converted to Cropland	**27.3**	**17.2**	**13.7**	**13.0**	**10.6**	**16.1**	**16.3**
Aboveground Live Biomass	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Belowground Live Biomass	+	+	+	+	+	+	+
Dead Wood	+	+	+	+	+	+	+
Litter	+	+	+	+	+	+	+
Mineral Soils	24.6	13.7	10.7	10.1	8.0	13.5	13.6
Organic Soils	2.4	3.3	2.7	2.7	2.4	2.4	2.4
Forest Land Converted to Cropland	**19.2**	**19.2**	**19.7**	**19.7**	**19.7**	**19.6**	**19.6**
Aboveground Live Biomass	11.4	11.6	11.9	11.9	11.9	11.9	11.9
Belowground Live Biomass	1.9	2.0	2.0	2.0	2.0	2.0	2.0
Dead Wood	2.2	2.2	2.2	2.2	2.2	2.2	2.2
Litter	3.2	3.3	3.3	3.4	3.4	3.4	3.4
Mineral Soils	0.4	0.2	0.1	0.1	0.1	0.1	0.1
Organic Soils	0.1	+	+	+	+	+	+
Other Lands Converted to Cropland	**(1.8)**	**(2.5)**	**(1.6)**	**(1.6)**	**(1.2)**	**(1.1)**	**(1.1)**
Mineral Soils	(1.9)	(2.6)	(1.7)	(1.6)	(1.2)	(1.1)	(1.1)
Organic Soils	0.1	0.1	+	+	+	+	+
Settlements Converted to Cropland	**(0.0)**	**(0.1)**	**(0.1)**	**(0.1)**	**(0.1)**	**(0.1)**	**(0.1)**
Mineral Soils	(0.1)	(0.1)	(0.2)	(0.2)	(0.2)	(0.2)	(0.2)
Organic Soils	+	+	+	+	+	+	+
Wetlands Converted to Cropland	**0.7**	**0.7**	**0.4**	**0.4**	**0.4**	**0.4**	**0.4**
Mineral Soils	0.2	0.2	0.2	0.2	0.2	0.1	0.2
Organic Soils	0.5	0.5	0.2	0.2	0.2	0.2	0.2
Aboveground Live Biomass	**11.6**	**11.7**	**12.0**	**12.0**	**12.1**	**12.1**	**12.1**
Belowground Live Biomass	**2.0**	**2.0**	**2.0**	**2.0**	**2.0**	**2.0**	**2.0**
Dead Wood	**2.2**	**2.2**	**2.3**	**2.3**	**2.3**	**2.3**	**2.3**

[46] Changes in biomass carbon stocks are estimated for forest land converted to cropland and grassland converted to cropland for woodland conversions. There is a planned improvement to include the effect of other land use conversions, in addition to herbaceous grassland conversions to cropland in a future *Inventory*. Note: changes in dead organic matter are assumed negligible for other land use conversions to cropland, except forest land and woodland conversions.

Litter	**3.3**	**3.3**	**3.4**	**3.4**	**3.4**	**3.4**	**3.4**
Total Mineral Soil Flux	**23.2**	**11.3**	**9.2**	**8.6**	**6.9**	**12.5**	**12.6**
Total Organic Soil Flux	**3.2**	**3.9**	**3.0**	**3.0**	**2.6**	**2.6**	**2.7**
Total Net Flux	**45.4**	**34.5**	**31.9**	**31.4**	**29.3**	**34.9**	**35.1**

+ Does not exceed 0.05 MMT CO_2 Eq.

Notes: Totals may not sum due to independent rounding. Parentheses indicate negative values or net sequestration.

Table 6-41: Net CO_2 Flux from Soil, Dead Organic Matter and Biomass Carbon Stock Changes in Land Converted to Cropland (MMT C)

	1990	2005	2018	2019	2020	2021	2022
Grassland Converted to Cropland	**7.4**	**4.7**	**3.7**	**3.6**	**2.9**	**4.4**	**4.4**
Aboveground Live Biomass	+	+	+	+	+	+	+
Belowground Live Biomass	+	+	+	+	+	+	+
Dead Wood	+	+	+	+	+	+	+
Litter	+	+	+	+	+	+	+
Mineral Soils	6.7	3.7	2.9	2.8	2.2	3.7	3.7
Organic Soils	0.7	0.9	0.7	0.7	0.6	0.6	0.7
Forest Land Converted to Cropland	**5.2**	**5.2**	**5.4**	**5.4**	**5.4**	**5.4**	**5.4**
Aboveground Live Biomass	3.1	3.2	3.2	3.3	3.3	3.3	3.3
Belowground Live Biomass	0.5	0.5	0.5	0.6	0.6	0.6	0.6
Dead Wood	0.6	0.6	0.6	0.6	0.6	0.6	0.6
Litter	0.9	0.9	0.9	0.9	0.9	0.9	0.9
Mineral Soils	0.1	+	+	+	+	+	+
Organic Soils	+	+	+	+	+	+	+
Other Lands Converted to Cropland	**(0.5)**	**(0.7)**	**(0.4)**	**(0.4)**	**(0.3)**	**(0.3)**	**(0.3)**
Mineral Soils	(0.5)	(0.7)	(0.5)	(0.4)	(0.3)	(0.3)	(0.3)
Organic Soils	+	+	+	+	+	+	+
Settlements Converted to Cropland	**+**	**+**	**+**	**+**	**+**	**+**	**+**
Mineral Soils	+	+	+	+	+	+	+
Organic Soils	+	+	+	+	+	+	+
Wetlands Converted to Cropland	**0.2**	**0.2**	**0.1**	**0.1**	**0.1**	**0.1**	**0.1**
Mineral Soils	0.1	0.1	+	+	+	+	+
Organic Soils	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Aboveground Live Biomass	**3.2**	**3.2**	**3.3**	**3.3**	**3.3**	**3.3**	**3.3**
Belowground Live Biomass	**0.5**	**0.5**	**0.6**	**0.6**	**0.6**	**0.6**	**0.6**
Dead Wood	**0.6**	**0.6**	**0.6**	**0.6**	**0.6**	**0.6**	**0.6**
Litter	**0.9**	**0.9**	**0.9**	**0.9**	**0.9**	**0.9**	**0.9**
Total Mineral Soil Flux	**6.3**	**3.1**	**2.5**	**2.4**	**1.9**	**3.4**	**3.4**
Total Organic Soil Flux	**0.9**	**1.1**	**0.8**	**0.8**	**0.7**	**0.7**	**0.7**
Total Net Flux	**12.4**	**9.4**	**8.7**	**8.6**	**8.0**	**9.5**	**9.6**

+ Does not exceed 0.05 MMT C.

Notes: Totals may not sum due to independent rounding. Parentheses indicate negative values or net sequestration.

Methodology and Time-Series Consistency

The following section includes a description of the methodology used to estimate carbon stock changes for land converted to cropland, including (1) loss of aboveground and belowground biomass, dead wood and litter carbon with conversion of forest lands to croplands, as well as (2) the impact from all land use conversions to cropland on mineral and soil organic carbon stocks.

Biomass, Dead Wood and Litter Carbon Stock Changes

A Tier 2 method is applied to estimate biomass, dead wood, and litter carbon stock changes for forest land converted to cropland. Estimates are calculated in the same way as those in the forest land remaining forest land category using data from the USDA Forest Service, Forest Inventory and Analysis (FIA) program (USDA Forest Service 2023). However, there is no country-specific data for cropland biomass, so only a default biomass estimate (IPCC 2006) for croplands was used to estimate carbon stock changes (litter and dead wood carbon stocks were assumed to be zero since no reference carbon density estimates exist for croplands). The difference between the stocks is reported as the stock change under the assumption that the change occurred in the year of the conversion. Details for each of the carbon attributes described below are available in Domke et al. (2022) and Westfall et al. (2023). If FIA plots include data on individual trees, aboveground and belowground carbon density estimates are based on Woodall et al. (2011) and Westfall et al. (2023). Aboveground and belowground biomass estimates also include live understory which is a minor component of biomass defined as all biomass of undergrowth plants in a forest, including woody shrubs and trees less than 2.54 cm dbh. For this *Inventory*, it was assumed that 10 percent of total understory carbon mass is belowground (Smith et al. 2006). Estimates of carbon density are based on information in Birdsey (1996) and biomass estimates from Jenkins et al. (2003).

For dead organic matter, if FIA plots include data on standing dead trees, standing dead tree carbon density is estimated following the basic method applied to live trees (Woodall et al. 2011; Westfall et al. 2023) with additional modifications for woodland species to account for decay and structural loss (Domke et al. 2011; Harmon et al. 2011). If FIA plots include data on downed dead wood, downed dead wood carbon density is estimated based on measurements of a subset of FIA plots for downed dead wood (Domke et al. 2013; Woodall and Monleon 2008). Downed dead wood is defined as pieces of dead wood greater than 7.5 cm diameter, at transect intersection, that are not attached to live or standing dead trees. This includes stumps and roots of harvested trees. To facilitate the downscaling of downed dead wood carbon estimates from the state-wide population estimates to individual plots, downed dead wood models specific to regions and forest types within each region are used. Litter carbon is the pool of organic carbon (also known as duff, humus, and fine woody debris) above the mineral soil and includes woody fragments with diameters of up to 7.5 cm. A subset of FIA plots are measured for litter carbon. If FIA plots include litter material, a modeling approach using litter carbon measurements from FIA plots is used to estimate litter carbon density (Domke et al. 2016). See Annex 3.13 for more information about reference carbon density estimates for forest land and the compilation system used to estimate carbon stock changes from forest land.

Soil Carbon Stock Changes

Soil organic stock changes are estimated for land converted to cropland according to land use histories recorded in the 2017 USDA NRI survey for non-federal lands (USDA-NRCS 2020). Land use and some management information (e.g., crop type, soil attributes, and irrigation) had been collected for each NRI point on a five-year cycle beginning in 1982. In 1998, the NRI program began collecting annual data, which are currently available through 2017 (USDA-NRCS 2020), and the time series for cropping histories was extended through 2020 using the USDA-NASS Crop Data Layer Product (CDL) (USDA-NASS 2021) and National Land Cover Dataset (NLCD) (Yang et al. 2018; Fry et al. 2011; Homer et al. 2007, 2015). The areas have been modified in the original NRI survey through a process in which the Forest Inventory and Analysis (FIA) survey data and the National Land Cover Dataset (NLCD; Yang et al. 2018) are harmonized with the NRI data. This process ensures that the land use areas are consistent across all land use categories (see Section 6.1 for more information).

NRI survey locations are classified as land converted to cropland in a given year between 1990 and 2020 if the land use is cropland but had been another use during the previous 20 years. NRI survey locations are classified according to land use histories starting in 1979, and consequently the classifications are based on less than 20 years from 1990 to 1998, which may have led to an underestimation of land converted to cropland in the early part of the time series to the extent that some areas are converted to cropland from 1971 to 1978. For federal lands, the land use history is derived from land cover changes in the NLCD (Yang et al. 2018; Homer et al. 2007; Fry et al. 2011; Homer et al. 2015).

Soil Carbon Stock Changes for Mineral Soils

An IPCC Tier 3 model-based approach using the DayCent ecosystem model (Ogle et al. 2010, 2023) is applied to estimate carbon stock changes from 1990 to 2020 for mineral soils on the majority of land that is used to produce annual crops and forage crops that are harvested and used as feed (e.g., hay and silage) in the United States. These crops include alfalfa hay, barley, corn, cotton, dry beans, grass hay, grass-clover hay, lentils, oats, onions, peanuts, peas, potatoes, rice, sorghum, soybeans, sugar beets, sunflowers, tobacco, tomatoes, and wheat. Soil organic carbon stock changes on the remaining mineral soils are estimated with the IPCC Tier 2 method (Ogle et al. 2003, 2006), including land used to produce some vegetables and perennial/horticultural crops and crops rotated with these crops; land on very gravelly, cobbly, or shaley soils (greater than 35 percent by volume); and land converted from another land use or federal ownership.[47]

For the years 2021 to 2022, a surrogate data method is used to estimate soil organic carbon stock changes at the national scale for land areas included in the Tier 2 and Tier 3 methods. Specifically, linear regression models with autoregressive moving-average (ARMA) errors (Brockwell and Davis 2016) are used to estimate the relationship between surrogate data and the 1990 to 2020 stock change data from the Tier 2 and 3 methods. Surrogate data for these regression models include corn and soybean yields from USDA-NASS statistics,[48] and weather data from the PRISM Climate Group (PRISM 2022). See Box 6-4 in the Methodology section of Cropland Remaining Cropland for more information about the surrogate data method. Stock change estimates for 2021 to 2022 will be recalculated in future *Inventories* when the time series of activity data are updated.

Tier 3 Approach. For the Tier 3 method, mineral soil organic carbon stocks and stock changes are estimated using the DayCent ecosystem model (Parton et al. 1998; Del Grosso et al. 2001, 2011). The DayCent model utilizes the soil carbon modeling framework developed in the Century model (Parton et al. 1987, 1988, 1994; Metherell et al. 1993), but has been refined to simulate dynamics at a daily time-step. National estimates are obtained by using the model to simulate historical land use change patterns as recorded in the USDA NRI survey (USDA-NRCS 2020). Carbon stocks and 95 percent confidence intervals are estimated for each year between 1990 and 2020. See the cropland remaining cropland section and Annex 3.12 for additional discussion of the Tier 3 methodology for mineral soils.

In order to ensure time-series consistency, the Tier 3 method is applied from 1990 to 2020 so that changes reflect anthropogenic activity and not methodological adjustments. Soil organic carbon stock changes from 2021 to 2022 are approximated using a linear extrapolation of emission patterns from 1990 to 2020. The extrapolation is based on a linear regression model with moving-average (ARMA) errors (described in Box 6-4 of the Methodology section in cropland remaining cropland). Linear extrapolation is a standard data splicing method for estimating emissions at the end of a time series (IPCC 2006). Time series of activity data will be updated in a future *Inventory*, and emissions from 2020 to 2022 will be recalculated.

Tier 2 Approach. For the mineral soils not included in the Tier 3 analysis, soil organic carbon stock changes are estimated using a Tier 2 Approach, as described in the Tier 2 Approach for mineral soils in cropland remaining cropland. In order to ensure time-series consistency, the Tier 2 method is applied from 1990 to 2020 so that changes reflect anthropogenic activity and not methodological adjustments. In addition, soil organic carbon stock changes are approximated for the remainder of the 2021 to 2022 time series with a linear extrapolation of emission patterns from 1990 to 2020. The extrapolation is based on a linear regression model with moving-average (ARMA) errors (see Box 6-4 of the Methodology section in Cropland Remaining Cropland). Linear extrapolation is a standard data splicing method for estimating emissions at the end of a time series (IPCC 2006). As with the Tier 3 method, time series of activity data will be updated in a future *Inventory*, and emissions from 2021 to 2022 will be recalculated.

[47] Federal land is not a land use, but rather an ownership designation that is treated as grassland for purposes of these calculations. The specific land use on federal lands is not identified in the NRI survey (USDA-NRCS 2018).

[48] See https://quickstats.nass.usda.gov/.

Soil Carbon Stock Changes for Organic Soils

Annual carbon emissions from drained organic soils in land converted to cropland are estimated using the Tier 2 method provided in IPCC (2006), with country-specific carbon loss rates (Ogle et al. 2003) as described in the cropland remaining cropland section for organic soils. Further elaboration on the methodology is also provided in Annex 3.12.

In order to ensure time-series consistency, the Tier 2 methods are applied from 1990 to 2020 so that changes reflect anthropogenic activity and not methodological adjustments. In addition, soil organic carbon stock changes for the remainder of the time series (i.e., 2021 to 2022) are approximated with a linear extrapolation of emission patterns from 1990 to 2020. The extrapolation is based on a linear regression model with moving-average (ARMA) errors (see Box 6-4 of the Methodology section in cropland remaining cropland). Linear extrapolation is a standard data splicing method for approximating emissions at the end of a time series (IPCC 2006). Estimates for 2021 to 2022 will be recalculated in a future *Inventory* when new activity data are incorporated into the analysis.

Uncertainty

The uncertainty analyses for biomass, dead wood and litter carbon losses with forest land converted to cropland and grassland converted to cropland for woodland conversions are conducted in the same way as the uncertainty assessment for forest ecosystem carbon flux associated with forest land remaining forest land. Sample and model-based error are combined using simple error propagation methods provided by the IPCC (2006) by taking the square root of the sum of the squares of the standard deviations of the uncertain quantities. For additional details, see the Uncertainty Analysis in Annex 3.13.

The uncertainty analyses for soil organic carbon stock changes using the Tier 3 and Tier 2 methodologies are quantified from two variance components (Ogle et al. 2010), as described in cropland remaining cropland. For 2021 to 2022, there is additional uncertainty propagated through the Monte Carlo analysis associated with the surrogate data method, which is also described in cropland remaining cropland.

Uncertainty estimates are presented in Table 6-42 for each sub-source (i.e., biomass carbon stocks, dead wood carbon stocks, litter carbon stocks, soil organic carbon stocks for mineral and organic soils) and the method applied in the *Inventory* analysis (i.e., Tier 2 and Tier 3). Uncertainty estimates for the total carbon stock changes for biomass, dead organic matter and soils are combined using the simple error propagation methods provided by the IPCC (2006). The combined uncertainty for total carbon stock changes in land converted to cropland ranged from 93 percent below to 93 percent above the 2022 stock change estimate of 35.1 MMT CO_2 Eq. The large relative uncertainty in the 2022 estimate is mostly due to variation in soil organic carbon stock changes that is not explained by the surrogate data method, leading to high prediction error with this splicing method.

Table 6-42: Approach 2 Quantitative Uncertainty Estimates for Soil, Dead Organic Matter and Biomass Carbon Stock Changes occurring within Land Converted to Cropland (MMT CO_2 Eq. and Percent)

Source	2022 Flux Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Flux Estimate[a] (MMT CO_2 Eq.)		(%)	
		Lower Bound	Upper Bound	Lower Bound	Upper Bound
Grassland Converted to Cropland	**16.3**	**(12.1)**	**44.7**	**-174%**	**174%**
Aboveground Live Biomass	0.1	+	0.3	-128%	124%
Belowground Live Biomass	+	+	+	-100%	56%
Dead Wood	+	+	0.1	-100%	173%
Litter	+	+	0.1	-100%	147%
Mineral Soil C Stocks: Tier 3	11.0	(17.2)	39.3	-256%	256%
Mineral Soil C Stocks: Tier 2	2.6	0.6	4.5	-77%	77%

Organic Soil C Stocks: Tier 2	2.4	0.5	4.4	-79%	79%
Forest Land Converted to Cropland	**19.6**	**3.4**	**35.8**	**-82%**	**82%**
Aboveground Live Biomass	11.9	(3.2)	27.1	-127%	127%
Belowground Live Biomass	2.0	(0.6)	4.6	-127%	127%
Dead Wood	2.2	(0.6)	5.1	-128%	127%
Litter	3.4	(0.9)	7.6	-127%	128%
Mineral Soil C Stocks: Tier 2	0.1	+	0.2	-107%	107%
Organic Soil C Stocks: Tier 2	+	+	0.1	-429%	429%
Other Lands Converted to Cropland	**(1.1)**	**(2.1)**	+	**-99%**	**99%**
Mineral Soil C Stocks: Tier 2	(1.1)	(2.1)	+	-99%	99%
Organic Soil C Stocks: Tier 2	+	+	+	0%	0%
Settlements Converted to Cropland	**(0.1)**	**(0.3)**	+	**-97%**	**97%**
Mineral Soil C Stocks: Tier 2	(0.2)	(0.3)	(0.1)	-71%	71%
Organic Soil C Stocks: Tier 2	+	+	0.1	-103%	103%
Wetlands Converted to Croplands	**0.4**	**(0.1)**	**0.8**	**-115%**	**115%**
Mineral Soil C Stocks: Tier 2	0.2	+	0.3	-124%	124%
Organic Soil C Stocks: Tier 2	0.2	(0.2)	0.6	-173%	173%
Total: Land Converted to Cropland	**35.1**	**2.4**	**67.8**	**-93%**	**93%**
Aboveground Live Biomass	**12.1**	**(3.1)**	**27.2**	**-126%**	**126%**
Belowground Live Biomass	**2.0**	**(0.5)**	**4.6**	**-126%**	**126%**
Dead Wood	**2.3**	**(0.6)**	**5.1**	**-126%**	**125%**
Litter	**3.4**	**(0.9)**	**7.7**	**-126%**	**126%**
Mineral Soil C Stocks: Tier 3	**11.0**	**(17.2)**	**39.3**	**-256%**	**256%**
Mineral Soil C Stocks: Tier 2	**1.6**	**(0.7)**	**3.8**	**-144%**	**144%**
Organic Soil C Stocks: Tier 2	**2.7**	**0.7**	**4.7**	**-73%**	**73%**

+ Does not exceed 0.05 MMT CO_2 Eq.

[a] Range of C stock change estimates is a 95 percent confidence interval.

Notes: Totals may not sum due to independent rounding. Parentheses indicate negative values or net sequestration.

Uncertainty is also associated with lack of reporting of agricultural biomass and dead organic matter carbon stock changes. Biomass carbon stock changes are likely minor in perennial crops, such as orchards and nut plantations, given the small amount of change in land that is used to produce these commodities in the United States. In contrast, agroforestry practices, such as shelterbelts, riparian forests and intercropping with trees, may have led to larger changes in biomass carbon stocks at least in some regions of the United States. However, there are currently no datasets to evaluate the trends. Changes in dead organic matter carbon stocks are assumed to be negligible with conversion of land to croplands with the exception of forest lands, which are included in this analysis. This assumption will be further explored in a future *Inventory*.

QA/QC and Verification

See the QA/QC and Verification section in Cropland Remaining Cropland for information on QA/QC steps.

Recalculations Discussion

Several improvements have been implemented in this *Inventory* leading to the need for recalculations. These improvements included a) incorporating new USDA-NRCS NRI data through 2017; b) extending the time series for crop histories through 2020 using USDA-NASS CDL data; c) incorporating USDA-NRCS CEAP survey data for 2013 to 2016; d) incorporating cover crop and tillage management information from the OpTIS remote-sensing data product from 2008 to 2020; e) modifying the statistical imputation method for the management activity data associated with about tillage practices, mineral fertilization, manure amendments, cover crop management, planting and harvest dates using gradient boosting instead of an artificial neural network; f) updating time series of synthetic nitrogen fertilizer sales data, PRP nitrogen and manure nitrogen available for application to soils; g)

constraining synthetic nitrogen fertilization and manure nitrogen applications in the Tier 3 method at the state scale rather than the national scale; h) re-calibrating the soil carbon module in the DayCent model using Bayesian methods; i) expanding the crops in the Tier 3 method to include dry beans, lentils, onions, peas and tomatoes, which shifted some NRI survey locations from the Tier 2 to the Tier 3 method, and j) updated FIA data from 1990 to 2022 on biomass, dead wood and litter carbon stocks associated with forest land converted to cropland. Finally, see further updates in Section 6.2, describing updates to the estimates for aboveground volume and biomass which impacted lands converted to cropland estimates. As a result, land converted to cropland has an estimated smaller carbon loss of 20.7 MMT CO_2 Eq. on average over the time series. This represents a 37 percent average decrease in carbon stock change losses for land converted to cropland compared to the previous *Inventory*, and is mainly due to less loss of carbon associated with forest land converted to cropland.

Planned Improvements

A key improvement is to estimate the biomass carbon stock changes for other land use changes beyond only forest land converted to cropland and grassland converted to cropland for woodland conversion, which is included in the current *Inventory*. Additional planned improvements are discussed in the Planned Improvements section of Cropland Remaining Cropland.

6.6 Grassland Remaining Grassland (CRT Category 4C1)

Carbon in grassland ecosystems occurs in biomass, dead organic matter, and soils. Soils are the largest pool of carbon in grasslands, and have the greatest potential for longer-term storage or release of carbon. Biomass and dead organic matter carbon pools are relatively ephemeral compared to the soil carbon pool, with the exception of carbon stored in tree and shrub biomass that occurs in grasslands. The *2006 IPCC Guidelines* recommend reporting changes in biomass, dead organic matter and soil organic carbon stocks with land use and management. Carbon stock changes for aboveground and belowground biomass, dead wood and litter pools are reported for woodlands (i.e., a subcategory of grasslands[49]), and may be extended to include agroforestry management associated with grasslands in the future. For soil organic carbon, the *2006 IPCC Guidelines* (IPCC 2006) recommend reporting changes due to (1) agricultural land use and management activities on mineral soils, and (2) agricultural land use and management activities on organic soils.[50]

Grassland remaining grassland includes all grassland in an inventory year that had been grassland for a continuous time period of at least 20 years (USDA-NRCS 2018). Grassland includes pasture and rangeland that are primarily, but not exclusively used for livestock grazing. Rangelands are typically extensive areas of native grassland that are not intensively managed, while pastures are typically seeded grassland (possibly following tree removal) that may also have additional management, such as irrigation or inter-seeding of legumes. Woodlands are also considered grassland and are areas of continuous tree cover that do not meet the definition of forest land (see Section 6.1 for more information about the criteria for forest land).

There is a discrepancy between the current land representation (see Section 6.1) and the area data that have been used in the inventory for grassland remaining grassland. Specifically, grasslands in Alaska are not included in the *Inventory*, and this land base is approximately 50 million hectares. This difference leads to a discrepancy between

[49] Woodlands are considered grasslands in the U.S. land representation because they do not meet the definition of forest land.

[50] CO_2 emissions associated with liming and urea fertilization are also estimated but included in the Agriculture chapter of the report.

the managed area in grassland remaining grassland in the land representation and the grassland area included in the emissions and removals estimation for the grassland remaining grassland land-use category (Table 6-46). Improvements are underway to incorporate grasslands in Alaska as part of future *Inventories* (see Planned Improvements section).

For grassland remaining grassland, there has been considerable variation in carbon stocks between 1990 and 2022. These changes are driven by variability in weather patterns and associated interaction with land management activity. Moreover, changes are small on a per hectare rate basis across the time series even in the years with a larger total change in stocks. The net change in total carbon stocks for 2022 led to net CO_2 emissions to the atmosphere of 13.4 MMT CO_2 Eq. (3.6 MMT C), including -1.3 MMT CO_2 Eq. (-0.4 MMT C) from net gains of aboveground biomass C, -0.2 MMT CO_2 Eq. (-0.1 MMT C) from net gains in belowground biomass carbon, 2.8 MMT CO_2 Eq. (0.8 MMT C) from net losses in dead wood carbon, less than 0.05 MMT CO_2 Eq. (less than 0.05 MMT C) from net gains in litter C, 6.5 MMT CO_2 Eq. (1.8 MMT C) from net losses in mineral soil organic carbon, and 5.5 MMT CO_2 Eq. (1.5 MMT C) from losses of carbon due to drainage and cultivation of organic soils (Table 6-43 and Table 6-44). Losses of carbon are 45.2 percent lower in 2022 compared to 1990, but as noted previously, stock changes are highly variable from 1990 to 2022, with an average annual change of 19.9 MMT CO_2 Eq. (5.4 MMT C).

Table 6-43: Net CO_2 Flux from Soil, Dead Organic Matter and Biomass Carbon Stock Changes in Grassland Remaining Grassland (MMT CO_2 Eq.)

	1990	2005	2018	2019	2020	2021	2022
Aboveground Live Biomass	(2.7)	(2.1)	(1.4)	(1.4)	(1.4)	(1.4)	(1.3)
Belowground Live Biomass	(0.4)	(0.3)	(0.3)	(0.2)	(0.2)	(0.2)	(0.2)
Dead Wood	3.2	3.1	2.9	2.9	2.9	2.9	2.8
Litter	(0.4)	(0.2)	+	+	+	+	+
Mineral Soils	18.6	18.6	22.0	22.0	9.3	3.8	6.5
Organic Soils	6.1	5.1	5.3	5.3	5.5	5.5	5.5
Total Net Flux	**24.4**	**24.1**	**28.6**	**28.5**	**16.1**	**10.6**	**13.4**

+ Does not exceed 0.05 MMT CO_2 Eq.

Notes: Totals may not sum due to independent rounding. Parentheses indicate negative values or net sequestration.

Table 6-44: Net CO_2 Flux from Soil, Dead Organic Matter and Biomass Carbon Stock Changes in Grassland Remaining Grassland (MMT C)

	1990	2005	2018	2019	2020	2021	2022
Aboveground Live Biomass	(0.7)	(0.6)	(0.4)	(0.4)	(0.4)	(0.4)	(0.4)
Belowground Live Biomass	(0.1)	(0.1)	(0.1)	(0.1)	(0.1)	(0.1)	(0.1)
Dead Wood	0.9	0.8	0.8	0.8	0.8	0.8	0.8
Litter	(0.1)	(0.1)	+	+	+	+	+
Mineral Soils	5.1	5.1	6.0	6.0	2.5	1.0	1.8
Organic Soils	1.7	1.4	1.4	1.4	1.5	1.5	1.5
Total Net Flux	**6.6**	**6.6**	**7.8**	**7.8**	**4.4**	**2.9**	**3.6**

+ Does not exceed 0.05 MMT C.

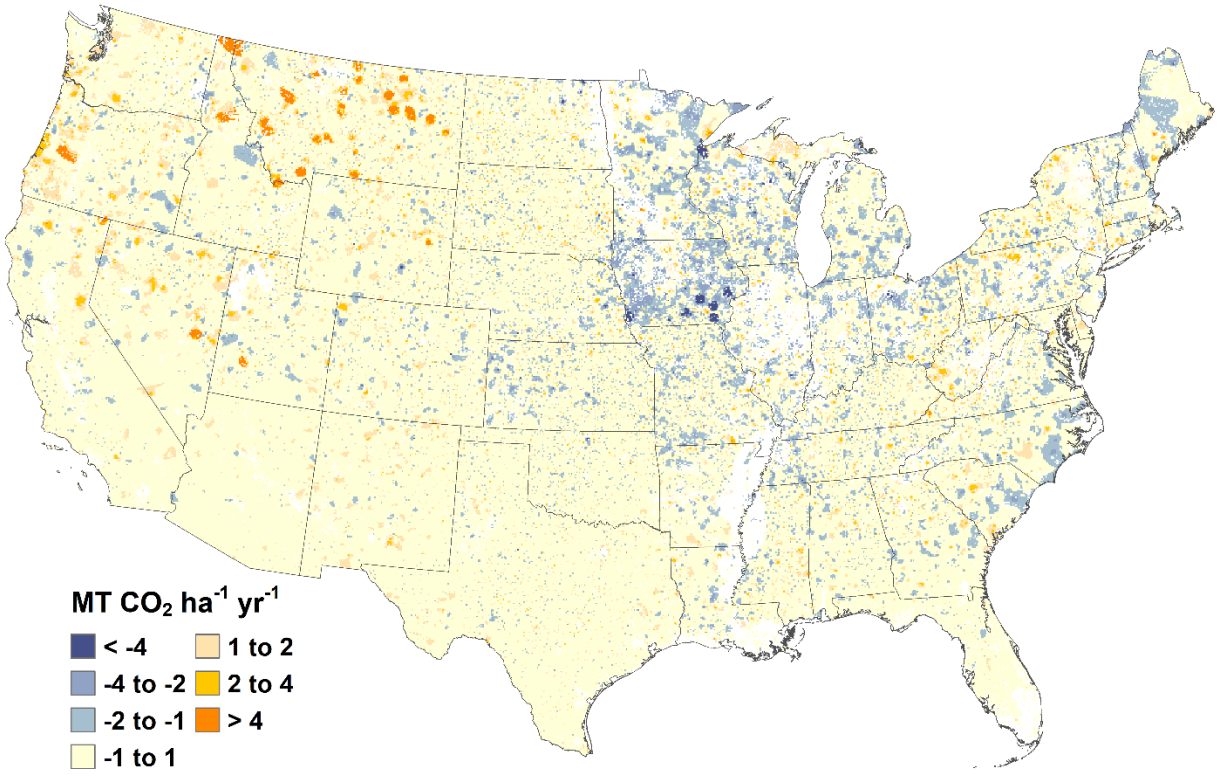
Notes: Totals may not sum due to independent rounding. Parentheses indicate negative values or net sequestration.

The spatial variability in soil organic carbon stock changes for 2020[51] is displayed in Figure 6-8 for mineral soils and in Figure 6-9 for organic soils. Although relatively small on a per-hectare basis, grassland soils gained carbon in

[51] Only national-scale emissions are estimated for 2021 to 2022 in the current *Inventory* using the surrogate data method, and therefore the fine-scale emission patterns in this map are based on land use data from 2020.

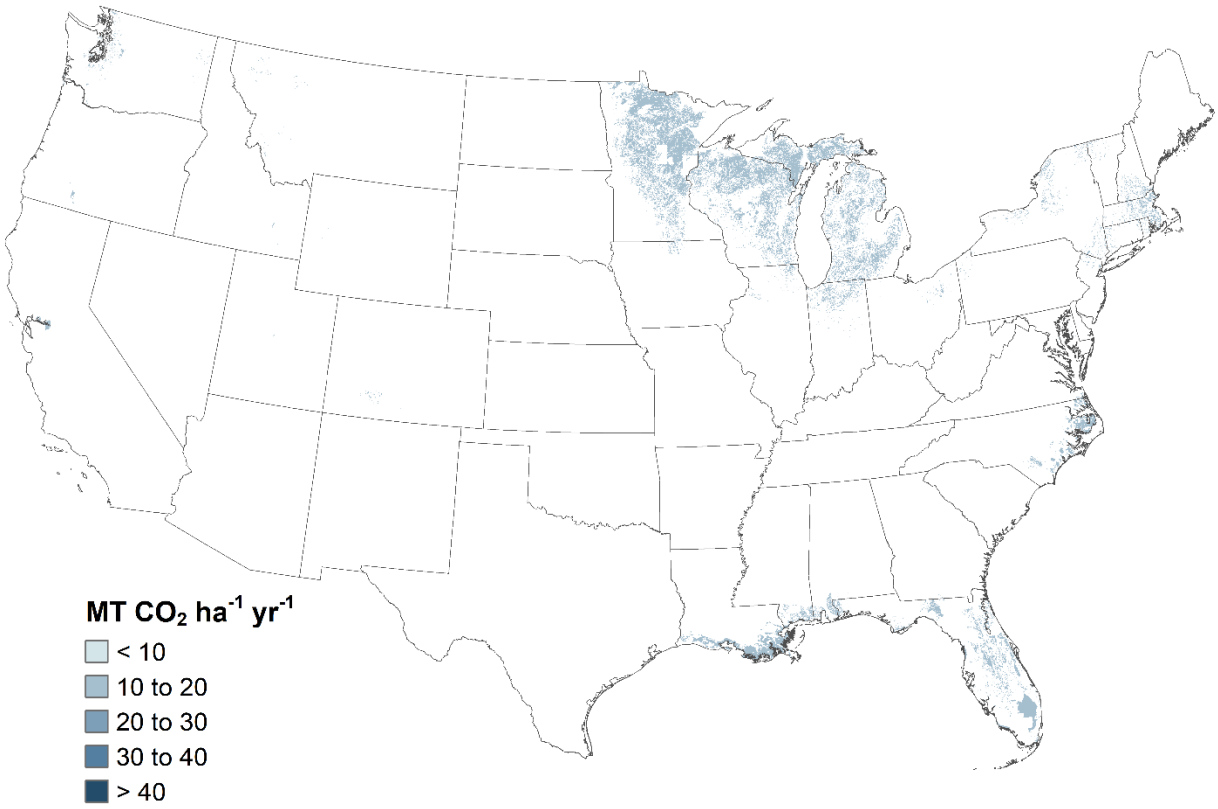
isolated areas that mostly occurred in pastures of the upper Midwest and eastern United States; losses occurred primarily in the northwestern region. For organic soils, the regions with the highest rates of emissions coincide with the largest concentrations of organic soils that occur in managed grassland, including the Southeastern Coastal Region (particularly Florida), areas surrounding the Great Lakes in the upper Midwest and Northeast, and a few isolated areas along the Pacific Coast.

Figure 6-8: Total Net Annual Soil Carbon Stock Changes for Mineral Soils under Agricultural Management within States, 2020, Grassland Remaining Grassland



Note: Only national-scale soil organic carbon stock changes are estimated for 2021 to 2022 in the current *Inventory* using a surrogate data method, and therefore the fine-scale emission patterns in this map are based on inventory data from 2020. Negative values represent a net increase in soil organic carbon stocks, and positive values represent a net decrease in soil organic carbon stocks.

Figure 6-9: Total Net Annual Soil Carbon Stock Changes for Organic Soils under Agricultural Management within States, 2020, Grassland Remaining Grassland



Note: Only national-scale soil organic carbon stock changes are estimated for 2021 to 2022 in the current *Inventory* using a surrogate data method, and therefore the fine-scale emission patterns in this map are based on inventory data from 2020.

Methodology and Time-Series Consistency

The following section includes a description of the methodology used to estimate carbon stock changes for grassland remaining grassland, including (1) aboveground and belowground biomass, dead wood and litter carbon for woodlands, as well as (2) soil organic carbon stocks for mineral and organic soils.

Biomass, Dead Wood and Litter Carbon Stock Changes

Woodlands are lands that do not meet the definition of forest land or agroforestry (see Section 6.1), but include woody vegetation with carbon storage in aboveground and belowground biomass, dead wood and litter carbon (IPCC 2006) as described in the Forest Land Remaining Forest Land section. Carbon stocks and net annual carbon stock change were determined according to the stock-difference method for the conterminous United States, which involved applying carbon estimation factors to annual forest inventories across time to obtain carbon stocks and then subtracting the values between years to estimate the stock changes. The methods for estimating carbon stocks and stock changes for woodlands in grassland remaining grassland are consistent with those in the forest

land remaining forest land section and are described in Annex 3.13. All annual National Forest Inventory (NFI) plots available in the public FIA database (USDA Forest Service 2023) were used in the current *Inventory*. While the NFI is an all-lands inventory, only those plots that meet the definition of forest land are typically measured. However, in some cases, particularly in the Central Plains and Southwest United States, woodlands have been measured as part of the survey. This analysis is limited to those plots and is not considered a comprehensive assessment of trees outside of forest land that meet the definition of grassland. The same methods are applied from 1990 to 2022 in order to ensure time-series consistency. This methodology is consistent with IPCC guidance (2006).

Soil Carbon Stock Changes

The following section includes a brief description of the methodology used to estimate changes in soil organic carbon stocks for grassland remaining grassland, including: (1) agricultural land use and management activities on mineral soils; and (2) agricultural land use and management activities on organic soils. Further elaboration on the methodologies and data used to estimate stock changes from mineral and organic soils is provided in the Cropland Remaining Cropland section and Annex 3.12.

Soil organic carbon stock changes are estimated for grassland remaining grassland on non-federal lands according to land use histories recorded in the USDA National Resources Inventory (NRI) (USDA-NRCS 2020). Land use and some management information (e.g., grass type, soil attributes, and irrigation) were originally collected for each NRI survey location on a five-year cycle beginning in 1982. In 1998, the NRI program began collecting annual data, and the annual data are currently available through 2017 (USDA-NRCS 2020). For 2018-2020, the time series is extended with the data provided in the National Land Cover Dataset (NLCD) (Yang et al. 2018; Fry et al. 2011; Homer et al. 2007, 2015). The areas have been modified in the original NRI survey through a process in which the Forest Inventory and Analysis (FIA) survey data and the NLCD are harmonized with the NRI data. This process ensures that the land use areas are consistent across all land use categories (see Section 6.1 for more information).

NRI survey locations are classified as grassland remaining grassland in a given year between 1990 and 2020 if the land use had been grassland for 20 years. NRI survey locations are classified according to land use histories starting in 1979, and consequently the classifications are based on less than 20 years from 1990 to 1998. This may have led to an overestimation of grassland remaining grassland in the early part of the time series to the extent that some areas are converted to grassland between 1971 and 1978. For federal lands, the land use history is derived from land cover changes in the NLCD (Yang et al. 2018; Homer et al. 2007; Fry et al. 2011; Homer et al. 2015).

Soil Carbon Stock Changes for Mineral Soils

An IPCC Tier 3 model-based approach (Ogle et al. 2010) is applied to estimate carbon stock changes from 1990 to 2020 for most mineral soils in grassland remaining grassland. The carbon stock changes for the remaining soils are estimated with an IPCC Tier 2 method (Ogle et al. 2003), including gravelly, cobbly, or shaley soils (greater than 35 percent by volume), as well as additional stock changes associated with biosolids (i.e., treated sewage sludge) amendments and federal land.[52]

A surrogate data method is used to estimate soil organic carbon stock changes from 2021 to 2022 at the national scale for land areas included in the Tier 2 and Tier 3 methods. Specifically, linear regression models with autoregressive moving-average (ARMA) errors (Brockwell and Davis 2016) are used to estimate the relationship between surrogate data and the 1990 to 2020 emissions data from the Tier 2 and 3 methods. Surrogate data for these regression models are based on weather data from the PRISM Climate Group (PRISM Climate Group 2022). See Box 6-4 in the Methodology section of Cropland Remaining Cropland for more information about the surrogate data method.

[52] Federal land is not a land use, but rather an ownership designation that is treated as grassland for purposes of these calculations. The specific land use on federal lands is not identified in the NRI survey (USDA-NRCS 2020).

Tier 3 Approach. Mineral soil organic carbon stocks and stock changes for grassland remaining grassland are estimated using the DayCent ecosystem model (Parton et al. 1998; Del Grosso et al. 2001, 2011), as described in Cropland Remaining Cropland. The DayCent model utilizes the soil carbon modeling framework developed in the Century model (Parton et al. 1987, 1988, 1994; Metherell et al. 1993), but has been refined to simulate dynamics at a daily time-step. Historical land-use patterns and irrigation histories are simulated with DayCent based on the 2017 USDA NRI survey (USDA-NRCS 2020). The amount of manure produced by each livestock type is calculated for managed and unmanaged waste management systems based on methods described in Section 5.2 and Annex 3.11. Manure nitrogen deposition from grazing animals (i.e., pasture/range/paddock (PRP) manure) is an input to the DayCent model to estimate the influence of PRP manure on carbon stock changes for lands included in the Tier 3 method. Carbon stocks and 95 percent confidence intervals are estimated for each year between 1990 and 2020 using the NRI survey data. Further elaboration on the Tier 3 methodology and data used to estimate carbon stock changes from mineral soils are described in Annex 3.12.

In order to ensure time-series consistency, the same methods are applied from 1990 to 2020 so that changes reflect anthropogenic activity and not methodological adjustments. In addition, soil organic carbon stock changes from 2021 to 2022 are approximated using a linear extrapolation of emission patterns from 1990 to 2020. The extrapolation is based on a linear regression model with moving-average (ARMA) errors, described in Box 6-4 of the Methodology section in Cropland Remaining Cropland. Linear extrapolation is a standard data splicing method for estimating emissions at the end of a time series (IPCC 2006). Stock change estimates for 2021 to 2022 will be recalculated in future *Inventories* with an updated time series of activity data (see the Planned Improvements section in Cropland Remaining Cropland).

Tier 2 Approach. The Tier 2 approach is based on the same methods described in the Tier 2 portion of the Cropland Remaining Cropland section for mineral soils, with the exception of the manure nitrogen deposition from grazing animals (i.e., PRP manure), and the land use and management data that are used in the *Inventory* for federal grasslands. First, the PRP nitrogen manure is included in the Tier 2 method that is not deposited on lands included in the Tier 3 method. Second, the NRI (USDA-NRCS 2020) provides land use and management histories for all non-federal lands, and is the basis for the Tier 2 analysis for these areas. However, NRI does not provide land use information on federal lands. The land use data for federal lands is based on the NLCD (Yang et al. 2018; Fry et al. 2011; Homer et al. 2007; Homer et al. 2015). In addition, the Bureau of Land Management (BLM) manages some of the federal grasslands, and compiles information on grassland condition through the BLM Rangeland Inventory (BLM 2014). To estimate soil organic carbon stock changes from federal grasslands, rangeland conditions in the BLM data are aligned with IPCC grassland management categories of nominal, moderately degraded, and severely degraded in order to apply the appropriate emission factors. Further elaboration on the Tier 2 methodology and data used to estimate carbon stock changes from mineral soils are described in Annex 3.12.

In order to ensure time-series consistency, the Tier 2 method is applied from 1990 to 2020 so that changes reflect anthropogenic activity and not methodological adjustments. In addition, soil organic carbon stock changes are approximated for the remainder of the time series with a linear extrapolation of emission patterns from 1990 to 2020. The extrapolation is based on a linear regression model with moving-average (ARMA) errors (see Box 6-4 of the Methodology section in Cropland Remaining Cropland). Linear extrapolation is a standard data splicing method for estimating emissions at the end of a time series (IPCC 2006). As with the Tier 3 method, time series of activity data will be updated in a future *Inventory*, and emissions from 2021 to 2022 will be recalculated.

Additional Mineral Carbon Stock Change Calculations

A Tier 2 method is used to adjust annual carbon stock change estimates for mineral soils between 1990 and 2022 to account for additional carbon stock changes associated with biosolids (i.e., treated sewage sludge) amendments. Estimates of the amounts of biosolids nitrogen applied to agricultural land are derived from national data on biosolids generation, disposition, and nitrogen content (see Section 7.2 for a detailed discussion of the methodology for estimating treated sewage sludge available for land application application). Although biosolids can be added to land managed for other land uses, it is assumed that agricultural amendments only occur in grassland remaining grassland. Total biosolids generation data for 1988, 1996, and 1998, in dry mass units, are

obtained from EPA (1999) and estimates for 2004 are obtained from an independent national biosolids survey (NEBRA 2007). These values are linearly interpolated to estimate values for the intervening years, and linearly extrapolated to estimate values for years since 2004. Nitrogen application rates from Kellogg et al. (2000) are used to determine the amount of area receiving biosolids amendments. The soil organic carbon storage rate is estimated at 0.38 metric tons carbon per hectare per year for biosolids amendments to grassland as described above. The stock change rate is based on country-specific factors and the IPCC default method (see Annex 3.12 for further discussion).

Soil Carbon Stock Changes for Organic Soils

Annual carbon emissions from drained organic soils in grassland remaining grassland are estimated using the Tier 2 method in IPCC (2006), which utilizes country-specific carbon loss rates (Ogle et al. 2003) rather than default IPCC rates. For more information, see the cropland remaining cropland section for organic soils and Annex 3.12.

In order to ensure time-series consistency, the Tier 2 methods are applied from 1990 to 2020 so that changes reflect anthropogenic activity and not methodological adjustments. In addition, soil organic carbon stock changes for the remainder of the time series (i.e., 2021 to 2022) are approximated with a linear extrapolation of emission patterns from 1990 to 2020. The extrapolation is based on a linear regression model with moving-average (ARMA) errors (see Box 6-4 of the Methodology section in cropland remaining cropland). Linear extrapolation is a standard data splicing method for approximating emissions at the end of a time series (IPCC 2006). Estimates for 2021 to 2022 will be recalculated in future *Inventories* with an updated time series of activity data.

Uncertainty

The uncertainty analysis for biomass, dead wood and litter carbon losses with woodlands is conducted in the same way as the uncertainty assessment for forest ecosystem carbon flux associated with forest land remaining forest land. Sample and model-based error are combined using simple error propagation methods provided by the IPCC (2006) by taking the square root of the sum of the squares of the standard deviations of the uncertain quantities. For additional details, see the Uncertainty Analysis in Annex 3.13.

Uncertainty analysis for soil organic carbon stock changes using the Tier 3 and Tier 2 methodologies are quantified from two variance components (Ogle et al. 2010), as described in Cropland Remaining Cropland. For 2021 to 2022, there is additional uncertainty propagated through the Monte Carlo analysis associated with the surrogate data method.

Uncertainty estimates are presented in Table 6-45 for each subcategory (i.e., soil organic carbon stocks for mineral and organic soils) and the method applied in the *Inventory* analysis (i.e., Tier 2 and Tier 3). Uncertainty estimates from the Tier 2 and 3 approaches are combined using the simple error propagation methods provided by the IPCC (2006), i.e., by taking the square root of the sum of the squares of the standard deviations of the uncertain quantities. The combined uncertainty for total carbon stock changes in grassland remaining grassland ranges from more than 926 percent below and above the 2022 stock change estimate of 13.4 MMT CO_2 Eq. The large relative uncertainty in the 2022 estimate is mostly due to variation in soil organic carbon stock changes that is not explained by the surrogate data method, leading to high prediction error with this data splicing method.

Table 6-45: Approach 2 Quantitative Uncertainty Estimates for Carbon Stock Changes Occurring Within Grassland Remaining Grassland (MMT CO_2 Eq. and Percent)

Source	2022 Flux Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Flux Estimate[a] (MMT CO_2 Eq.)		(%)	
		Lower Bound	Upper Bound	Lower Bound	Upper Bound
Woodland Biomass:					
Aboveground live biomass	(1.3)	(1.5)	(1.2)	-10%	12%
Belowground live biomass	(0.2)	(0.3)	(0.2)	-8%	8%
Dead wood	2.8	2.5	3.2	-13%	14%
Litter	+	+	0.1	-22%	22%
Mineral Soil C Stocks Grassland Remaining Grassland, Tier 3 Methodology	7.4	(116.1)	131.0	-1,663%	1,663%
Mineral Soil C Stocks: Grassland Remaining Grassland, Tier 2 Methodology	0.1	(0.4)	0.6	-448%	448%
Mineral Soil C Stocks: Grassland Remaining Grassland, Tier 2 Methodology (Change in Soil C due to Biosolids [i.e., Treated Sewage Sludge] Amendments)	(1.0)	(1.5)	(0.5)	-50%	50%
Organic Soil C Stocks: Grassland Remaining Grassland, Tier 2 Methodology	5.5	1.2	9.9	-79%	79%
Combined Uncertainty for Flux Associated with Carbon Stock Changes Occurring in Grassland Remaining Grassland	**13.4**	**(110.3)**	**137.0**	**-926%**	**926%**

+ Does not exceed 0.05 MMT CO_2 Eq.

[a] Range of C stock change estimates is a 95 percent confidence interval.

Notes: Totals may not sum due to independent rounding. Parentheses indicate negative values or net sequestration.

Uncertainty is also associated with a lack of reporting on biomass, dead wood and litter carbon stock changes for agroforestry systems. Changes in biomass and dead organic matter carbon stocks are assumed to be negligible in other grasslands, largely comprised of herbaceous biomass, although there are significant changes at sub-annual time scales across seasons.

QA/QC and Verification

See the QA/QC and Verification section in Cropland Remaining Cropland.

Recalculations Discussion

Several improvements have been implemented in this *Inventory* leading to recalculations. These improvements included a) incorporating new USDA-NRCS NRI data through 2017; b) updated FIA data from 1990 to 2022 on biomass, dead wood and litter carbon stocks in woodlands for grassland remaining grassland; c) constraining manure N applications in the Tier 3 method at the state scale rather than the national scale; and d) re-calibrating the soil carbon module in the DayCent model using Bayesian methods. See the Recalculations Discussion in the cropland remaining cropland section for other improvements. As a result of these improvements, grassland remaining grassland has a larger average loss of 10.7 MMT CO_2 Eq. across the time series compared to the previous *Inventory*, which is an 1,850 percent change on average over the time series. The large average value for the percentage change is due to an increase from near zero to 7.0 MMT CO_2 Eq. for the estimated carbon stock change in 1994.

Planned Improvements

A key improvement planned for the *Inventory* includes conducting an analysis of carbon stock changes for grasslands in Alaska. This improvement will be a significant development that will resolve the majority of the discrepancy between the managed land base for grassland remaining grassland and amount of area currently included in grassland remaining grassland emissions and removals calculations (see Table 6-46).

Table 6-46: Comparison of Managed Land Area in Grassland Remaining Grassland and the Area in the current Grassland Remaining Grassland Inventory (Thousand Hectares)

	Area (Thousand Hectares)		
Year	Managed Land	*Inventory*	Difference
1990	328,565	279,705	48,861
1991	328,058	279,205	48,853
1992	327,601	278,755	48,846
1993	325,869	277,030	48,839
1994	324,249	275,418	48,831
1995	323,373	274,549	48,824
1996	322,517	273,701	48,816
1997	321,752	272,944	48,808
1998	319,811	271,010	48,801
1999	318,903	270,110	48,793
2000	317,917	269,131	48,785
2001	317,060	268,282	48,778
2002	316,443	267,883	48,560
2003	316,545	268,206	48,340
2004	316,350	268,232	48,118
2005	315,930	268,034	47,897
2006	315,422	267,748	47,675
2007	315,164	267,712	47,452
2008	315,090	267,861	47,228
2009	315,163	268,159	47,005
2010	314,765	267,984	46,781
2011	314,270	267,712	46,557
2012	313,977	267,586	46,391
2013	314,640	268,416	46,224
2014	315,329	269,271	46,058
2015	315,427	269,535	45,891
2016	315,327	269,602	45,725
2017	316,056	270,339	45,717
2018	318,959	273,168	45,791
2019	320,255	274,471	45,784
2020	320,855	275,079	45,777
2021	321,909	*	*
2022	322,779	*	*

Activity data on land use have not been incorporated into the *Inventory* after 2020, designated with asterisks (*).

Additionally, a review of available data on biosolids (i.e., treated sewage sludge) application will be undertaken to improve the distribution of biosolids application on croplands, grasslands and settlements. For information about

other improvements, see the Planned Improvements section in Cropland Remaining Cropland.

Non-CO_2 Emissions from Grassland Fires (CRT Source Category 4C1)

Fires are common in grasslands and are thought to have been a key feature shaping the evolution of the grassland vegetation in North America (Daubenmire 1968; Anderson 2004). Fires can occur naturally through lightning strikes but are also an important management practice to remove standing dead vegetation and improve forage for grazing livestock. Woody and herbaceous biomass will be oxidized in a fire, although in this section the current focus is primarily on herbaceous biomass.[53] Biomass burning emits a variety of trace gases including non-CO_2 greenhouse gases such as CH_4 and N_2O, as well as CO and NO_x that can become greenhouse gases when they react with other gases in the atmosphere (Andreae and Merlet 2001). IPCC (2006) recommends reporting non-CO_2 greenhouse gas emissions from all wildfires and prescribed burning occurring in managed grasslands.

Biomass burning in grasslands of the United States (including burning emissions in grassland remaining grassland and land converted to grassland) is a relatively small source of emissions, but it has increased by 184 percent since 1990. In 2022, CH_4 and N_2O emissions from biomass burning in grasslands were 0.3 MMT CO_2 Eq. (12 kt) and 0.3 MMT CO_2 Eq. (1 kt), respectively. Annual emissions from 1990 to 2022 have averaged approximately 0.4 MMT CO_2 Eq. (14 kt) of CH_4 and 0.3 MMT CO_2 Eq. (1 kt) of N_2O (see Table 6-47 and Table 6-48).

Table 6-47: CH_4 and N_2O Emissions from Biomass Burning in Grassland (MMT CO_2 Eq.)

	1990	2005	2018	2019	2020	2021	2022
CH_4	0.1	0.4	0.6	0.2	0.6	0.5	0.3
N_2O	0.1	0.4	0.5	0.2	0.5	0.4	0.3
Total Net Flux	**0.2**	**0.8**	**1.1**	**0.3**	**1.1**	**0.9**	**0.6**

Note: Totals may not sum due to independent rounding.

Table 6-48: CH_4, N_2O, CO, and NO_x Emissions from Biomass Burning in Grassland (kt)

	1990	2005	2018	2019	2020	2021	2022
CH_4	4	15	22	6	20	18	12
N_2O	+	1	2	1	2	2	1
CO	122	430	610	170	575	509	346
NO_x	7	26	37	10	35	31	21

+ Does not exceed 0.5 kt.

Methodology and Time-Series Consistency

The following section includes a description of the methodology used to estimate non-CO_2 greenhouse gas emissions from biomass burning in grassland, including (1) determination of the land base that is classified as managed grassland; (2) assessment of managed grassland area that is burned each year, and (3) estimation of emissions resulting from the fires. For this *Inventory*, the IPCC Tier 1 method is applied to estimate non-CO_2 greenhouse gas emissions from biomass burning in grassland from 1990 to 2020 (IPCC 2006). A data splicing method is used to estimate the emissions from 2021 to 2022, which is discussed later in this section.

The land area designated as managed grassland is based primarily on the USDA National Resources Inventory (NRI) (Nusser and Goebel 1997; USDA-NRCS 2020). NRI has survey locations across the entire United States, but does not

[53] A planned improvement is underway to incorporate woodland tree biomass into the *Inventory* for non-CO_2 emissions from grassland fires.

classify land use on federally-owned areas, and so survey locations on federal lands are designated as grassland using land cover data from the National Land Cover Dataset (NLCD) (Fry et al. 2011; Homer et al. 2007; Homer et al. 2015) (see Section 6.1).

The area of biomass burning in grasslands (grassland remaining grassland and land converted to grassland) is determined using 30-m burned area data from the Monitoring Trends in Burn Severity (MTBS) program for 1990 through 2020 (MTBS 2023; Picotte, et al. 2020).[54] NRI survey locations on grasslands are designated as burned in a year if there is a fire within 500 m of the survey point according to the MTBS fire data. The area of biomass burning is estimated from the NRI spatial weights and aggregated to the country (Table 6-49).

Table 6-49: Thousands of Grassland Hectares Burned Annually

Year	1990	2005	2018	2019	2020	2021	2022
Thousand Hectares	457	1,612	2,290	637	2156	NE	NE

NE (Not Estimated)

Notes: Burned area was not estimated (NE) for 2021 to 2022, but will be updated in a future *Inventory*.

For 1990 to 2020, the total area of grassland burned is multiplied by the IPCC default factor for grassland biomass (4.1 tonnes dry matter per ha) (IPCC 2006) to estimate the amount of combusted biomass. A combustion factor of 1 is assumed in this *Inventory*, and the resulting biomass estimate is multiplied by the IPCC default grassland emission factors for CH_4 (2.3 g CH_4 per kg dry matter), N_2O (0.21 g N_2O per kg dry matter), CO (65 g CO per kg dry matter) and NO_x (3.9 g NO_x per kg dry matter) (IPCC 2006).

A linear extrapolation of the trend in the time series is applied to estimate emissions for 2021 to 2022. Specifically, a linear regression model with autoregressive moving-average (ARMA) errors (Brockwell and Davis 2016) is used to derive the trend in emissions over time from 1990 to 2020, and the trend is used to approximate the 2021 to 2022 emissions. The Tier 1 method described previously will be applied to recalculate the 2021 to 2022 emissions in a future *Inventory*.

The same methods are applied from 1990 to 2020, and a data splicing method is used to extend the time series from 2021 to 2022 ensuring a consistent time series of emissions data. The trend extrapolation is a standard data splicing method for estimating emissions at the end of a time series if activity data are not available (IPCC 2006).

Uncertainty

Emissions are estimated using a linear regression model with ARMA errors for 2021 to 2022. The model produces estimates for the upper and lower bounds of the emission estimate and the results are summarized in Table 6-50. Methane emissions from biomass burning in grassland for 2022 are estimated to be between approximately 0.0 and 0.8 MMT CO_2 Eq. at a 95 percent confidence level. This indicates a range of 100 percent below and 137 percent above the 2022 emission estimate of 0.3 MMT CO_2 Eq. Nitrous oxide emissions are estimated to be between approximately 0.0 and 0.7 MMT CO_2 Eq., or 100 percent below and 137 percent above the 2022 emission estimate of 0.3 MMT CO_2 Eq.

[54] See http://www.mtbs.gov.

Table 6-50: Uncertainty Estimates for Non-CO_2 Greenhouse Gas Emissions from Biomass Burning in Grassland (MMT CO_2 Eq. and Percent)

Source	Gas	2022 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Grassland Burning	CH_4	0.3	+	0.8	-100%	+137%
Grassland Burning	N_2O	0.3	+	0.7	-100%	+137%

+ Does not exceed 0.05 MMT CO_2 Eq.

[a] Range of emission estimates predicted by linear regression time-series model for a 95 percent confidence interval.

Uncertainty is also associated with lack of reporting of emissions from biomass burning in grasslands of Alaska. Grassland burning emissions could be relatively large in this region of the United States, and therefore extending this analysis to include Alaska is a planned improvement for the *Inventory*. There is also uncertainty due to lack of reporting on the combustion of woody biomass, and this is another planned improvement.

QA/QC and Verification

Quality control measures included checking input data, model scripts, and results to ensure data are properly handled throughout the inventory process consistent with the U.S. *Inventory* QA/QC plan, which is in accordance with Volume 1, Chapter 6 of the *2006 IPCC Guidelines* (see Annex 8 for more details). Inventory reporting forms and text are reviewed and revised as needed to correct transcription errors.

Recalculations Discussion

While the methods for calculating non-CO_2 emissions from grassland burning remained the same, the two primary data sources have been updated from the previous *Inventory*. We used the current NRI 2017 dataset (USDA-NRCS 2020) and the current release of MTBS burn perimeter data (MTBS 2023). In the original estimation of non-CO_2 emissions, the same set of NRI survey locations was used for the entire time series, but the locations identified with burning were allowed to vary inter-annually with this revision. These changes resulted in a net increase in CO_2-equivalent emissions by an annual average of 0.1 MMT CO_2 Eq., or 19 percent from 1990 to 2021 compared to the previous *Inventory*.

Planned Improvements

Two key planned improvements have been identified for this source category, including 1) incorporation of country-specific grassland biomass factors, and 2) extending the analysis to include Alaska. In the current *Inventory*, biomass factors are based on a global default for grasslands that is provided by the IPCC (2006). There is considerable variation in grassland biomass, however, which would affect the amount of fuel available for combustion in a fire. Alaska has an extensive area of grassland and includes tundra vegetation, although some of the areas are not managed. There has been an increase in fire frequency in boreal forest of the region (Chapin et al. 2008), and this may have led to an increase in burning of neighboring grassland areas. There is also an effort under development to incorporate grassland fires into DayCent model simulations. Lastly, a future *Inventory* will incorporate non-CO_2 greenhouse emissions from burning woodland tree biomass in grasslands. These improvements are expected to reduce uncertainty and produce more accurate estimates of non-CO_2 greenhouse gas emissions from grassland burning.

6.7 Land Converted to Grassland (CRT Category 4C2)

Land converted to grassland includes all current grassland in an inventory year that had been in another land use(s) during the previous 20 years (IPCC 2006).[55] For example, cropland or forest land converted to grassland during the past 20 years would be reported in this category. Recently converted lands are retained in this category for 20 years as recommended by IPCC (2006). Grassland includes pasture and rangeland that are used primarily but not exclusively for livestock grazing. Rangelands are typically extensive areas of native grassland that are not intensively managed, while pastures are typically seeded grassland (possibly following tree removal) that may also have additional management, such as irrigation or interseeding of legumes.

Land use change can lead to large losses of carbon to the atmosphere, particularly conversions from forest land (Houghton et al. 1983, Houghton and Nassikas 2017). Moreover, conversion of forest to another land use (i.e., deforestation) is one of the largest anthropogenic sources of emissions to the atmosphere globally, although this source may be declining according to a recent assessment (Tubiello et al. 2015).

IPCC (2006) recommends reporting changes in biomass, dead organic matter, and soil organic carbon stocks due to land use change. All soil organic carbon stock changes are estimated and reported for land converted to grassland, but there is limited reporting of other pools in this *Inventory*. Losses of aboveground and belowground biomass, dead wood and litter carbon from forest land converted to grassland are reported, as well as gains and losses associated with conversions to woodlands[56] from other land uses, including croplands converted to grasslands, settlements converted to grasslands and other lands converted to grasslands. However, the current *Inventory* does not include the gains and losses in aboveground and belowground biomass, dead wood and litter carbon for other land use conversions to grassland that are not woodlands.[57]

There is a discrepancy between the current land representation (see Section 6.1) and the area data that have been used in the inventory for land converted to grassland. Specifically, grassland in Alaska is not included in the *Inventory*, and this leads to a difference between the managed area in land converted to grassland in the land representation and the grassland area included in the emissions and removal calculations for land converted to grassland (Table 6-54). Improvements are underway to incorporate grassland area in Alaska as part of future *Inventories* (see Planned Improvements section).

The largest carbon losses with land converted to grassland are associated with aboveground biomass, belowground biomass, and litter carbon losses from forest land converted to grassland (see Table 6-51 and Table 6-52). These three pools led to net emissions in 2022 of 31.3, 4.3, and 8.0 MMT CO_2 Eq. (8.5, 1.2, and 2.2 MMT C), respectively. The losses associated with forest land converted to grassland are partially offset by gains associated with other land converted to grassland and due to cropland converted to grassland, which leads to less intensive management of the soil. Drainage of organic soils for grassland management led to CO_2 emissions to the atmosphere of 1.4 MMT CO_2 Eq. (0.4 MMT C). The total net carbon stock change in 2022 for land converted to

[55] USDA NRI survey locations are classified according to land use histories starting in 1979, and consequently the classifications are based on less than 20 years from 1990 to 2001. This may have led to an underestimation of land converted to grassland in the early part of the time series to the extent that some areas are converted to grassland between 1971 and 1978.

[56] Woodlands are considered grasslands in the U.S. land representation because they do not meet the definition of forest land.

[57] Changes in biomass carbon stocks are not currently reported for other conversions to grassland (other than forest land conversion to grassland and other land-use conversions to woodlands), but this is a planned improvement for a future Inventory. Note: changes in dead organic matter are assumed negligible for other land use conversions (i.e., other than forest land) to grassland based on the Tier 1 method in IPCC (2006).

grassland is estimated as a loss of 25.6 MMT CO_2 Eq. (7.0 MMT C) or a net source of emissions, which represents a decrease in carbon stock loss by 27 percent compared to the initial reporting year of 1990.

Table 6-51: Net CO_2 Flux from Soil, Dead Organic Matter and Biomass Carbon Stock Changes for Land Converted to Grassland (MMT CO_2 Eq.)

	1990	2005	2018	2019	2020	2021	2022
Cropland Converted to Grassland	**(10.2)**	**(16.9)**	**(10.8)**	**(10.3)**	**(9.3)**	**(13.6)**	**(12.5)**
Aboveground Live Biomass	(0.2)	(0.1)	(0.1)	(0.1)	(0.1)	(0.1)	(0.1)
Belowground Live Biomass	+	+	+	+	+	+	+
Dead Wood	(0.1)	(0.1)	+	+	+	+	+
Litter	(0.1)	(0.1)	+	+	+	+	+
Mineral Soils	(10.4)	(18.1)	(11.7)	(11.1)	(10.1)	(14.4)	(13.3)
Organic Soils	0.6	1.4	1.1	1.1	1.0	1.0	1.0
Forest Land Converted to Grassland	**50.2**	**49.0**	**46.9**	**46.9**	**46.8**	**46.8**	**46.8**
Aboveground Live Biomass	34.5	33.4	31.8	31.8	31.8	31.8	31.8
Belowground Live Biomass	4.8	4.6	4.4	4.4	4.4	4.4	4.4
Dead Wood	2.4	2.4	2.4	2.4	2.4	2.4	2.4
Litter	8.6	8.5	8.2	8.2	8.2	8.2	8.2
Mineral Soils	(0.1)	(0.1)	(0.1)	(0.1)	(0.1)	(0.1)	(0.1)
Organic Soils	+	0.1	0.1	0.1	0.1	0.1	0.1
Other Lands Converted to Grassland	**(4.0)**	**(9.6)**	**(10.2)**	**(10.5)**	**(8.2)**	**(8.0)**	**(8.0)**
Aboveground Live Biomass	(0.1)	(0.1)	(0.1)	(0.1)	(0.1)	(0.1)	(0.1)
Belowground Live Biomass	+	+	+	+	+	+	+
Dead Wood	+	+	+	+	+	+	+
Litter	(0.1)	(0.1)	(0.1)	(0.1)	(0.1)	(0.1)	(0.1)
Mineral Soils	(3.8)	(9.4)	(10.1)	(10.4)	(8.1)	(7.9)	(7.9)
Organic Soils	+	+	0.1	0.1	0.1	0.1	0.1
Settlements Converted to Grassland	**(0.6)**	**(0.7)**	**(0.8)**	**(0.8)**	**(0.8)**	**(0.8)**	**(0.8)**
Aboveground Live Biomass	(0.2)	(0.2)	(0.2)	(0.2)	(0.2)	(0.2)	(0.2)
Belowground Live Biomass	+	+	+	+	+	+	+
Dead Wood	(0.1)	(0.1)	+	+	+	+	+
Litter	(0.1)	(0.1)	(0.1)	(0.1)	(0.1)	(0.1)	(0.1)
Mineral Soils	(0.1)	(0.3)	(0.5)	(0.5)	(0.4)	(0.4)	(0.4)
Organic Soils	+	+	+	+	+	+	+
Wetlands Converted to Grassland	**(0.1)**	**+**	**0.1**	**0.1**	**0.1**	**0.1**	**0.1**
Aboveground Live Biomass	(0.1)	(0.1)	(0.1)	(0.1)	(0.1)	(0.1)	(0.1)
Belowground Live Biomass	+	+	+	+	+	+	+
Dead Wood	+	+	+	+	+	+	+
Litter	+	+	+	+	+	+	+
Mineral Soils	+	+	+	+	+	+	+
Organic Soils	0.1	0.2	0.2	0.2	0.2	0.2	0.2
Aboveground Live Biomass	**33.9**	**32.9**	**31.4**	**31.4**	**31.3**	**31.3**	**31.3**
Belowground Live Biomass	**4.7**	**4.5**	**4.4**	**4.3**	**4.3**	**4.3**	**4.3**
Dead Wood	**2.2**	**2.3**	**2.3**	**2.3**	**2.3**	**2.3**	**2.3**
Litter	**8.4**	**8.2**	**8.0**	**8.0**	**8.0**	**8.0**	**8.0**
Total Mineral Soil Flux	**(14.6)**	**(27.9)**	**(22.4)**	**(22.1)**	**(18.7)**	**(22.8)**	**(21.7)**
Total Organic Soil Flux	**0.7**	**1.8**	**1.5**	**1.5**	**1.4**	**1.4**	**1.4**
Total Net Flux	**35.3**	**21.8**	**25.2**	**25.4**	**28.7**	**24.5**	**25.6**

+ Does not exceed 0.05 MMT CO_2 Eq.

Notes: Totals may not sum due to independent rounding. Parentheses indicate negative values or net sequestration.

Table 6-52: Net CO_2 Flux from Soil, Dead Organic Matter and Biomass Carbon Stock Changes for Land Converted to Grassland (MMT C)

	1990	2005	2018	2019	2020	2021	2022
Cropland Converted to Grassland	**(2.8)**	**(4.6)**	**(3.0)**	**(2.8)**	**(2.5)**	**(3.7)**	**(3.4)**
Aboveground Live Biomass	+	+	+	+	+	+	+
Belowground Live Biomass	+	+	+	+	+	+	+
Dead Wood	+	+	+	+	+	+	+
Litter	+	+	+	+	+	+	+
Mineral Soils	(2.8)	(4.9)	(3.2)	(3.0)	(2.8)	(3.9)	(3.6)
Organic Soils	0.2	0.4	0.3	0.3	0.3	0.3	0.3
Forest Land Converted to Grassland	**13.7**	**13.3**	**12.8**	**12.8**	**12.8**	**12.8**	**12.8**
Aboveground Live Biomass	9.4	9.1	8.7	8.7	8.7	8.7	8.7
Belowground Live Biomass	1.3	1.3	1.2	1.2	1.2	1.2	1.2
Dead Wood	0.7	0.7	0.7	0.7	0.7	0.7	0.7
Litter	2.4	2.3	2.2	2.2	2.2	2.2	2.2
Mineral Soils	+	+	+	+	+	+	+
Organic Soils	+	+	+	+	+	+	+
Other Lands Converted to Grassland	**(1.1)**	**(2.6)**	**(2.8)**	**(2.9)**	**(2.2)**	**(2.2)**	**(2.2)**
Aboveground Live Biomass	+	+	+	+	+	+	+
Belowground Live Biomass	+	+	+	+	+	+	+
Dead Wood	+	+	+	+	+	+	+
Litter	+	+	+	+	+	+	+
Mineral Soils	(1.0)	(2.6)	(2.8)	(2.8)	(2.2)	(2.2)	(2.2)
Organic Soils	+	+	+	+	+	+	+
Settlements Converted to Grassland	**(0.2)**	**(0.2)**	**(0.2)**	**(0.2)**	**(0.2)**	**(0.2)**	**(0.2)**
Aboveground Live Biomass	(0.1)	(0.1)	(0.1)	(0.1)	(0.1)	(0.1)	(0.1)
Belowground Live Biomass	+	+	+	+	+	+	+
Dead Wood	+	+	+	+	+	+	+
Litter	+	+	+	+	+	+	+
Mineral Soils	+	(0.1)	(0.1)	(0.1)	(0.1)	(0.1)	(0.1)
Organic Soils	+	+	+	+	+	+	+
Wetlands Converted to Grassland	**+**	**+**	**+**	**+**	**+**	**+**	**+**
Aboveground Live Biomass	+	+	+	+	+	+	+
Belowground Live Biomass	+	+	+	+	+	+	+
Dead Wood	+	+	+	+	+	+	+
Litter	+	+	+	+	+	+	+
Mineral Soils	+	+	+	+	+	+	+
Organic Soils	+	0.1	0.1	0.1	0.1	0.1	0.1
Aboveground Live Biomass	**9.2**	**9.0**	**8.6**	**8.6**	**8.5**	**8.5**	**8.5**
Belowground Live Biomass	**1.3**	**1.2**	**1.2**	**1.2**	**1.2**	**1.2**	**1.2**
Dead Wood	**0.6**	**0.6**	**0.6**	**0.6**	**0.6**	**0.6**	**0.6**
Litter	**2.3**	**2.2**	**2.2**	**2.2**	**2.2**	**2.2**	**2.2**
Total Mineral Soil Flux	**(4.0)**	**(7.6)**	**(6.1)**	**(6.0)**	**(5.1)**	**(6.2)**	**(5.9)**
Total Organic Soil Flux	**0.2**	**0.5**	**0.4**	**0.4**	**0.4**	**0.4**	**0.4**
Total Net Flux	**9.6**	**5.9**	**6.9**	**6.9**	**7.8**	**6.7**	**7.0**

+ Does not exceed 0.05 MMT C.

Notes: Totals may not sum due to independent rounding. Parentheses indicate negative values or net sequestration.

Methodology and Time-Series Consistency

The following section includes a description of the methodology used to estimate carbon stock changes for land converted to grassland, including (1) loss of aboveground and belowground biomass, dead wood and litter carbon with forest land converted to grassland and other land use conversions to woodlands, as well as (2) the impact from all land use conversions to grassland on mineral and organic soil organic carbon stocks.

Biomass, Dead Wood, and Litter Carbon Stock Changes

A Tier 3 method is applied to estimate biomass, dead wood and litter carbon stock changes for forest land converted to grassland. Estimates are calculated in the same way as those in the forest land remaining forest land category using data from the USDA Forest Service, Forest Inventory and Analysis (FIA) program (USDA Forest Service 2023) and in the Eastern US, IPCC (2006) defaults for biomass in grasslands. There is limited data on grassland carbon stocks so only default biomass estimates (IPCC 2006) for grasslands were used to estimate carbon stock changes (litter and dead wood carbon stocks were assumed to be zero since no reference carbon density estimates exist for croplands) in the eastern United States. The difference between the stocks is reported as the stock change under the assumption that the change occurred in the year of the conversion.

The amount of biomass carbon that is lost abruptly with forest land converted to grasslands is estimated based on the amount of carbon before conversion and the amount of carbon following conversion according to remeasurements in the FIA program. This approach is consistent with IPCC (2006) that assumes there is an abrupt change during the first year, but does not necessarily capture the slower change over the years following conversion until a new steady state is reached. It was determined that using an IPCC Tier 1 approach that assumes all carbon is lost in the year of conversion for forest land converted to grasslands in the West and Great Plains states does not accurately characterize the transfer of carbon in woody biomass during abrupt or gradual land use change. To estimate this transfer of carbon in woody biomass, state-specific carbon densities for woody biomass remaining on these former forest lands following conversion to grasslands were developed and included in the estimation of carbon stock changes from forest land converted to grasslands in the West and Great Plains states. A review of the literature in grassland and rangeland ecosystems (Asner et al. 2003; Huang et al. 2009; Tarhouni et al. 2016), as well as an analysis of FIA data, suggests that a conservative estimate of 50 percent of the woody biomass carbon density was lost during conversion from forest land to grasslands. This estimate was used to develop state-specific carbon density estimates for biomass, dead wood, and litter for grasslands in the West and Great Plains states, and these state-specific carbon densities were applied in the compilation system to estimate the carbon losses associated with conversion from forest land to grassland in the West and Great Plains states. Further, losses from forest land to what are often characterized as woodlands are included in this category using FIA plot remeasurements and the methods and models briefly described below and in detail in Domke et al. (2022) and Westfall et al. (2023).

If FIA plots include data on individual trees, aboveground and belowground carbon density estimates are based on Woodall et al. (2011) and Westfall et al. (2023). Aboveground and belowground biomass estimates also include live understory which is a minor component of biomass defined as all biomass of undergrowth plants in a forest, including woody shrubs and trees less than 2.54 cm dbh. For this *Inventory*, it was assumed that 10 percent of total understory carbon mass is belowground (Smith et al. 2006). Estimates of carbon density are based on information in Birdsey (1996) and biomass estimates from Jenkins et al. (2003). If FIA plots include data on standing dead trees, standing dead tree carbon density is estimated following the basic method applied to live trees (Woodall et al. 2011, Westfall et al. 2023) with additional modifications to woodland species to account for decay and structural loss (Domke et al. 2011; Harmon et al. 2011).

If FIA plots include data on downed dead wood, downed dead wood carbon density is estimated based on measurements of a subset of FIA plots for downed dead wood (Domke et al. 2013; Woodall and Monleon 2008). Downed dead wood is defined as pieces of dead wood greater than 7.5 cm diameter, at transect intersection, that are not attached to live or standing dead trees. This includes stumps and roots of harvested trees. To facilitate the downscaling of downed dead wood carbon estimates from the state-wide population estimates to individual plots, downed dead wood models specific to regions and forest types within each region are used. Litter carbon is the pool of organic carbon (also known as duff, humus, and fine woody debris) above the mineral soil and includes woody fragments with diameters of up to 7.5 cm. A subset of FIA plots are measured for litter carbon. If FIA plots include litter material, a modeling approach using litter carbon measurements from FIA plots is used to estimate litter carbon density (Domke et al. 2016). See Annex 3.13 for more information about reference carbon density estimates for forest land.

Soil Carbon Stock Changes

Soil organic carbon stock changes are estimated for land converted to grassland according to land use histories recorded in the 2017 USDA NRI survey for non-federal lands (USDA-NRCS 2020). Land use and some management information (e.g., crop type, soil attributes, and irrigation) were originally collected for each NRI survey location on a five-year cycle beginning in 1982. In 1998, the NRI Program began collecting annual data, and the annual data are currently available through 2017 (USDA-NRCS 2020). For 2018 through 2020, the time series is extended with the crop data provided in USDA-NASS CDL (USDA-NASS 2021), while survey locations identified as grasslands are assumed to not change over this time period. However, the areas have been modified in the original NRI survey through a process in which the Forest Inventory and Analysis (FIA) survey data and the National Land Cover Dataset (NLCD; Yang et al. 2018) are harmonized with the NRI data. This process ensures that the land use areas are consistent across all land use categories (see Section 6.1 for more information).

NRI survey locations are classified as land converted to grassland in a given year between 1990 and 2020 if the land use is grassland but had been classified as another use during the previous 20 years. NRI survey locations are classified according to land use histories starting in 1979, and consequently the classifications are based on less than 20 years from 1990 to 1998. This may have led to an underestimation of land converted to grassland in the early part of the time series to the extent that some areas are converted to grassland between 1971 and 1978. For federal lands, the land use history is derived from land cover changes in the NLCD (Yang et al. 2018; Homer et al. 2007; Fry et al. 2011; Homer et al. 2015).

Soil Carbon Stock Changes for Mineral Soils

An IPCC Tier 3 model-based approach (Ogle et al. 2010) is applied to estimate carbon stock changes in mineral soils for most of the area in land converted to grassland. Carbon stock changes on the remaining area are estimated with an IPCC Tier 2 approach (Ogle et al. 2003), including prior cropland used to produce vegetables, tobacco, and perennial/horticultural crops; land areas with very gravelly, cobbly, or shaley soils (greater than 35 percent by volume); and land converted to grassland from another land use other than cropland.

A surrogate data method is used to estimate soil organic carbon stock changes from 2021 to 2022 at the national scale for land areas included in the Tier 2 and Tier 3 methods. Specifically, linear regression models with autoregressive moving-average (ARMA) errors (Brockwell and Davis 2016) are used to estimate the relationship between surrogate data and the 1990 to 2020 emissions data that are derived using the Tier 2 and 3 methods. Surrogate data for these regression models includes weather data from the PRISM Climate Group (PRISM Climate Group 2022). See Box 6-4 in the Methodology section of cropland remaining cropland for more information about the surrogate data method.

Tier 3 Approach. Mineral soil organic carbon stocks and stock changes are estimated using the DayCent ecosystem model (Parton et al. 1998; Del Grosso et al. 2001, 2011). The DayCent model utilizes the soil carbon modeling framework developed in the Century model (Parton et al. 1987, 1988, 1994; Metherell et al. 1993), but has been refined to simulate dynamics at a daily time-step. Historical land use patterns and irrigation histories are simulated with DayCent based on the 2017 USDA NRI survey (USDA-NRCS 2018). Carbon stocks and 95 percent confidence intervals are estimated for each year between 1990 and 2020. See the cropland remaining cropland section and Annex 3.12 for additional discussion of the Tier 3 methodology for mineral soils.

In order to ensure time-series consistency, the same methods are applied from 1990 to 2020 so that changes reflect anthropogenic activity and not methodological adjustments. In addition, soil organic carbon stock changes from 2021 to 2022 are approximated using a linear extrapolation of emission patterns from 1990 to 2020. The extrapolation is based on a linear regression model with moving-average (ARMA) errors, described in Box 6-4 of the Methodology section in cropland remaining cropland. Linear extrapolation is a standard data splicing method for estimating emissions at the end of a time series (IPCC 2006). Stock change estimates for 2021 to 2022 will be recalculated in future Inventories with an updated time series of activity data (see the Planned Improvements section in cropland remaining cropland).

Tier 2 Approach. For the mineral soils not included in the Tier 3 analysis, soil organic carbon stock changes are estimated using a Tier 2 Approach, as described in the Tier 2 Approach for mineral soils in grassland remaining grassland and Annex 3.12. In order to ensure time-series consistency, the Tier 2 method is applied from 1990 to 2020 so that changes reflect anthropogenic activity and not methodological adjustments. In addition, soil organic carbon stock changes are approximated for the remainder of the time series with a linear extrapolation of emission patterns from 1990 to 2020. The extrapolation is based on a linear regression model with moving-average (ARMA) (see Box 6-4 of the Methodology section in Cropland Remaining Cropland). Linear extrapolation is a standard data splicing method for estimating emissions at the end of a time series (IPCC 2006). As with the Tier 3 method, stock change estimates for 2021 to 2022 will be recalculated in future Inventories with an updated time series of activity data.

Soil Carbon Stock Changes for Organic Soils

Annual carbon emissions from drained organic soils in land converted to grassland are estimated using the Tier 2 method provided in IPCC (2006), with country-specific carbon loss rates (Ogle et al. 2003) as described in the cropland remaining cropland section. Further elaboration on the methodology is also provided in Annex 3.12 for organic soils.

In order to ensure time-series consistency, the Tier 2 method is applied from 1990 to 2020 so that changes reflect anthropogenic activity and not methodological adjustments. In addition, soil organic carbon stock changes are approximated for the remainder of the time series with a linear extrapolation of emission patterns from 1990 to 2020. The extrapolation is based on a linear regression model with moving-average (ARMA) errors (see Box 6-4 of the Methodology section in Cropland Remaining Cropland). Linear extrapolation is a standard data splicing method for estimating emissions at the end of a time series (IPCC 2006). Annual carbon emissions from drained organic soils from 2021 to 2022 will be recalculated in future *Inventories* with an updated time series of activity data.

Uncertainty

The uncertainty analyses for biomass, dead wood and litter carbon losses with forest land converted to grassland and other land use conversions to woodlands are conducted in the same way as the uncertainty assessment for forest ecosystem carbon flux in the forest land remaining forest land category. Sample and model-based error are combined using simple error propagation methods provided by the IPCC (2006), by taking the square root of the sum of the squares of the standard deviations of the uncertain quantities. For additional details see the Uncertainty Analysis in Annex 3.13.

The uncertainty analyses for soil organic carbon stock changes using the Tier 3 and Tier 2 methodologies are quantified from two variance components (Ogle et al. 2010), as described in cropland remaining cropland. For 2021 to 2022, there is additional uncertainty propagated through the Monte Carlo analysis associated with a surrogate data method, which is also described in the Cropland Remaining Cropland section.

Uncertainty estimates are presented in Table 6-53 for each subsource (i.e., biomass carbon stocks, mineral and organic carbon stocks in soils) and the method applied in the inventory analysis (i.e., Tier 2 and Tier 3). Uncertainty estimates from the Tier 2 and 3 approaches are combined using the simple error propagation methods provided by the IPCC (2006), as discussed in the previous paragraph. The combined uncertainty for total carbon stocks in land converted to grassland ranges from 156 percent below to 156 percent above the 2022 stock change estimate of 25.6 MMT CO_2 Eq. The large relative uncertainty around the 2022 stock change estimate is partly due to large uncertainties in biomass and dead organic matter carbon losses with forest land conversion to grassland, in addition to variation in soil organic carbon stock changes that is not explained by the surrogate data method.

Table 6-53: Approach 2 Quantitative Uncertainty Estimates for Soil, Dead Organic Matter and Biomass Carbon Stock Changes occurring within Land Converted to Grassland (MMT CO_2 Eq. and Percent)

Source	2022 Flux Estimate[a] (MMT CO_2 Eq.)	Uncertainty Range Relative to Flux Estimate[a] (MMT CO_2 Eq.)		Uncertainty Range Relative to Flux Estimate[a] (%)	
		Lower Bound	Upper Bound	Lower Bound	Upper Bound
Cropland Converted to Grassland	**(12.5)**	**(32.1)**	**7.0**	**-156%**	**156%**
Aboveground Live Biomass	(0.1)	(0.3)	+	-136%	134%
Belowground Live Biomass	+	+	+	-78%	100%
Dead Wood	+	(0.1)	+	-128%	100%
Litter	+	(0.1)	+	-170%	100%
Mineral Soil C Stocks: Tier 3	(11.6)	(31.0)	7.8	-167%	167%
Mineral Soil C Stocks: Tier 2	(1.7)	(3.7)	0.2	-114%	114%
Organic Soil C Stocks: Tier 2	1.0	+	2.0	-96%	96%
Forest Land Converted to Grassland	**46.8**	**12.2**	**81.4**	**-74%**	**74%**
Aboveground Live Biomass	31.8	(1.4)	64.9	-104%	104%
Belowground Live Biomass	4.4	(0.2)	9.0	-104%	105%
Dead Wood	2.4	(0.1)	5.0	-105%	104%
Litter	8.2	(0.4)	16.8	-104%	104%
Mineral Soil C Stocks: Tier 2	(0.1)	(0.2)	+	-140%	140%
Organic Soil C Stocks: Tier 2	0.1	(0.0)	0.2	-130%	130%
Other Lands Converted to Grassland	**(8.0)**	**(12.9)**	**(3.1)**	**-61%**	**61%**
Aboveground Live Biomass	(0.1)	(0.1)	+	-69%	44%
Belowground Live Biomass	+	+	+	-100%	100%
Dead Wood	+	(0.1)	+	-85%	100%
Litter	(0.1)	(0.1)	+	-60%	47%
Mineral Soil C Stocks: Tier 2	(7.9)	(12.8)	(3.0)	-62%	62%
Organic Soil C Stocks: Tier 2	0.1	+	0.1	-111%	111%
Settlements Converted to Grassland	**(0.8)**	**(1.0)**	**(0.5)**	**-35%**	**35%**
Aboveground Live Biomass	(0.2)	(0.3)	(0.1)	-56%	61%
Belowground Live Biomass	+	+	+	-42%	100%
Dead Wood	+	(0.1)	+	-67%	100%
Litter	(0.1)	(0.1)	+	-66%	59%
Mineral Soil C Stocks: Tier 2	(0.4)	(0.6)	(0.2)	-56%	56%
Organic Soil C Stocks: Tier 2	+	+	+	-432%	432%
Wetlands Converted to Grasslands	**0.1**	**(0.2)**	**0.3**	**-289%**	**283%**
Aboveground Live Biomass	(0.1)	(0.1)	+	-85%	38%
Belowground Live Biomass	+	+	+	-100%	100%
Dead Wood	+	+	+	-95%	100%
Litter	+	+	+	-112%	100%
Mineral Soil C Stocks: Tier 2	+	+	+	-173%	173%
Organic Soil C Stocks: Tier 2	0.2	+	0.4	-112%	112%
Total: Land Converted to Grassland	**25.6**	**(14.4)**	**65.7**	**-156%**	**156%**
Aboveground Live Biomass	**31.3**	**(1.8)**	**64.5**	**-106%**	**106%**
Belowground Live Biomass	**4.3**	**(0.2)**	**9.0**	**-106%**	**106%**
Dead Wood	**2.3**	**(0.3)**	**4.8**	**-111%**	**111%**
Litter	**8.0**	**(0.6)**	**16.6**	**-107%**	**107%**
Mineral Soil C Stocks: Tier 3	**(11.6)**	**(31.0)**	**7.8**	**-167%**	**167%**
Mineral Soil C Stocks: Tier 2	**(10.1)**	**(15.4)**	**(4.9)**	**-52%**	**52%**

Organic Soil C Stocks: Tier 2	**1.4**	**0.4**	**2.4**	**-74%**	**74%**

+ Absolute value does not exceed 0.05 MMT CO_2 Eq.

[a] Range of C stock change estimates is a 95 percent confidence interval.

Notes: Totals may not sum due to independent rounding. Parentheses indicate negative values or net sequestration.

Uncertainty is also associated with a lack of reporting on biomass, dead wood and litter carbon stock changes for conversions to agroforestry systems and herbaceous grasslands. The influence of agroforestry is difficult to address because there are currently no datasets to evaluate the trends in the area and associated carbon stocks in agroforestry systems. The influence of land use change to herbaceous grasslands and agroforestry will be further explored in a future *Inventory*.

QA/QC and Verification

See the QA/QC and Verification section in Cropland Remaining Cropland for information on QA/QC steps.

Recalculations Discussion

Several improvements have been implemented in this *Inventory* leading to recalculations. These improvements included a) incorporating new USDA-NRCS NRI data through 2017; b) updated FIA data from 1990 to 2022 on biomass, dead wood and litter carbon stocks associated with forest land converted to grassland (see Recalculations Discussion of Chapter 6.2 Forest Land Remaining Forest Land for more details); c) constraining manure nitrogen applications in the Tier 3 method at the state scale rather than the national scale; and d) re-calibrating the soil carbon module in the DayCent model using Bayesian methods. See the Recalculations Discussion in the cropland remaining cropland section for other improvements. Finally, see further updates in Section 6.2, describing updates to the estimates for aboveground volume and biomass which impacted lands converted to grassland estimates. As a result, land converted to grassland has an estimated increase in losses of carbon stock changes, leading to a net change of 53 MMT CO_2 Eq. on average over the time series, representing a 237 percent change on average compared to the previous *Inventory*. Land converted to grassland is a net source of emissions across the time series based on the recalculations in this *Inventory*. This change from a net sink to a net source is mostly due to larger estimated losses of biomass and dead organic matter with forest land converted to grassland, and smaller estimated gains in mineral soil carbon stocks for cropland and other lands converted to grasslands.

Planned Improvements

The key improvement planned for the inventory is conducting an analysis of carbon stock changes for grassland in Alaska. This will resolve the majority of the discrepancy between the managed land base for land converted to grassland and amount of area currently included in land converted to grassland emissions and removals calculations (see Table 6-54).

Table 6-54: Comparison of Managed Land Area in Land Converted to Grassland and Area in the current Land Converted to Grassland Inventory (Thousand Hectares)

	Area (Thousand Hectares)		
Year	**Managed Land**	***Inventory***	**Difference**
1990	9,301	9,297	4
1991	9,492	9,488	4
1992	9,710	9,706	4
1993	11,619	11,615	4
1994	13,372	13,368	4
1995	14,039	14,035	4
1996	14,727	14,723	4

1997	15,411	15,408	4
1998	19,289	19,285	4
1999	20,143	20,139	4
2000	21,257	21,253	4
2001	22,349	22,345	4
2002	23,087	22,817	270
2003	22,986	22,445	541
2004	23,920	23,108	811
2005	24,091	23,009	1,082
2006	24,693	23,341	1,352
2007	24,694	23,072	1,622
2008	25,266	23,373	1,893
2009	25,424	23,260	2,163
2010	25,769	23,336	2,434
2011	26,176	23,471	2,704
2012	26,164	23,292	2,871
2013	25,154	22,116	3,038
2014	23,981	20,776	3,205
2015	24,101	20,730	3,372
2016	23,531	19,993	3,538
2017	22,808	19,270	3,538
2018	19,968	16,429	3,538
2019	19,546	16,008	3,538
2020	18,706	15,168	3,538
2021	17,351	*	*
2022	16,269	*	*

Activity data on land use have not been incorporated into the *Inventory* after 2020, designated with asterisks (*).

In addition, the amount of biomass carbon that is lost abruptly or the slower changes that continue to occur over a decade or longer with forest land converted to grasslands will be further refined in a future *Inventory*. The current values are estimated based on the amount of carbon before conversion and an estimated level of carbon left after conversion based on limited plot data from the FIA and published literature for the Western United States and Great Plains Regions. The amount of carbon left after conversion will be further investigated with additional data collection, particularly in the Western United States and Great Plains, including tree biomass, understory biomass, dead wood and litter carbon pools. In addition, biomass carbon stock changes will be estimated for conversions from other land uses to herbaceous grasslands. For information about other improvements, see the Planned Improvements section in Cropland Remaining Cropland.

6.8 Wetlands Remaining Wetlands (CRT Category 4D1)

Wetlands remaining wetlands includes all wetlands in an inventory year that have been classified as a wetland for the previous 20 years, and in this *Inventory*, the flux estimates include peatlands, coastal wetlands, and flooded land.

Peatlands Remaining Peatlands

Emissions from Managed Peatlands

Managed peatlands are peatlands that have been cleared and drained for the production of peat. The production cycle of a managed peatland has three phases: land conversion in preparation for peat extraction (e.g., clearing surface biomass, draining), extraction (which results in the emissions reported under peatlands remaining peatlands), and abandonment, restoration, rewetting, or conversion of the land to another use.

Carbon dioxide emissions from the removal of biomass and the decay of drained peat constitute the major greenhouse gas flux from managed peatlands. Managed peatlands may also emit CH_4 and N_2O. The natural production of CH_4 is largely reduced but not entirely eliminated when peatlands are drained in preparation for peat extraction (Strack et al. 2004 as cited in the *2006 IPCC Guidelines*). Drained land surface and ditch networks contribute to the CH_4 flux in peatlands managed for peat extraction. Methane emissions were considered insignificant under the IPCC Tier 1 methodology (IPCC 2006), but are included in the emissions estimates for peatlands remaining peatlands consistent with the *2013 Supplement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories: Wetlands* (IPCC 2013). Nitrous oxide emissions from managed peatlands depend on site fertility. In addition, abandoned and restored peatlands continue to release greenhouse gas emissions. Although methodologies are provided to estimate emissions and removals from rewetted organic soils (which includes rewetted/restored peatlands) in IPCC (2013) guidelines, information on the areal extent of rewetted/restored peatlands in the United States is currently unavailable. The current *Inventory* estimates CO_2, CH_4 and N_2O emissions from peatlands managed for peat extraction in accordance with IPCC (2006 and 2013) guidelines.

CO_2, N_2O, and CH_4 Emissions from Peatlands Remaining Peatlands

IPCC (2013) recommends reporting CO_2, N_2O, and CH_4 emissions from lands undergoing active peat extraction (i.e., peatlands remaining peatlands) as part of the estimate for emissions from managed wetlands. Peatlands occur where plant biomass has sunk to the bottom of water bodies and water-logged areas and exhausted the oxygen supply below the water surface during the course of decay. Due to these anaerobic conditions, much of the plant matter does not decompose but instead forms layers of peat over decades and centuries. In the United States, peat is extracted for horticulture and landscaping growing media, and for a wide variety of industrial, personal care, and other products. It has not been used for fuel in the United States for many decades. Peat is harvested from two types of peat deposits in the United States: *Sphagnum* bogs in northern states (e.g., Minnesota) and wetlands in states further south (e.g., Florida). The peat from *Sphagnum* bogs in northern states, which is nutrient-poor, is generally corrected for acidity and mixed with fertilizer. Production from more southerly states is relatively coarse (i.e., fibrous) but nutrient-rich.

IPCC (2006 and 2013) recommend considering both on-site and off-site emissions when estimating CO_2 emissions from peatlands remaining peatlands using the Tier 1 approach. Current IPCC methodologies estimate only on-site N_2O and CH_4 emissions. This is because off-site N_2O estimates are complicated by the risk of double-counting emissions from nitrogen fertilizers added to horticultural peat where subsequent runoff or leaching into waterbodies can result in indirect N_2O emissions that are already included within the agricultural soil management category.

On-site emissions from managed peatlands occur as the land is drained and cleared of vegetation, and the underlying peat is exposed to sun, weather and oxygen. As this occurs, some of the peat deposit is lost and CO_2 is emitted from the oxidation of the peat. Since N_2O emissions from saturated ecosystems tend to be low unless there is an exogenous source of nitrogen, N_2O emissions from drained peatlands are dependent on nitrogen mineralization and therefore on soil fertility. Peatlands occurring on highly fertile/nutrient-rich soils, mostly located in the southern peatlands in Florida, contain significant amounts of organic nitrogen in inert/microbially inaccessible forms. Draining land in preparation for peat extraction allows bacteria to convert the organic nitrogen

into nitrates through nitrogen mineralization which leach to the surface where they are reduced to N_2O during nitrification. Nitrate availability also contributes to the activity of methanogens and methanotrophs that result in CH_4 emissions (Blodau 2002; Treat et al. 2007 as cited in IPCC 2013). Drainage ditches, which are constructed to drain the land in preparation for peat extraction, also contribute to the flux of CH_4 through *in situ* production and lateral transfer of CH_4 from the organic soil matrix (IPCC 2013).

Off-site CO_2 emissions from managed peatlands occur from waterborne dissolved organic carbon losses and the horticultural and landscaping use of peat. Dissolved organic carbon from water drained off peatlands reacts within aquatic ecosystems and is converted to CO_2, which is then emitted to the atmosphere (Billet et al. 2004 as cited in IPCC 2013). During the horticultural and landscaping use of peat, nutrient-poor (but fertilizer-enriched) peat tends to be used in bedding plants and in greenhouse and plant nursery production, whereas nutrient-rich (but relatively coarse) peat is used directly in landscaping, athletic fields, golf courses, and plant nurseries. Most (nearly 94 percent) of the CO_2 emissions from peat occur off-site, as the peat is processed and sold to firms which, in the United States, use it predominantly for the aforementioned horticultural and landscaping purposes.

Total emissions from peatlands remaining peatlands are estimated to be 0.6 MMT CO_2 Eq. in 2022 (see Table 6-55 and Table 6-56) comprising 0.6 MMT CO_2 Eq. (572 kt) of CO_2, 0.004 MMT CO_2 Eq. (0.13 kt) of CH_4 and 0.0004 MMT CO_2 Eq. (0.002 kt) of N_2O. Total emissions in 2022 are 4.7 percent greater than total emissions in 2021.

Total emissions from peatlands remaining peatlands have fluctuated between 0.6 and 1.3 MMT CO_2 Eq. across the time series with a decreasing trend from 1990 until 1993, followed by an increasing trend until reaching peak emissions in 2000. After 2000, emissions generally decreased until 2006 and then increased until 2009. The trend reversed in 2009 and total emissions have generally decreased between 2009 and 2021, however, total emissions from peatlands increased slightly in 2022 compared to 2021. Carbon dioxide emissions from peatlands remaining peatlands have fluctuated between 0.6 and 1.3 MMT CO_2 across the time series, and these emissions drive the trends in total emissions. Methane and N_2O emissions remained close to zero across the time series.

Table 6-55: Emissions from Peatlands Remaining Peatlands (MMT CO_2 Eq.)

Gas	1990	2005	2018	2019	2020	2021	2022
CO_2	**1.1**	**1.1**	**0.7**	**0.6**	**0.6**	**0.5**	**0.6**
Off-site	1.0	1.0	0.6	0.6	0.5	0.5	0.5
On-site	0.1	0.1	+	+	+	+	+
CH_4 (On-site)	**+**	**+**	**+**	**+**	**+**	**+**	**+**
N_2O (On-site)	**+**	**+**	**+**	**+**	**+**	**+**	**+**
Total	**1.1**	**1.1**	**0.7**	**0.6**	**0.6**	**0.6**	**0.6**

+ Does not exceed 0.05 MMT CO_2 Eq.

Note: Totals may not sum due to independent rounding.

Table 6-56: Emissions from Peatlands Remaining Peatlands (kt)

Gas	1990	2005	2018	2019	2020	2021	2022
CO_2	**1,055**	**1,101**	**650**	**613**	**590**	**547**	**572**
Off-site	985	1,030	608	572	550	509	533
On-site	70	71	42	41	41	38	39
CH_4 (On-site)	**+**	**+**	**+**	**+**	**+**	**+**	**+**
N_2O (On-site)	**+**	**+**	**+**	**+**	**+**	**+**	**+**

+ Does not exceed 0.5 kt.

Note: Totals may not sum due to independent rounding.

Methodology and Time-Series Consistency

Off-Site CO_2 Emissions

Carbon dioxide emissions from domestic peat production were estimated using a Tier 1 methodology consistent with IPCC (2006). Off-site CO_2 emissions from peatlands remaining peatlands were calculated by apportioning the annual weight of peat produced in the United States (Table 6-57) into peat extracted from nutrient-rich deposits and peat extracted from nutrient-poor deposits using annual percentage-by-weight figures. These nutrient-rich and nutrient-poor production values were then multiplied by the appropriate default C fraction conversion factor taken from IPCC (2006) in order to obtain off-site emission estimates. For the conterminous 48 states, both annual percentages of peat type by weight and domestic peat production data were sourced from estimates and industry statistics provided in the *Minerals Yearbook* and *Mineral Commodity Summaries* from the U.S. Geological Survey (USGS; USGS 1995 through 2018; USGS 2023a; USGS 2023b; USGS 2023c). Hawaii is assumed to have no peat production due to its absence from these sources. To develop these data, the USGS (U.S. Bureau of Mines prior to 1997) obtained production and use information by surveying domestic peat producers. On average, about 75 percent of the peat operations respond to the survey; USGS estimates data for non-respondents on the basis of prior-year production levels (Apodaca 2011).

The estimates for Alaska rely on reported peat production from the annual *Alaska's Mineral Industry* reports (DGGS 1993 through 2015). Similar to the U.S. Geological Survey, the Alaska Department of Natural Resources, Division of Geological & Geophysical Surveys (DGGS) solicits voluntary reporting of peat production from producers for the *Alaska's Mineral Industry* report. However, the report does not estimate production for the non-reporting producers, resulting in larger inter-annual variation in reported peat production from Alaska depending on the number of producers who report in a given year (Szumigala 2011). In addition, in both the conterminous United States and Alaska, large variations in peat production can also result from variation in precipitation and the subsequent changes in moisture conditions, since unusually wet years can hamper peat production. The methodology estimates emissions from Alaska separately from the conterminous United States because Alaska previously conducted its own mineral surveys and reported peat production by volume, rather than by weight (Table 6-58). However, volume production data were used to calculate off-site CO_2 emissions from Alaska applying the same methodology but with volume-specific C fraction conversion factors from IPCC (2006).[58] Peat production was not reported for 2015 in *Alaska's Mineral Industry 2014* report (DGGS 2015), and reliable data are not available beyond 2012, so Alaska's peat production in 2013 through 2021 (reported in cubic yards) was assumed to be equal to the 2012 value.

Consistent with IPCC (2013) guidelines, off-site CO_2 emissions from dissolved organic carbon were estimated based on the total area of peatlands managed for peat extraction, which is calculated from production data using the methodology described in the On-Site CO_2 Emissions section below. Carbon dioxide emissions from dissolved organic carbon were estimated by multiplying the area of managed peatlands by the default emission factor for dissolved organic C provided in IPCC (2013).

The United States has largely imported peat from Canada for horticultural purposes; in 2022, imports of *Sphagnum* moss (nutrient-poor) peat from Canada represented 96 percent of total U.S. peat imports and 80 percent of U.S. domestic consumption (USGS 2023c). Most peat produced in the United States is reed-sedge peat, generally from southern states, which is classified as nutrient-rich by IPCC (2006). To be consistent with the Tier 1 method, only domestic peat production is accounted for when estimating off-site emissions. Higher-tier calculations of CO_2 emissions from apparent consumption would involve consideration of the percentages of peat types stockpiled (nutrient-rich versus nutrient-poor) as well as the percentages of peat types imported and exported.

[58] Peat produced from Alaska was assumed to be nutrient poor; as is the case in Canada, "where deposits of high-quality [but nutrient poor] *Sphagnum* moss are extensive" (USGS 2008).

Table 6-57: Peat Production of Conterminous 48 States (kt)

Type of Deposit	1990	2005	2018	2019	2020	2021	2022
Nutrient-Rich	595.1	657.6	338.4	329.4	343.4	291.6	306.0
Nutrient-Poor	55.4	27.4	50.6	36.6	10.6	32.4	34.0
Total Production	**692.0**	**685.0**	**389.0**	**366.0**	**354.0**	**324.0**	**340.0**

Note: Totals may not sum due to independent rounding.

Sources: United States Geological Survey (USGS) (1991–2017) *Minerals Yearbook: Peat (1994–2016);* United States Geological Survey (USGS) (2018) *Minerals Yearbook: Peat – Tables-only release (2018);* United States Geological Survey (USGS) (2023) *Mineral Commodity Summaries: Peat (2023).*

Table 6-58: Peat Production of Alaska (Thousand Cubic Meters)

	1990	2005	2018	2019	2020	2021	2022
Total Production	49.7	47.8	93.1	93.1	93.1	93.1	93.1

Sources: Division of Geological & Geophysical Surveys (DGGS), Alaska Department of Natural Resources (1997–2015) *Alaska's Mineral Industry Report (1997–2014)*.

On-site CO_2 Emissions

IPCC (2006) suggests basing the calculation of on-site emission estimates on the area of peatlands managed for peat extraction differentiated by the nutrient type of the deposit (rich versus poor). Information on the area of land managed for peat extraction is currently not available for the United States, but consistent with IPCC (2006), an average production rate for the industry was applied to derive a land area estimate. In a mature industrialized peat industry, such as exists in the United States and Canada, the vacuum method can extract up to 100 metric tons per hectare per year (Cleary et al. 2005 as cited in IPCC 2006).[59] The area of land managed for peat extraction in the conterminous United States was estimated using both nutrient-rich and nutrient-poor production data and the assumption that 100 metric tons of peat are extracted from a single hectare in a single year, see Table 6-59. The annual land area estimates were then multiplied by the IPCC (2013) default emission factor in order to calculate on-site CO_2 emission estimates.

Production data are not available by weight for Alaska. In order to calculate on-site emissions resulting from peatlands remaining peatlands in Alaska, the production data by volume were converted to weight using annual average bulk peat density values, and then converted to land area estimates using the assumption that a single hectare yields 100 metric tons, see Table 6-60. The IPCC (2006) on-site emissions equation also includes a term that accounts for emissions resulting from the change in carbon stocks that occurs during the clearing of vegetation prior to peat extraction. Area data on land undergoing conversion to peatlands for peat extraction is also unavailable for the United States. However, USGS records show that the number of active operations in the United States has been declining since 1990; therefore, it seems reasonable to assume that no new areas are being cleared of vegetation for managed peat extraction. Other changes in carbon stocks in living biomass on managed peatlands are also assumed to be zero under the Tier 1 methodology (IPCC 2006 and 2013).

Table 6-59: Peat Production Area of Conterminous 48 States (Hectares)

	1990[a]	2005	2018	2019	2020	2021	2022
Nutrient-Rich	5,951	6,576	3,384	3,294	3,434	2,916	3,060
Nutrient-Poor	554	274	506	366	106	324	340
Total Production	**6,920**	**6,850**	**3,890**	**3,660**	**3,540**	**3,240**	**3,400**

[59] The vacuum method is one type of extraction that annually "mills" or breaks up the surface of the peat into particles, which then dry during the summer months. The air-dried peat particles are then collected by vacuum harvesters and transported from the area to stockpiles (IPCC 2006).

[a] A portion of the production in 1990 is of unknown nutrient type, resulting in a total production value greater than the sum of nutrient-rich and nutrient-poor.
Note: Totals may not sum due to independent rounding.

Table 6-60: Peat Production Area of Alaska (Hectares)

	1990	2005	2018	2019	2020	2021	2022
Nutrient-Rich	0	0	0	0	0	0	0
Nutrient-Poor	286	104	212	329	428	428	428
Total Production	**286**	**104**	**212**	**329**	**428**	**428**	**428**

Note: Totals may not sum due to independent rounding.

On-site N_2O Emissions

IPCC (2006) indicates the calculation of on-site N_2O emission estimates using Tier 1 methodology only considers nutrient-rich peatlands managed for peat extraction. These area data are not available directly for the United States, but the on-site CO_2 emissions methodology above details the calculation of nutrient-rich area data from production data. In order to estimate N_2O emissions, the land area estimate of nutrient-rich peatlands remaining peatlands was multiplied by the appropriate default emission factor taken from IPCC (2013). See the Planned Improvements section for additional information on identified research activities to improve peatland land area estimates.

On-site CH_4 Emissions

IPCC (2013) also suggests basing the calculation of on-site CH_4 emission estimates on the total area of peatlands managed for peat extraction. Area data is derived using the calculation from production data described in the On-site CO_2 Emissions section above. In order to estimate CH_4 emissions from drained land surface, the land area estimate of peatlands remaining peatlands was multiplied by the emission factor for direct CH_4 emissions taken from IPCC (2013). In order to estimate CH_4 emissions from drainage ditches, the total area of peatland was multiplied by the default fraction of peatland area that contains drainage ditches, and the appropriate emission factor taken from IPCC (2013). See Table 6-61 for the calculated area of ditches and drained land.

Table 6-61: Peat Production (Hectares)

	1990	2005	2018	2019	2020	2021	2022
Conterminous 48 States							
Area of Drained Land	6,574	6,508	3,696	3,477	3,363	3,078	3,230
Area of Ditches	346	343	195	183	177	162	170
Total Production	**6,920**	**6,850**	**3,890**	**3,660**	**3,540**	**3,240**	**3,400**
Alaska							
Area of Drained Land	272	99	202	312	407	407	407
Area of Ditches	14	5	11	16	21	21	21
Total Production	**286**	**104**	**212**	**329**	**428**	**428**	**428**

Note: Totals may not sum due to independent rounding.

Methodological recalculations were applied to the entire time series to ensure time-series consistency from 1990 through 2022. The same data sources were used throughout the time series, when available. When data were unavailable or the available data were outliers, missing values were estimated based on the past available data.

Uncertainty

A Monte Carlo (Approach 2) uncertainty analysis was applied to estimate the uncertainty of CO_2, CH_4, and N_2O emissions from peatlands remaining peatlands for 2022, using the following assumptions:

- The uncertainty associated with peat production data was estimated to be ± 25 percent (Apodaca 2008) and assumed to be normally distributed.
- The uncertainty associated with peat production data stems from the fact that the USGS receives data from smaller peat producers but estimates production from some larger peat distributors. The peat type production percentages were assumed to have the same uncertainty values and distribution as the peat production data (i.e., ± 25 percent with a normal distribution).
- The uncertainty associated with the reported production data for Alaska was assumed to be the same as for the conterminous United States, or ± 25 percent with a normal distribution. It should be noted that the DGGS estimates that around half of producers do not respond to their survey with peat production data; therefore, the production numbers reported are likely to underestimate Alaska peat production (Szumigala 2008).
- The uncertainty associated with the average bulk density values was estimated to be ± 25 percent with a normal distribution (Apodaca 2008).
- IPCC (2006 and 2013) gives uncertainty values for the emissions factors for the area of peat deposits managed for peat extraction based on the range of underlying data used to determine the emission factors. The uncertainty associated with the emission factors was assumed to be triangularly distributed.
- The uncertainty values surrounding the C fractions were based on IPCC (2006) and the uncertainty was assumed to be uniformly distributed.
- The uncertainty values associated with the fraction of peatland covered by ditches was assumed to be ± 100 percent with a normal distribution based on the assumption that greater than 10 percent coverage, the upper uncertainty bound, is not typical of drained organic soils outside of The Netherlands (IPCC 2013).

The results of the Approach 2 quantitative uncertainty analysis are summarized in Table 6-62. Carbon dioxide emissions from peatlands remaining peatlands in 2022 were estimated to be between 0.5 and 0.7 MMT CO_2 Eq. at the 95 percent confidence level. This indicates a range of 16 percent below to 16 percent above the 2022 emission estimate of 0.6 MMT CO_2 Eq. Methane emissions from peatlands remaining peatlands in 2022 were estimated to be between 0.001 and 0.006 MMT CO_2 Eq. This indicates a range of 59 percent below to 79 percent above the 2022 emission estimate of 0.004 MMT CO_2 Eq. Nitrous oxide emissions from peatlands remaining peatlands in 2022 were estimated to be between 0.0002 and 0.0006 MMT CO_2 Eq. at the 95 percent confidence level. This indicates a range of 52 percent below to 53 percent above the 2022 emission estimate of 0.0004 MMT CO_2 Eq.

Table 6-62: Approach 2 Quantitative Uncertainty Estimates for CO_2, CH_4, and N_2O Emissions from Peatlands Remaining Peatlands (MMT CO_2 Eq. and Percent)

Source	Gas	2022 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Peatlands Remaining Peatlands	CO_2	0.6	0.5	0.7	-16%	+16%
Peatlands Remaining Peatlands	CH_4	+	+	+	-59%	+79%
Peatlands Remaining Peatlands	N_2O	+	+	+	-52%	+53%

+ Does not exceed 0.05 MMT CO_2 Eq.

[a] Range of emission estimates predicted by Monte Carlo stochastic simulation for a 95 percent confidence interval.

QA/QC and Verification

A QA/QC analysis was performed to review input data and calculations, and no issues were identified. In addition, the emission trends were analyzed to ensure they reflected activity data trends.

Recalculations Discussion

The conterminous United States peat production estimates for peatlands remaining peatlands were updated using the Peat section of the *Mineral Commodity Summaries 2023*. The 2023 edition updated 2018, 2019, 2020, and 2021 peat production data and provided peat type production estimates for 2022. Updated data decreased previously estimated emissions for 2018 by 18 percent, 2019 by 19 percent, 2020 by 19 percent, and 2021 by 22 percent versus estimated emissions for 2018, 2019, 2020, and 2021 in the previous (i.e., 1990 through 2021) *Inventory* for peatlands remaining peatlands. According to USGS, peat production estimations for 2018 through 2022 were revised in the *Mineral Commodity Summaries 2023* due to a company having shut down sometime in 2017 (USGS 2023d). Previously, USGS was estimating production for this company due to lack of peat production survey responses.

Although Alaska peat production data for 2015 through 2022 were unavailable, 2014 data are available in the *Alaska's Mineral Industry 2014* report. However, the reported values represented an apparent 98 percent decrease in production since 2012. Due to the uncertainty of the most recent data, 2013 through 2022 value were assumed to be equal to the 2012 value, seen in the *Alaska's Mineral Industry 2013* report. If updated Alaska data are available for the next *Inventory* cycle, this will result in a recalculation in the next (i.e., 1990 through 2023) *Inventory* report.

Planned Improvements

Edits to the trends and methodology sections are planned based on expert review comments.

EPA notes the following improvements may be implemented or investigated within the next two or three *Inventory* cycles pending time and resource:

- The implied emission factors will be calculated and included in this chapter for future *Inventories*. Currently, the N_2O emissions calculation uses different land areas than the CO_2 and CH_4 emission calculations (see Methodology and Time Series Consistency in this chapter), so estimating the implied emission factor per total land area is not appropriate. The inclusion of implied emission factors in this chapter will provide another method of QA/QC and verification for *Inventory* data.

EPA notes the following improvements will continue to be investigated as time and resources allow, but there are no immediate plans to implement until data are available or identified:

- In order to further improve estimates of CO_2, N_2O, and CH_4 emissions from peatlands remaining peatlands, future efforts will investigate if improved data sources exist for determining the quantity of peat harvested per hectare and the total area of land undergoing peat extraction.
- EPA plans to identify a new source for Alaska peat production. The current source has not been reliably updated since 2012 and Alaska Department of Natural Resources indicated future publication of data has been discontinued.

Coastal Wetlands Remaining Coastal Wetlands

Consistent with ecological definitions of wetlands,[60] the United States has historically included under the category of wetlands those coastal shallow water areas of estuaries and bays that lie within the extent of the Land Representation. Guidance on quantifying greenhouse gas emissions and removals on coastal wetlands is provided in the *2013 Supplement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories: Wetlands* (*Wetlands Supplement*), which recognizes the particular importance of vascular plants in sequestering CO_2 from the atmosphere within biomass, dead organic material (DOM; including litter and dead wood stocks) and soils. Thus, the *Wetlands Supplement* provides specific guidance on quantifying emissions and removals on organic and

[60] See https://water.usgs.gov/nwsum/WSP2425/definitions.html; accessed August 2023.

mineral soils that are covered or saturated for part of the year by tidal fresh, brackish or saline water and are vegetated by vascular plants and may extend seaward to the maximum depth of vascular plant vegetation. The United States calculates emissions and removals based upon the stock change method for soil carbon (C) and the gain-loss method for biomass and DOM. Presently, this *Inventory* does not calculate the lateral flux of carbon to or from any land use. Lateral transfer of organic carbon to coastal wetlands and to marine sediments within U.S. waters is the subject of ongoing scientific investigation; there is currently no IPCC methodological guidance for lateral fluxes of carbon.

The United States recognizes both vegetated wetlands and unvegetated open water as coastal wetlands. Per guidance provided by the *Wetlands Supplement*, sequestration of carbon into biomass, DOM and soil carbon pools is recognized only in vegetated coastal wetlands and does not occur in unvegetated open water coastal wetlands. The United States takes the additional step of recognizing that carbon stock losses occur when vegetated coastal wetlands are converted to Unvegetated open water coastal wetlands.

This *Inventory* includes all privately- and publicly-owned coastal wetlands (i.e., mangroves and tidal marsh) along the oceanic shores of the conterminous United States, including the District of Columbia., but does not include coastal wetlands remaining coastal wetlands in Alaska, Hawaii, or any of the United States Territories. Seagrasses are not currently included within the *Inventory* due to insufficient data on distribution, change through time and carbon stocks or carbon stock changes as a result of anthropogenic influence (see Planned Improvements).

Under the coastal wetlands remaining coastal wetlands category, the following emissions and removals are quantified in this chapter:

1) Carbon stock changes and CH_4 emissions on vegetated coastal wetlands remaining vegetated coastal wetlands,

2) Carbon stock changes on vegetated coastal wetlands converted to unvegetated open water coastal wetlands,

3) Carbon stock changes on unvegetated open water coastal wetlands converted to vegetated coastal wetlands, and

4) Nitrous oxide emissions from aquaculture in coastal wetlands.

Vegetated coastal wetlands hold carbon in all five carbon pools (i.e., aboveground biomass, belowground biomass, dead organic matter [DOM; dead wood and litter], and soil), though typically soil carbon and, to a lesser extent, aboveground and belowground biomass are the dominant pools, depending on wetland type (i.e., forested vs. marsh). vegetated coastal wetlands are net accumulators of carbon over centuries to millennia as soils accumulate carbon under anaerobic soil conditions and carbon accumulates in plant biomass. Large emissions from soil carbon and biomass stocks occur when vegetated coastal wetlands are converted to unvegetated open water coastal wetlands (e.g., when vegetated coastal wetlands are lost due to subsidence, channel cutting through vegetated coastal wetlands), but are still recognized as coastal wetlands in this *Inventory*. These carbon stock losses resulting from conversion to unvegetated open water coastal wetlands can cause the release of decades to centuries of accumulated soil carbon, as well as the standing stock of biomass carbon. Conversion of unvegetated open water coastal wetlands to vegetated coastal wetlands, either through restoration efforts or naturally, initiates the building of carbon stocks within soils and biomass. In applying the *Wetlands Supplement* methodologies for estimating CH_4 emissions, coastal wetlands in salinity conditions greater than 18 parts per thousand have little to no CH_4 emissions compared to those experiencing lower salinity brackish and freshwater conditions. Therefore, conversion of vegetated coastal wetlands to or from unvegetated open water coastal wetlands are conservatively assumed to not result in a change in salinity condition and are assumed to have no impact on CH_4 emissions. The *Wetlands Supplement* provides methodologies to estimate N_2O emissions from coastal wetlands that occur due to aquaculture. The N_2O emissions from aquaculture result from the nitrogen derived from consumption of the applied food stock that is then excreted as nitrogen load available for conversion to N_2O. While N_2O emissions can also occur due to anthropogenic nitrogen loading from the watershed and atmospheric deposition, these

emissions are not reported here to avoid double-counting of indirect N_2O emissions with the agricultural soils management, forest land and settlements categories.

The *Wetlands Supplement* provides methodologies for estimating carbon stock changes and CH_4 emissions from mangroves, tidal marshes and seagrasses. Depending upon their height and area, carbon stock changes from mangroves may be reported under the forest land category or under coastal wetlands. If mangrove stature is 5 m or greater or if there is evidence that trees can obtain that height, mangroves are reported under the forest land category because they meet the definition of forest land. Mangrove forests that are less than 5 m are reported under coastal wetlands because they meet the definition of wetlands. All other non-drained, intact coastal marshes are reported under coastal wetlands.

Because of human activities and level of regulatory oversight, all coastal wetlands within the conterminous United States are included within the managed land area described in Section 6.1, and as such, estimates of carbon stock changes, emissions of CH_4, and emissions of N_2O from aquaculture from all coastal wetlands are included in this *Inventory.* At the present stage of inventory development, coastal wetlands are not explicitly shown in the land representation analysis while work continues to harmonize data from NOAA's Coastal Change Analysis Program (C-CAP)[61] with NRI, FIA and NLDC data used to compile the land representation (see Section 6.1). However, a check was undertaken to confirm that coastal wetlands recognized by C-CAP represented a subset of wetlands recognized by the NRI for marine coastal states.

The greenhouse gas fluxes for all four wetland categories described above are summarized in Table 6-63. Coastal wetlands remaining coastal wetlands are generally a net carbon sink, with the fluxes ranging from -5.6 to -6.7 MMT CO_2 Eq. across the majority of the time series; however, between 2006 and 2010, they were a net source of emissions (ranging from 3.2 to 53.5 MMT CO_2 Eq.), resulting from a large loss of vegetated coastal wetlands to open water due to hurricanes (Table 6-63). Recognizing removals of CO_2 to soil of 12.5 MMT CO_2 Eq. and CH_4 emissions of 4.3 MMT CO_2 Eq. in 2022, vegetated coastal wetlands remaining vegetated coastal wetlands are a net sink of 8.2MMT CO_2 Eq. Loss of coastal wetlands, primarily in the Mississippi Delta as a result of hurricane impacts and sediment diversion and other human impacts, recognized as vegetated coastal wetlands converted to unvegetated coastal wetlands, drive an emission of 1.5 MMT CO_2 Eq. since 2011, primarily from soils. Building of new wetlands from open water, recognized as unvegetated coastal wetlands converted to vegetated coastal, results each year in removal of 0.1 MMT CO_2 Eq. Aquaculture is a minor industry in the United States, resulting in an emission of N_2O across the time series of between 0.1 to 0.2 MMT CO_2 Eq. In total, coastal wetlands are a net sink of 6.7 MMT CO_2 Eq. in 2022.

Table 6-63: Emissions and Removals from Coastal Wetlands Remaining Coastal Wetlands (MMT CO_2 Eq.)

Land Use/Carbon Pool	1990	2005	2018	2019	2020	2021	2022
Vegetated Coastal Wetlands Remaining Vegetated Coastal Wetlands	**(8.4)**	**(8.4)**	**(8.3)**	**(8.3)**	**(8.3)**	**(8.2)**	**(8.2)**
Biomass C Flux	(+)	(+)	(+)	(+)	(+)	(+)	(+)
Soil C Flux	(12.5)	(12.6)	(12.5)	(12.5)	(12.5)	(12.5)	(12.5)
Net CH_4 Flux	4.2	4.2	4.3	4.3	4.3	4.3	4.3
Vegetated Coastal Wetlands Converted to Unvegetated Open Water Coastal Wetlands	**1.8**	**2.6**	**1.5**	**1.5**	**1.5**	**1.5**	**1.5**
Biomass C Flux	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Dead Organic Matter C Flux	+	+	+	+	+	+	+
Soil C Flux	1.7	2.5	1.5	1.5	1.5	1.5	1.5
Unvegetated Open Water Coastal Wetlands Converted to Vegetated	**(+)**	**(0.1)**	**(0.1)**	**(0.1)**	**(0.1)**	**(0.1)**	**(0.1)**

[61] See https://coast.noaa.gov/digitalcoast/tools/lca.html; accessed September 2023.

Coastal Wetlands							
Biomass C Flux	(+)	(0.1)	(0.1)	(0.1)	(0.1)	(0.1)	(0.1)
Dead Organic Matter C Flux	(+)	(+)	+	+	+	+	+
Soil C Flux	(+)	(+)	(+)	(+)	(+)	(+)	(+)
Net N_2O Flux from Aquaculture in Coastal Wetlands	**0.1**	**0.2**	**0.1**	**0.1**	**0.1**	**0.1**	**0.1**
Total Biomass C Flux	**+**	**+**	**(0.1)**	**(0.1)**	**(0.1)**	**(0.1)**	**(0.1)**
Total Dead Organic Matter C Flux	**(+)**	**(+)**	**+**	**+**	**+**	**+**	**+**
Total Soil C Flux	**(10.8)**	**(10.1)**	**(11.0)**	**(11.0)**	**(11.0)**	**(11.0)**	**(11.1)**
Total CH_4 Flux	**4.2**	**4.2**	**4.3**	**4.3**	**4.3**	**4.3**	**4.3**
Total N_2O Flux	**0.1**	**0.2**	**0.1**	**0.1**	**0.1**	**0.1**	**0.1**
Total Flux	**(6.5)**	**(5.7)**	**(6.7)**	**(6.7)**	**(6.7)**	**(6.7)**	**(6.7)**

+ Absolute value does not exceed 0.05 MMT CO_2 Eq.

Note: Totals may not sum due to independent rounding. Parentheses indicate net sequestration.

Emissions and Removals from Vegetated Coastal Wetlands Remaining Vegetated Coastal Wetlands

The conterminous United States currently has 2.98 million hectares of intertidal vegetated coastal wetlands remaining vegetated coastal wetlands comprised of tidally influenced palustrine emergent marsh (663,014 ha), palustrine scrub shrub (133,582 ha) and estuarine emergent marsh (1,892,507 ha), estuarine scrub shrub (95,225 ha) and estuarine forested wetlands (195,199 ha). Mangroves fall under both estuarine forest and estuarine scrub shrub categories depending upon height. Dwarf mangroves, found in subtropical states along the Gulf of Mexico, do not attain the height status to be recognized as forest land, and are therefore always classified within vegetated coastal wetlands. vegetated coastal wetlands remaining vegetated coastal wetlands are found in cold temperate (53,968 ha), warm temperate (896,583 ha), subtropical (1,966,101 ha) and Mediterranean (62,874 ha) climate zones.

Soils are the largest carbon pool in vegetated coastal wetlands remaining vegetated coastal wetlands, reflecting long-term removal of atmospheric CO_2 by vegetation and transfer into the soil pool in the form of both autochthonous and allochthonous decaying organic matter. Soil carbon emissions are not assumed to occur in coastal wetlands that remain vegetated. This *Inventory* includes changes in carbon stocks in both biomass and soils. Changes in DOM carbon stocks are not included. Methane emissions from decomposition of organic matter in anaerobic conditions are present at salinity less than half that of sea water. Mineral and organic soils are not differentiated in terms of carbon stock changes or CH_4 emissions.

Table 6-64 through Table 6-66 summarize nationally aggregated biomass and soil carbon stock changes and CH_4 emissions on vegetated coastal wetlands remaining vegetated coastal wetlands. Intact vegetated coastal wetlands remaining vegetated coastal wetlands hold a total biomass carbon stock of 35.96 MMT C. Removals from biomass carbon stocks in 2022 were 0.05 MMT CO_2 Eq. (0.01 MMT C), which has increased over the time series (Table 6-64 and Table 6-65). Carbon dioxide emissions from biomass in vegetated coastal wetlands remaining vegetated coastal wetlands between 2002 and 2011, with very low sequestration between 2002 and 2006 and emissions of 0.21 MMT CO_2 Eq. between 2007 and 2011, are not inherently typical and are a result of coastal wetland loss over time. Most of the coastal wetland loss has occurred in palustrine and estuarine emergent wetlands. Vegetated coastal wetlands maintain a large carbon stock within the top 1 meter of soil (estimated to be 804 MMT C) to which carbon accumulated at a rate of 12.5 MMT CO_2 Eq. (3.4 MMT C) in 2022, a value that has remained relatively constant across the reporting period. For vegetated coastal wetlands remaining vegetated coastal wetlands, methane emissions of 4.3 of MMT CO_2 Eq. (154 kt CH_4) in 2022 (Table 6-66) offset carbon removals resulting in a net removal of 8.2 MMT CO_2 Eq. in 2022; this rate has been relatively consistent across the reporting period. Dead organic matter stock changes are not calculated in vegetated coastal wetlands remaining vegetated coastal wetlands since this stock is considered to be in a steady state when using Tier 1 methods (IPCC 2014). Due to federal regulatory protection, loss of vegetated coastal wetlands through human activities slowed considerably

in the 1970s and the current annual rates of carbon stock change and CH_4 emissions are relatively constant over time.

Table 6-64: Net CO_2 Flux from Carbon Stock Changes in Vegetated Coastal Wetlands Remaining Vegetated Coastal Wetlands (MMT CO_2 Eq.)

Year	1990	2005	2018	2019	2020	2021	2022
Biomass Flux	(+)	(+)	(+)	(+)	(+)	(+)	(+)
Soil Flux	(12.5)	(12.6)	(12.5)	(12.5)	(12.5)	(12.5)	(12.5)
Total C Stock Change	**(12.6)**	**(12.6)**	**(12.5)**	**(12.5)**	**(12.5)**	**(12.5)**	**(12.5)**

+ Absolute value does not exceed 0.05 MMT $C0_2$ Eq.

Note: Parentheses indicate net sequestration. Totals may not sum due to independent rounding.

Table 6-65: Net CO_2 Flux from Carbon Stock Changes in Vegetated Coastal Wetlands Remaining Vegetated Coastal Wetlands (MMT C)

Year	1990	2005	2018	2019	2020	2021	2022
Biomass Flux	(+)	+	(+)	(+)	(+)	(+)	(+)
Soil Flux	(3.4)	(3.4)	(3.4)	(3.4)	(3.4)	(3.4)	(3.4)
Total C Stock Change	**(3.4)**	**(3.4)**	**(3.4)**	**(3.4)**	**(3.4)**	**(3.4)**	**(3.4)**

+ Absolute value does not exceed 0.05 MMT C.

Note: Parentheses indicate net sequestration. Totals may not sum due to independent rounding.

Table 6-66: CH_4 Emissions from Vegetated Coastal Wetlands Remaining Vegetated Coastal Wetlands (MMT CO_2 Eq. and kt CH_4)

Year	1990	2005	2018	2019	2020	2021	2022
Methane Emissions (MMT CO_2 Eq.)	4.2	4.2	4.3	4.3	4.3	4.3	4.3
Methane Emissions (kt CH_4)	149	151	153	153	154	154	154

Methodology and Time-Series Consistency

The following section includes a description of the methodology used to estimate changes in biomass carbon stocks, soil carbon stocks and emissions of CH_4 for vegetated coastal wetlands remaining vegetated coastal wetlands. Dead organic matter is not calculated for vegetated coastal wetlands remaining vegetated coastal wetlands since it is assumed to be in steady state (IPCC 2014).

Methodological recalculations were applied to the entire time series to ensure time-series consistency from 1990 through 2022.

Biomass Carbon Stock Changes

Above- and belowground biomass carbon stocks for palustrine (freshwater) and estuarine (saline) marshes are estimated for vegetated coastal wetlands remaining vegetated coastal wetlands on land below the elevation of high tides (taken to be mean high water spring tide elevation) and as far seawards as the extent of intertidal vascular plants according to the national LiDAR dataset, the national network of tide gauges and land use histories recorded in the 1996, 2001, 2006, 2010, and 2016 NOAA C-CAP surveys (NOAA OCM 2020). C-CAP areas are calculated at the state/territory level and summed according to climate zone to national values. Federal and non-federal lands are represented. Trends in land cover change are extrapolated to 1990 and 2022 from these datasets. Based upon NOAA C-CAP, coastal wetlands are subdivided into palustrine and estuarine classes and further subdivided into emergent marsh, scrub shrub and forest classes (Table 6-67). Biomass is not sensitive to soil organic matter content but is differentiated based on climate zone. Aboveground biomass carbon stocks for non-forested wetlands data are derived from a national assessment combining field plot data and aboveground biomass mapping by remote sensing (Byrd et al. 2017; Byrd et al. 2018; Byrd et al. 2020). The aboveground

biomass carbon stock for subtropical estuarine forested wetlands (dwarf mangroves that are not classified as forests due to their stature) is derived from a meta-analysis by Lu and Megonigal (2017). Root to shoot ratios from the *Wetlands Supplement* (Table 6-69; IPCC 2014) were used to account for belowground biomass, which were multiplied by the aboveground carbon stock. Above- and belowground values were summed to obtain total biomass carbon stocks. Biomass carbon stock changes per year for wetlands remaining wetlands were determined by calculating the difference in area between that year and the previous year to calculate gain/loss of area for each climate type, which was multiplied by the mean biomass for that climate type.

Table 6-67: Area of Vegetated Coastal Wetlands Remaining Vegetated Coastal Wetlands, Vegetated Coastal Wetlands Converted to Unvegetated Open Water Coastal Wetlands, and Unvegetated Open Water Coastal Wetlands Converted to Vegetated Coastal Wetlands (ha)

Year	1990	2005	2018	2019	2020	2021	2022
Vegetated Coastal Wetlands Remaining Vegetated Coastal Wetlands	2,975,477	2,985,783	2,974,523	2,975,789	2,977,055	2,978,322	2,979 588
Vegetated Coastal Wetlands Converted to Unvegetated Open Water Coastal Wetlands	1,720	2,515	1,488	1,488	1,488	1,488	1,488
Unvegetated Open Water Coastal Wetlands Converted to Vegetated Coastal Wetlands	952	1,769	2,406	2,406	2,406	2,406	2,406

Table 6-68: Aboveground Biomass Carbon Stocks for Vegetated Coastal Wetlands (t C ha^{-1})

	Climate Zone			
Wetland Type	Cold Temperate	Warm Temperate	Subtropical	Mediterranean
Palustrine Scrub/Shrub Wetland	3.25	3.17	2.24	4.69
Palustrine Emergent Wetland	3.25	3.17	2.24	4.69
Estuarine Forested Wetland	N/A	N/A	17.83	N/A
Estuarine Scrub/Shrub Wetland	3.05	3.05	2.43	3.44
Estuarine Emergent Wetland	3.05	3.10	2.43	3.44

Source: All data from Byrd et al. (2017, 2018 and 2020) except for subtropical estuarine forested wetlands, which is from Lu and Megonigal (2017); N/A means there are currently no estuarine forested wetlands that are less than 5 meters tall; these forested wetlands meet the definition of forest land and are included in the Forest Land section.

Table 6-69: Root to Shoot Ratios for Vegetated Coastal Wetlands

	Climate Zone			
Wetland Type	Cold Temperate	Warm Temperate	Subtropical	Mediterranean
Palustrine Scrub/Shrub Wetland	1.15	1.15	3.65	3.63
Palustrine Emergent Wetland	1.15	1.15	3.65	3.63
Estuarine Forested Wetland	N/A	N/A	0.96	N/A
Estuarine Scrub/Shrub Wetland	2.11	2.11	3.65	3.63
Estuarine Emergent Wetland	2.11	2.11	3.65	3.63

Source: All values from IPCC (2014); N/A means there are currently no estuarine forested wetlands that are less than 5 meters tall; these forested wetlands meet the definition of forest land and are included in the Forest Land section.

Soil Carbon Stock Changes

Soil carbon stock changes are estimated for vegetated coastal wetlands remaining vegetated coastal wetlands for both mineral and organic soils. Soil carbon stock changes, stratified by climate zones and wetland classes, are derived from a synthesis of peer-reviewed literature (Table 6-70; Lynch 1989; Orson et al. 1990; Kearny & Stevenson 1991; Thom et al. 1992; Roman et al. 1997; Craft et al. 1998; Orson et al. 1998; Merrill 1999; Weis et al.

2001; Hussein et al. 2004; Church et al. 2006; Köster et al. 2007; Drexler et al. 2009; Boyd 2012; Callaway et al. 2012a&b; Bianchi et al. 2013; Drexler et al. 2013; Watson and Byrne 2013; Breithaupt et al. 2014; Crooks et al. 2014; Weston et al. 2014; Smith et al. 2015; Villa & Mitsch 2015; Boyd and Sommerfield 2016; Marchio et al. 2016; Noe et al. 2016; Arriola and Cable 2017; Boyd et al. 2017; Gerlach et al. 2017; Giblin and Forbrich 2018; Krauss et al. 2018; Abbott et al. 2019; Drexler et al. 2019; Poppe and Rybczyk 2019; Ensign et al. 2020; Kemp et al. 2020; Lagomasino et al. 2020; Luk et al. 2020; McTigue et al. 2020; Peck et al. 2020; Vaughn et al. 2020; Weston et al. 2020; Arias-Ortiz et al. 2021; Baustian et al. 2021; Allen et al. 2022; Miller et al. 2022).

Tier 2 estimates of soil carbon removals associated with annual soil carbon accumulation on managed vegetated coastal wetlands remaining vegetated coastal wetlands were developed with country-specific soil carbon removal factors multiplied by activity data of land area for vegetated coastal wetlands remaining vegetated coastal wetlands. The methodology follows Eq. 4.7, Chapter 4 of the *Wetlands Supplement*, and is applied to the area of vegetated coastal wetlands remaining vegetated coastal wetlands on an annual basis. To estimate soil carbon stock changes, no differentiation is made between organic and mineral soils since currently, no statistical evidence supports disaggregation (Holmquist et al. 2018).

Table 6-70: Annual Soil Carbon Accumulation Rates for Vegetated Coastal Wetlands (t C ha^{-1} yr^{-1})

Climate Zone	Cold Temperate	Warm Temperate	Subtropical	Mediterranean
Palustrine Scrub/Shrub Wetland	1.010	1.544	0.45	0.845
Palustrine Emergent Wetland	1.010	1.544	0.454	0.845
Estuarine Forested Wetland	N/A	N/A	0.821	N/A
Estuarine Scrub/Shrub Wetland	1.254	1.039	0.821	0.845
Estuarine Emergent Wetland	1.254	1.039	1.587	0.845

Source: All data from CCRCN (2023)[62]; N/A means there are no estuarine forested wetlands outside of subtropical regions.

Soil Methane Emissions

Tier 1 estimates of CH_4 emissions for vegetated coastal wetlands remaining vegetated coastal wetlands are derived from the same wetland map used in the analysis of wetland soil C fluxes, produced from C-CAP, LiDAR and tidal data, in combination with default CH_4 emission factors provided in Table 4.14 of the *Wetlands Supplement.* The methodology follows Equation 4.9, Chapter 4 of the *Wetlands Supplement*; Tier 1 emissions factors are multiplied by the area of freshwater (palustrine) coastal wetlands. The CH_4 fluxes applied are determined based on salinity; only palustrine wetlands are assumed to emit CH_4. Estuarine coastal wetlands in the C-CAP classification include wetlands with salinity less than 18 ppt, a threshold at which methanogenesis begins to occur (Poffenbarger et al. 2011), but the dataset currently does not differentiate estuarine wetlands based on their salinities and, as a result, CH_4 emissions from estuarine wetlands are not included at this time.

Uncertainty

Underlying uncertainties in the estimates of soil and biomass carbon stock changes and CH_4 emissions include uncertainties associated with Tier 2 literature values of soil carbon stocks, biomass carbon stocks and CH_4 flux, assumptions that underlie the methodological approaches applied and uncertainties linked to interpretation of remote sensing data. Uncertainty specific to vegetated coastal wetlands remaining vegetated coastal wetlands include differentiation of palustrine and estuarine community classes, which determines the soil carbon stock and CH_4 flux applied. Uncertainties for soil and biomass carbon stock data for all subcategories are not available and thus assumptions were applied using expert judgment about the most appropriate assignment of a carbon stock to a disaggregation of a community class. Because mean soil and biomass carbon stocks for each available community

[62] Coastal Carbon Network (2023). Database: Coastal Carbon Library (Version 1.0.0). Smithsonian Environmental Research Center. Dataset. https://doi.org/10.25573/serc.21565671. Accessed September 2023.

class are in a fairly narrow range, the same overall uncertainty was assigned to each, respectively (i.e., applying approach for asymmetrical errors, the largest uncertainty for any soil carbon stock value should be applied in the calculation of error propagation; IPCC 2000). Uncertainty for root to shoot ratios, which are used for quantifying belowground biomass, are derived from the *2013 Wetlands Supplement*. Uncertainties for CH_4 flux are the Tier 1 default values reported in the *2013 IPCC Wetlands Supplement*. Overall uncertainty of the NOAA C-CAP remote sensing product is 15 percent. This is in the range of remote sensing methods (±10 to 15 percent; IPCC 2003). However, there is significant uncertainty in salinity ranges for tidal and non-tidal estuarine wetlands and activity data used to apply CH_4 flux emission factors (delineation of an 18 ppt boundary) that will need significant improvement to reduce uncertainties. Details on the emission/removal trends and methodologies through time are described in more detail in the introduction and the Methodology section. The combined uncertainty was calculated using the IPCC Approach 1 method of summing the squared uncertainty for each individual source (C-CAP, soil, biomass and CH_4) and taking the square root of that total.

Uncertainty estimates are presented in Table 6-71 for each subcategory (i.e., soil carbon, biomass carbon and CH_4 emissions). The combined uncertainty across all subcategory is 37.0 percent below and above the estimate of -6.4 MMT CO_2 Eq, which is primarily driven by the uncertainty in the CH_4 estimates because there is high variability in CH_4 emissions when the salinity is less than 18 ppt. In 2021, the total flux was -8.2 MMT CO_2 Eq., with lower and upper estimates of -11.3 and -5.2 MMT CO_2 Eq.

Table 6-71: IPCC Approach 1 Quantitative Uncertainty Estimates for Carbon Stock Changes and CH_4 Emissions occurring within Vegetated Coastal Wetlands Remaining Vegetated Coastal Wetlands in 2021 (MMT CO_2 Eq. and Percent)

Source/Sink	Gas	2022 Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Estimate (MMT CO_2 Eq.)		Uncertainty Range Relative to Estimate (%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Biomass C Stock Change	CO_2	(0.05)	(0.06)	(0.03)	-24.1%	+24.1%
Soil C Stock Change	CO_2	(12.5)	(14.7)	(10.3)	-17.7	+17.7%
CH_4 emissions	CH_4	4.3	3.0	5.6	-29.9%	+29.9%
Total Flux		**(8.2)**	**(11.3)**	**(5.2)**	**-36.5%**	**+36.5%**

Note: Parentheses indicate net sequestration. Totals may not sum due to independent rounding.

QA/QC and Verification

NOAA provided the National LiDAR Dataset, tide data, and C-CAP land cover and land cover change mapping, all of which are subject to agency internal QA/QC assessment consistent with the general QC checks outlined in the Inventory QA/QC Plan. Acceptance of final datasets into archive and dissemination are contingent upon the product compilation being compliant with mandatory QA/QC requirements (McCombs et al. 2016). QA/QC and verification of soil carbon stock datasets have been provided by the Smithsonian Environmental Research Center and coastal wetland inventory team leads who reviewed summary tables against reviewed sources. Biomass carbon stocks are derived from peer-review literature and reviewed by the U.S. Geological Survey prior to publishing, by the peer-review process during publishing, and by the coastal wetland inventory team leads before inclusion in this *Inventory*. A team of two evaluated and verified there were no computational errors within the calculation worksheets. Soil and biomass carbon stock change data are based upon peer-reviewed literature and CH_4 emission factors derived from the *Wetlands Supplement*.

Recalculations Discussion

A recalculation of emission factors for soil carbon accretion rates was performed using the same methodology and criteria as in Lu and Megonigal (2017) and described above. This new analysis incorporated data published since 2016 and other relevant data that were not previously included. Table 6-70 shows the new values. The updated synthesis resulted in a general increase in soil carbon accumulation rates for estuarine emergent and scrub/shrub

wetlands, which resulted in an annual average increase of removals of 2.3 MMT CO_2 Eq. for the entire time series. For vegetated coastal wetlands remaining vegetated coastal wetlands in 2022, inclusion of the updated values resulted in an increase of the sink from -5.9 MMT CO_2 Eq. to -8.2 MMT CO_2 Eq.

Planned Improvements

Harmonization across all spatial datasets used to calculate activity data is underway. Once completed, a better representation of forested tidal wetlands, palustrine tidal wetlands, and forest land near the tidal boundary will be obtained.

Work is currently underway to examine the feasibility of incorporating seagrass soil and biomass carbon stocks into the vegetated coastal wetlands remaining vegetated coastal wetlands estimates. Additionally, investigation into quantifying the distribution, area, and emissions resulting from impounded waters (i.e., coastal wetlands where tidal connection to the ocean has been restricted or eliminated completely) is underway.

Box 6-6: State-Level Case Studies for the Estimation of GHG Removals in Seagrasses

North Carolina and Maryland are the first states to include seagrasses within their state-level inventory. North Carolina has the largest extent of seagrass coverage along the U.S. Atlantic coast, measuring approximately 86,412 acres in 2021. Seagrass mapping efforts occurred in 2007, 2013, and 2020 using a field-validated aerial image classification. The Tier 1 soil carbon accumulation rate was used and currently, biomass is not included due to lack of local data. The analysis shows that these high salinity seagrass habitats provided a net carbon sink to the state, although greenhouse gas removals decreased over time due to loss in seagrass coverage. Overall, seagrass beds in 2021 sequestered approximately 0.055 MMT CO_2 Eq. (55.14 kt CO_2 Eq.) in the soils alone.

In Maryland, the state greenhouse gas inventory comprises blue carbon stocks and fluxes from estuarine wetlands and seagrasses. Maryland currently has long-term monitoring of submerged aquatic vegetation (SAV) extent and density through annual surveying, and the rate of carbon sequestration and methane emission was a regional average for coastal wetlands. This study at state-level calculation offers an opportunity to maintain consistency in reporting across spatial scales and allows positioning SAV in its role as a carbon sink, in addition to its benefits in water quality and habitat conservation, perpetuating Maryland's role as a leader in blue carbon accounting.

These two case studies demonstrate the importance of refining emission factor data and harmonizing the inclusion of this ecosystem in the land representation analysis (reconciling the National Ocean and Atmospheric Administration [NOAA] Coastal Change Analysis Program [C-CAP] data with the National Resource Inventory, Forest Inventory Analysis, and the National Land Cover Database).

Emissions from Vegetated Coastal Wetlands Converted to Unvegetated Open Water Coastal Wetlands

Vegetated coastal wetlands converted to unvegetated open water coastal wetlands is a source of emissions from soil, biomass, and DOM carbon stocks. An estimated 1,488 ha of vegetated coastal wetlands were converted to unvegetated open water coastal wetlands in 2022, which largely occurred within estuarine and palustrine emergent wetlands. Prior to 2006, annual conversion to unvegetated open water coastal wetlands was higher than current rates: 1,720 between 1990 and 2000 and 2,515 ha between 2001 and 2005. The Mississippi Delta represents more than 40 percent of the total coastal wetland of the United States, and over 90 percent of the area of vegetated coastal wetlands converted to unvegetated open water coastal wetlands. The drivers of coastal wetlands loss include legacy human impacts on sediment supply through rerouting river flow, direct impacts of channel cutting on hydrology, salinity and sediment delivery, and accelerated subsidence from aquifer extraction.

Each of these drivers directly contributes to wetland erosion and subsidence, while also reducing the resilience of the wetland to build with sea-level rise or recover from hurricane disturbance. Over recent decades, the rate of Mississippi Delta wetland loss has slowed, though episodic mobilization of sediment occurs during hurricane events (Couvillion et al. 2011; Couvillion et al. 2016). The land cover analysis between the 2006 and 2011 C-CAP surveys coincides with two such events, hurricanes Katrina and Rita (both making landfall in the late summer of 2005), that occurred between these C-CAP survey dates. The subsequent 2016 C-CAP survey determined that erosion rates had slowed.

Shallow nearshore open water within the U.S. land representation is recognized as falling under the coastal wetlands category within this *Inventory*. While high resolution mapping of coastal wetlands provides data to support IPCC Approach 2 methods for tracking land cover change, the depth in the soil profile to which sediment is lost is less clear. This *Inventory* adopts the Tier 1 methodological guidance from the *Wetlands Supplement* for estimating emissions following the methodology for excavation (see Methodology section, below) when vegetated coastal wetlands are converted to unvegetated open water coastal wetlands, assuming a 1 m depth of disturbed soil. This 1 m depth of disturbance is consistent with estimates of wetland carbon loss provided in the literature and the *Wetlands Supplement* (Crooks et al. 2009; Couvillion et al. 2011; Delaune and White 2012; IPCC 2014). The same assumption on depth of soils impacted by erosion has been applied here. It is a reasonable Tier 1 assumption, based on experience, but estimates of emissions are sensitive to the depth to which the assumed disturbances have occurred (Holmquist et al. 2018). A Tier 1 assumption is also adopted in that all mobilized carbon is immediately returned to the atmosphere (as assumed for terrestrial land-use categories), rather than redeposited in long-term carbon storage. The science is currently under evaluation to adopt more refined emissions factors for mobilized coastal wetland carbon based upon the geomorphic setting of the depositional environment.

In 2022, there were 1,488 ha of vegetated coastal wetlands converted to unvegetated open water coastal wetlands (Table 6-67) across all wetland types and climates, which resulted in 1.5 MMT CO_2 Eq. (0.4 MMT C) and 0.06 MMT CO_2 Eq. (0.02 MMT C) lost through soil and biomass, respectively, with minimal DOM C stock loss (Table 6-72, and Table 6-73). Across the reporting period, the area of vegetated coastal wetlands converted to unvegetated open water coastal wetlands was greatest between the 2006 to 2011 C-CAP reporting period (11,373 ha) and has decreased since then to current levels (Table 6-67).

Table 6-72: Net CO_2 Flux from Carbon Stock Changes in Vegetated Coastal Wetlands Converted to Unvegetated Open Water Coastal Wetlands (MMT CO_2 Eq.)

Year	1990	2005	2018	2019	2020	2021	2022
Biomass Flux	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Dead Organic Matter Flux	+	+	+	+	+	+	+
Soil Flux	1.7	2.5	1.5	1.5	1.5	1.5	1.5
Total C Stock Change	**1.8**	**2.6**	**1.5**	**1.5**	**1.5**	**1.5**	**1.5**

+ Absolute value does not exceed 0.05 MMT CO_2 Eq.

Note: Totals may not sum due to independent rounding.

Table 6-73: Net CO_2 Flux from Carbon Stock Changes in Vegetated Coastal Wetlands Converted to Unvegetated Open Water Coastal Wetlands (MMT C)

Year	1990	2005	2018	2019	2020	2021	2022
Biomass Flux	+	+	+	+	+	+	+
Dead Organic Matter Flux	+	+	+	+	+	+	+
Soil Flux	0.5	0.7	0.4	0.4	0.4	0.4	0.4
Total C Stock Change	**0.5**	**0.7**	**0.4**	**0.4**	**0.4**	**0.4**	**0.4**

+ Absolute value does not exceed 0.05 MMT C.

Note: Totals may not sum due to independent rounding.

Methodology and Time-Series Consistency

The following section includes a brief description of the methodology used to estimate changes in soil, biomass and DOM carbon stocks for vegetated coastal wetlands converted to unvegetated open water coastal wetlands.

Methodological recalculations were applied to the entire time series to ensure time-series consistency from 1990 through 2022.

Biomass Carbon Stock Changes

Biomass carbon stock changes for palustrine and estuarine marshes are estimated for vegetated coastal wetlands converted to unvegetated open water coastal wetlands on lands below the elevation of high tides (taken to be mean high water spring tide elevation) within the U.S. land representation according to the national LiDAR dataset, the national network of tide gauges and land use histories recorded in the 1996, 2001, 2006, 2010, and 2016 NOAA C-CAP surveys. C-CAP areas are calculated at the state/territory level and summed according to climate zone to national values. Publicly-owned and privately-owned lands are represented. Trends in land cover change are extrapolated to 1990 and 2021 from these datasets. The C-CAP database provides peer reviewed country-specific mapping to support IPCC Approach 3 quantification of coastal wetland distribution, including conversion to and from open water. Biomass carbon stocks are not sensitive to soil organic content but are differentiated based on climate zone. Non-forested aboveground biomass carbon stock data are derived from a national assessment combining field plot data and aboveground biomass mapping by remote sensing (Byrd et al. 2017; Byrd et al. 2018; Byrd et al. 2020). The aboveground biomass carbon stock for estuarine forested wetlands (dwarf mangroves that are not classified as forests due to their stature) is derived from a meta-analysis by Lu and Megonigal (2017[63]; Table 6-68). Aboveground biomass carbon stock data for all subcategories are not available and thus assumptions were applied using expert judgment about the most appropriate assignment of a carbon stock to a disaggregation of a community class. Root to shoot ratios from the *Wetlands Supplement* were used to account for belowground biomass, which were multiplied by the aboveground carbon stock (Table 6-69; IPCC 2014). Above- and belowground values were summed to obtain total biomass carbon stocks. Conversion to open water results in emissions of all biomass carbon stocks during the year of conversion; therefore, emissions are calculated by multiplying the C-CAP derived area of vegetated coastal wetlands lost that year in each climate zone by its mean biomass.

Dead Organic Matter

Dead organic matter (DOM) carbon stocks, which include litter and dead wood stocks for subtropical estuarine forested wetlands, are an emission from vegetated coastal wetlands converted to unvegetated open water coastal wetlands across all years in the time series. Data on DOM carbon stocks are not currently available for either palustrine or estuarine scrub/shrub wetlands for any climate zone. Data for estuarine forested wetlands in other climate zones are not included since there is no estimated loss of these forests to unvegetated open water coastal wetlands across any year based on C-CAP data. For subtropical estuarine forested wetlands, Tier 1 estimates of mangrove DOM were used (IPCC 2014). Trends in land cover change are derived from the NOAA C-CAP dataset and extrapolated to cover the entire 1990 through 2021 time series. Conversion to open water results in emissions of all DOM carbon stocks during the year of conversion; therefore, emissions are calculated by multiplying the C-CAP derived area of vegetated coastal wetlands lost that year by its Tier 1 DOM carbon stock.

Soil Carbon Stock Changes

Soil carbon stock changes are estimated for vegetated coastal wetlands converted to unvegetated open water coastal wetlands. Country-specific soil carbon stocks were updated in 2018 based upon analysis of an assembled dataset of 1,959 cores from across the conterminous United States (Holmquist et al. 2018). This analysis

[63] See https://github.com/Smithsonian/Coastal-Wetland-NGGI-Data-Public; accessed September 2023.

demonstrated that it was not justified to stratify carbon stocks based upon mineral or organic soil classification, climate zone, or wetland classes; therefore, a single soil carbon stock of 270 t C ha^{-1} was applied to all classes. Following the Tier 1 approach for estimating CO_2 emissions with extraction provided within the *Wetlands Supplement*, soil carbon loss with conversion of vegetated coastal wetlands to unvegetated open water coastal wetlands is assumed to affect soil carbon stock to one-meter depth (Holmquist et al. 2018) with all emissions occurring in the year of wetland conversion, and multiplied by activity data of vegetated coastal wetland area converted to unvegetated open water wetlands. The methodology follows Eq. 4.6 in the *Wetlands Supplement*.

Soil Methane Emissions

A Tier 1 assumption has been applied that salinity conditions are unchanged and hence CH_4 emissions are assumed to be zero with conversion of vegetated coastal wetlands to unvegetated open water coastal wetlands.

Uncertainty

Underlying uncertainties in estimates of soil and biomass carbon stock changes are associated with country-specific (Tier 2) literature values of these stocks, while the uncertainties with the Tier 1 estimates are associated with subtropical estuarine forested wetland DOM stocks. Assumptions that underlie the methodological approaches applied and uncertainties linked to interpretation of remote sensing data are also included in this uncertainty assessment. The IPCC default assumption of 1 m of soil erosion with anthropogenic activities was adopted to provide standardization in U.S. tidal carbon accounting (Holmquist et al. 2018). This depth of potentially erodible tidal wetland soil has not been comprehensively addressed since most soil cores analyzed were shallow (e.g., less than 50 cm) and do not necessarily reflect the depth to non-wetland soil or bedrock (Holmquist et al. 2018). Uncertainty specific to coastal wetlands include differentiation of palustrine and estuarine community classes, which determines the soil carbon stock applied. Because mean soil and biomass carbon stocks for each available community class are in a fairly narrow range, the same overall uncertainty was assigned to each (i.e., applying approach for asymmetrical errors, the largest uncertainty for any soil carbon stock value should be applied in the calculation of error propagation; IPCC 2000). For aboveground biomass carbon stocks, the mean standard error was very low and largely influenced by the uncertainty associated with the estimated map area (Byrd et al. 2018). Uncertainty for root to shoot ratios, which are used for quantifying belowground biomass, are derived from the *Wetlands Supplement*. Uncertainty for subtropical estuarine forested wetland DOM stocks was derived from those listed for the Tier 1 estimates (IPCC 2014). Overall uncertainty of the NOAA C-CAP remote sensing product is 15 percent. This is in the range of remote sensing methods (+/-10 to 15 percent; IPCC 2003). The combined uncertainty was calculated by summing the squared uncertainty for each individual source (C-CAP, soil, biomass, and DOM) and taking the square root of that total.

Uncertainty estimates are presented in Table 6-74 for each subcategory (i.e., soil carbon, biomass carbon, and DOM emissions). The combined uncertainty across all subcategory is 32.0 percent above and below the estimate of 1.5 MMT CO_2 Eq, which is driven by the uncertainty in the soil carbon estimates. In 2022, the total carbon flux was 1.5 MMT CO_2 Eq., with lower and upper estimates of 1.0 and 2.0 MMT CO_2 Eq.

Table 6-74: Approach 1 Quantitative Uncertainty Estimates for CO_2 Flux Occurring within Vegetated Coastal Wetlands Converted to Unvegetated Open Water Coastal Wetlands in 2022 (MMT CO_2 Eq. and Percent)

Source	2022 Flux Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Flux Estimate (MMT CO_2 Eq.)		(%)	
		Lower Bound	Upper Bound	Lower Bound	Upper Bound
Biomass C Stock	0.06	0.05	0.08	-24.1%	+24.1%
Dead Organic Matter C Stock	0.0005	0.000	0.001	-25.8%	+25.8%
Soil C Stock	1.5	1.3	1.7	-15.0%	+15.0%
Total Flux	**1.5**	**1.0**	**2.0**	**-32.0%**	**+32.0%**

Note: Totals may not sum due to independent rounding.

QA/QC and Verification

Data provided by NOAA (i.e., National LiDAR Dataset, NOS Tide Data, and C-CAP land cover and land cover change mapping) undergo internal agency QA/QC procedures. Acceptance of final datasets into archive and dissemination are contingent upon assurance that the data product is compliant with mandatory NOAA QA/QC requirements (McCombs et al. 2016). QA/QC and Verification of the soil carbon stock dataset have been provided by the Smithsonian Environmental Research Center and by the Coastal Wetlands project team leads who reviewed the estimates against primary scientific literature. Biomass carbon stocks are derived from peer-review literature and reviewed by the U.S. Geological Survey prior to publishing, by the peer-review process during publishing, and by the coastal wetland inventory team leads before inclusion in the *Inventory*. For subtropical estuarine forested wetlands, Tier 1 estimates of mangrove DOM were used (IPCC 2014). Land cover estimates were assessed to ensure that the total land area did not change over the time series in which the inventory was developed, and were verified by a second QA team. A team of two evaluated and verified there were no computational errors within the calculation worksheets.

Recalculations Discussion

No recalculations were performed for the current *Inventory*.

Planned Improvements

The depth of soil carbon affected by conversion of vegetated coastal wetlands converted to unvegetated coastal wetlands will be updated from the IPCC default assumption of 1 m of soil erosion when mapping and modeling advancements can quantitatively improve accuracy and precision. Improvements are underway to address this, first conducting a review of literature publications. Until the time where these more detailed and spatially distributed data are available, the IPCC default assumption that the top 1 m of soil is disturbed by anthropogenic activity will be applied. This is a longer-term improvement.

More detailed research is in development that provides a longer-term assessment and more highly refined rates of wetlands loss across the Mississippi Delta (e.g., Couvillion et al. 2016). The Mississippi Delta is the largest extent of coastal wetlands in the United States. Higher resolution imagery analysis would improve quantification of conversation to open water, which occurs not only at the edge of the marsh but also within the interior. Improved mapping could provide a more refined regional Approach 2-3 land representation to support the national-scale assessment provided by C-CAP.

An approach for calculating the fraction of remobilized coastal wetland soil carbon returned to the atmosphere as CO_2 is currently under review and may be included in future reports.

Research by USGS is investigating higher resolution mapping approaches to quantify conversion of coastal wetlands is also underway. Such approaches may form the basis for a full Approach 3 land representation assessment in future years. C-CAP data harmonization with the National Land Cover Dataset (NLCD) will be incorporated into a future iteration of the *Inventory*.

Stock Changes from Unvegetated Open Water Coastal Wetlands Converted to Vegetated Coastal Wetlands

Open water within the U.S. land base, as described in Section 6.1, is recognized as coastal wetlands within this *Inventory*. The appearance of vegetated tidal wetlands on lands previously recognized as open water reflects either the building of new vegetated marsh through sediment accumulation or the transition from other lands uses through an intermediary open water stage as flooding intolerant plants are displaced and then replaced by wetland plants. Biomass, DOM and soil carbon accumulation on unvegetated open water coastal wetlands converted to vegetated coastal wetlands begins with vegetation establishment.

Within the United States, conversion of unvegetated open water coastal wetlands to vegetated coastal wetlands is predominantly due to engineered activities, which include active restoration of wetlands (e.g., wetlands restoration in San Francisco Bay), dam removals or other means to reconnect sediment supply to the nearshore (e.g., Atchafalaya Delta, Louisiana, Couvillion et al. 2011). Wetland restoration projects have been ongoing in the United States since the 1970s. Early projects were small, a few hectares in size. By the 1990s, restoration projects, each hundreds of hectares in size, were becoming common in major estuaries. In several coastal areas e.g., San Francisco Bay, Puget Sound, Mississippi Delta and south Florida, restoration activities are in planning and implementation phases, each with the goal of recovering tens of thousands of hectares of wetlands.

In 2022, 2,406 ha of unvegetated open water coastal wetlands were converted to vegetated coastal wetlands across all wetland types and climates, which has steadily increased over the reporting period (Table 6-66). This resulted in 0.007 MMT CO_2 Eq. (0.002 MMT C) and 0.1 MMT CO_2 Eq. (0.03 MMT C) sequestered in soil and biomass, respectively (Table 6-75 and Table 6-76). The soil carbon stock has increased during the *Inventory* reporting period, likely due to increasing vegetated coastal wetland restoration over time. While DOM carbon stock increases are present, they are minimal in the early part of the time series and zero in the later because there are no conversions from unvegetated open water coastal wetlands to subtropical estuarine forested wetlands between 2011 and 2016 (and by proxy through 2022), and that is the only coastal wetland type where DOM data is currently available.

Throughout the reporting period, the amount of open water coastal wetlands converted to vegetated coastal wetlands has increased over time, reflecting the increase in engineered restoration activities mentioned above.

Table 6-75: CO_2 Flux from Carbon Stock Changes from Unvegetated Open Water Coastal Wetlands Converted to Vegetated Coastal Wetlands (MMT CO_2 Eq.)

Year	1990	2005	2018	2019	2020	2021	2022
Biomass C Flux	(+)	(0.1)	(0.1)	(0.1)	(0.1)	(0.1)	(0.1)
Dead Organic Matter C Flux	(+)	(+)	0	0	0	0	0
Soil C Flux	(+)	(+)	(+)	(+)	(+)	(+)	(+)
Total C Stock Change	**(+)**	**(0.1)**	**(0.1)**	**(0.1)**	**(0.1)**	**(0.1)**	**(0.1)**

+ Absolute value does not exceed 0.05 MMT CO_2 Eq.

Notes: Parentheses indicate net sequestration. Totals may not sum due to independent rounding.

Table 6-76: CO_2 Flux from Carbon Stock Changes from Unvegetated Open Water Coastal Wetlands Converted to Vegetated Coastal Wetlands (MMT C)

Year	1990	2005	2018	2019	2020	2021	2022
Biomass C Flux	(0.01)	(0.02)	(0.03)	(0.03)	(0.03)	(0.03)	(0.03)
Dead Organic Matter C Flux	(+)	(+)	0	0	0	0	0
Soil C Flux	(+)	(+)	(+)	(+)	(+)	(+)	(+)
Total C Stock Change	**(0.01)**	**(0.02)**	**(0.03)**	**(0.03)**	**(0.03)**	**(0.03)**	**(0.03)**

+ Absolute value does not exceed 0.005 MMT C.

Notes: Parentheses indicate net sequestration. Totals may not sum due to independent rounding.

Methodology and Time-Series Consistency

The following section includes a brief description of the methodology used to estimate changes in soil, biomass and DOM carbon stocks, and CH_4 emissions for unvegetated open water coastal wetlands converted to vegetated coastal wetlands.

Methodological recalculations were applied to the entire time series to ensure time-series consistency from 1990 through 2022.

Biomass Carbon Stock Changes

Quantification of regional coastal wetland biomass carbon stock changes for palustrine and estuarine marsh vegetation are presented for unvegetated open water coastal wetlands converted to vegetated coastal wetlands on lands below the elevation of high tides (taken to be mean high water spring tide elevation) according to the national LiDAR dataset, the national network of tide gauges and land use histories recorded in the 1996, 2001, 2005, 2011, and 2016 NOAA C-CAP surveys. C-CAP areas are calculated at the state/territory level and summed according to climate zone to national values. Privately-owned and publicly-owned lands are represented. Trends in land cover change are extrapolated to 1990 and 2022 from these datasets (Table 6-65). C-CAP provides peer reviewed high resolution level mapping of coastal wetland distribution, including conversion to and from open water. Biomass carbon stock is not sensitive to soil organic content but differentiated based on climate zone. Data for non-forested wetlands are derived from a national assessment combining field plot data and aboveground biomass mapping by remote sensing (Table 6-68; Byrd et al. 2017; Byrd et al. 2018; Byrd et al. 2020). The aboveground biomass carbon stock for subtropical estuarine forested wetlands (dwarf mangroves that are not classified as forests due to their stature) is derived from a meta-analysis by Lu and Megonigal (2017[64]). Aboveground biomass carbon stock data for all subcategories are not available and thus assumptions were applied using expert judgment about the most appropriate assignment of a carbon stock to a disaggregation of a community class. Root to shoot ratios from the *Wetlands Supplement* were used to account for belowground biomass, which were multiplied by the aboveground carbon stock (Table 6-69; IPCC 2014). Above- and belowground values were summed to obtain total biomass carbon stocks.

Conversion of open water to vegetated coastal wetlands results in the establishment of a standing biomass carbon stock; therefore, stock changes that occur are calculated by multiplying the C-CAP derived area gained that year in each climate zone by its mean biomass. While the process of revegetation of unvegetated open water wetlands can take many years to occur, it is assumed in the calculations that the total biomass is reached in the year of conversion.

Dead Organic Matter

Dead organic matter (DOM) carbon stocks, which include litter and dead wood stocks, are included for subtropical estuarine forested wetlands for vegetated coastal wetlands converted to unvegetated open water coastal wetlands across all years. Tier 1 default or country-specific data on DOM are not currently available for either palustrine or estuarine scrub/shrub wetlands for any climate zone. Data for estuarine forested wetlands in other climate zones are not included since there is no estimated loss of these forests to unvegetated open water coastal wetlands across any year based on C-CAP data. Tier 1 estimates of subtropical estuarine forested wetland DOM were used (IPCC 2014). Trends in land cover change are derived from the NOAA C-CAP dataset and extrapolated to cover the entire 1990 through 2021 time series. Dead organic matter removals are calculated by multiplying the C-CAP derived area gained that year by its Tier 1 DOM C stock. Similar to biomass carbon stock gains, gains in DOM can take many years to occur, but for this analysis, the total DOM stock is assumed to accumulate during the first year of conversion.

Soil Carbon Stock Change

Soil carbon stock changes are estimated for unvegetated open water coastal wetlands converted to vegetated coastal wetlands. Country-specific soil carbon removal factors associated with soil carbon accretion, stratified by climate zones and wetland classes, are derived from a synthesis of peer-reviewed literature and updated this year based upon refined review of the dataset (Lynch 1989; Orson et al. 1990; Kearny & Stevenson 1991; Thom et al. 1992; Roman et al. 1997; Craft et al. 1998; Orson et al. 1998; Merrill 1999; Weis et al. 2001; Hussein et al. 2004; Church et al. 2006; Köster et al. 2007; Drexler et al. 2009; Boyd 2012; Callaway et al. 2012 a & b; Bianchi et al.

[64] See https://doi.org/10.25573/serc.21565671; accessed September 2023.

2013; Drexler et al. 2013; Watson and Byrne 2013; Crooks et al. 2014; Breithaupt et al. 2014; Weston et al. 2014; Smith et al. 2015; Villa & Mitsch 2015; Boyd and Sommerfield 2016; Marchio et al. 2016; Noe et al. 2016; Arriola and Cable 2017; Boyd et al. 2017; Gerlach et al. 2017; Giblin and Forbrich 2018; Krauss et al. 2018; Abbott et al. 2019; Drexler et al. 2019; Poppe and Rybczyk 2019; Ensign et al. 2020; Kemp et al. 2020; Lagomasino et al. 2020; Luk et al. 2020; McTigue et al. 2020; Peck et al. 2020; Vaughn et al. 2020; Weston et al. 2020; Arias-Ortiz et al. 2021; Baustian et al. 2021; Allen et al. 2022; Miller et al. 2022). Soil carbon stock changes are stratified based upon wetland class (Estuarine, Palustrine) and subclass (Emergent Marsh, Scrub Shrub). For soil carbon stock change, no differentiation is made for soil type (i.e., mineral, organic). Soil carbon removal factors were developed from literature references that provided soil carbon removal factors disaggregated by climate region and vegetation type by salinity range (estuarine or palustrine) as identified using NOAA C-CAP as described above (see Table 6-70 for values).

Tier 2 level estimates of carbon stock changes associated with annual soil carbon accumulation in vegetated coastal wetlands were developed using country-specific soil carbon removal factors multiplied by activity data on unvegetated coastal wetlands converted to vegetated coastal wetlands. The methodology follows Eq. 4.7, Chapter 4 of the *Wetlands Supplement*, and is applied to the area of unvegetated coastal wetlands converted to vegetated coastal wetlands on an annual basis.

Soil Methane Emissions

A Tier 1 assumption has been applied that salinity conditions are unchanged and hence CH_4 emissions are assumed to be zero with conversion of vegetated open water coastal wetlands to vegetated coastal wetlands.

Uncertainty

Underlying uncertainties in estimates of soil and biomass carbon stock changes include uncertainties associated with country-specific (Tier 2) literature values of these carbon stocks, assumptions that underlie the methodological approaches applied and uncertainties linked to interpretation of remote sensing data. Uncertainty specific to coastal wetlands include differentiation of palustrine and estuarine community classes that determines the soil carbon stock applied. Because mean soil and biomass carbon stocks for each available community class are in a fairly narrow range, the same overall uncertainty was applied to each, respectively (i.e., applying approach for asymmetrical errors, the largest uncertainty for any soil carbon stock value should be applied in the calculation of error propagation; IPCC 2000). For aboveground biomass carbon stocks, the mean standard error was very low and largely influenced by error in estimated map area (Byrd et al. 2018). Uncertainty for root to shoot ratios, which are used for quantifying belowground biomass (Table 6-69), are derived from the *Wetlands Supplement*. Uncertainty for subtropical estuarine forested wetland DOM stocks were derived from those listed for the Tier 1 estimates (IPCC 2014). Overall uncertainty of the NOAA C-CAP remote sensing product is 15 percent. This is in the range of remote sensing methods (±10 to 15 percent; IPCC 2003). The combined uncertainty was calculated by summing the squared uncertainty for each individual source (C-CAP, soil, biomass, and DOM) and taking the square root of that total.

Uncertainty estimates are presented in Table 6-77 for each subcategory (i.e., soil carbon, biomass carbon and DOM emissions). The combined uncertainty across all subsources is 33.43 percent above and below the estimate of -0.1 MMT CO_2 Eq. In 2022, the total carbon flux was -0.1 MMT CO_2 Eq., with lower and upper estimates of -0.1 and -0.08 MMT CO_2 Eq.

Table 6-77: Approach 1 Quantitative Uncertainty Estimates for Carbon Stock Changes Occurring within Unvegetated Open Water Coastal Wetlands Converted to Vegetated Coastal Wetlands in 2022 (MMT CO_2 Eq. and Percent)

Source	2022 Flux Estimate (MMT CO_2 Eq.)	Uncertainty Range (MMT CO_2 Eq.)		Relative to Flux Estimate (%)	
		Lower Bound	Upper Bound	Lower Bound	Upper Bound
Biomass C Stock Flux	(0.1)	(0.12)	(0.08)	-20.0%	+20.0%
Dead Organic Matter C Stock Flux	0	0	0	-25.8%	+25.8%
Soil C Stock Flux	(0.008)	(0.009)	(0.006)	-17.7%	+17.7%
Total Flux	**(0.1)**	**(0.14)**	**(0.01)**	**-33.3%**	**+33.3%**

Notes: Parentheses indicate net sequestration. Totals may not sum due to independent rounding.

QA/QC and Verification

NOAA provided data (i.e., National LiDAR Dataset, NOS Tide Data, and C-CAP land cover and land cover change mapping), which undergo internal agency QA/QC assessment procedures. Acceptance of final datasets into the archive for dissemination are contingent upon assurance that the product is compliant with mandatory NOAA QA/QC requirements (McCombs et al. 2016). QA/QC and Verification of soil carbon stock dataset has been provided by the Smithsonian Environmental Research Center and Coastal Wetlands project team leads who reviewed the summary tables against primary scientific literature. Aboveground biomass carbon reference stocks are derived from an analysis by the Blue Carbon Monitoring project and reviewed by U.S. Geological Survey prior to publishing, the peer-review process during publishing, and the coastal wetland inventory team leads before inclusion in the *Inventory*. Root to shoot ratios and DOM data are derived from peer-reviewed literature and undergo review as per IPCC methodology. Land cover estimates were assessed to ensure that the total land area did not change over the time series in which the inventory was developed and verified by a second QA team. A team of two evaluated and verified there were no computational errors within calculation worksheets. Two biogeochemists at the USGS, also members of the NASA Carbon Monitoring System Science Team, corroborated the simplifying assumption that where salinities are unchanged CH_4 emissions are constant with conversion of unvegetated open water coastal wetlands to vegetated coastal wetlands.

Recalculations Discussion

A recalculation of emission factors for soil carbon accretion rates was performed using the same methodology and criteria as in Lu and Megonigal (2017) and described above. This new analysis incorporated data published since 2016 and other relevant data that were not previously included. Table 6-70 shows the new values. The updated synthesis resulted in a general increase in soil carbon accumulation rates for estuarine emergent and scrub/shrub wetlands, which resulted in a minimal annual average increases in removals of 0.001 MMT CO_2 Eq. for the entire time series.

Planned Improvements

The USGS is investigating higher resolution mapping approaches to quantify conversion of coastal wetlands. Such approaches may form the basis for a full Approach 3 land representation assessment in future years. C-CAP data harmonization with the National Land Cover Dataset (NLCD) will be incorporated into a future iteration of the *Inventory*.

N_2O Emissions from Aquaculture in Coastal Wetlands

Shrimp and fish cultivation in coastal areas increases nitrogen loads resulting in direct emissions of N_2O. Nitrous oxide is generated and emitted as a byproduct of the conversion of ammonia (contained in fish urea) to nitrate

through nitrification and nitrate to N_2 gas through denitrification (Hu et al. 2012). Nitrous oxide emissions can be readily estimated from data on fish production (IPCC 2014).

Aquaculture production in the United States has fluctuated slightly from year to year, with resulting N_2O emissions between 0.1 and 0.2 MMT CO_2 Eq. between 1990 and 2022 (Table 6-78). Aquaculture production data were updated through 2019; data through 2022 are not yet available and in this analysis are held constant with 2019 emissions of 0.2 MMT CO_2 Eq. (0.5 Kt N_2O).

Table 6-78: N_2O Emissions from Aquaculture in Coastal Wetlands (MMT CO_2 Eq. and kt N_2O)

Year	1990	2005	2018	2019	2020	2021	2022
Emissions (MMT CO_2 Eq.)	0.1	0.2	0.1	0.1	0.1	0.1	0.1
Emissions (kt N_2O)	0.4	0.6	0.5	0.5	0.5	0.5	0.5

Methodology and Time-Series Consistency

The methodology to estimate N_2O emissions from aquaculture in coastal wetlands follows the Tier 1 guidance in the *Wetlands Supplement* by applying country-specific fisheries production data and the IPCC Tier 1 default emission factor.

Each year NOAA Fisheries document the status of U.S. marine fisheries in the annual report of *Fisheries of the United States* (National Marine Fisheries Service 2022), from which activity data for this analysis is derived.[65] The fisheries report has been produced in various forms for more than 100 years, primarily at the national level, on U.S. recreational catch and commercial fisheries landings and values. In addition, data are reported on U.S. aquaculture production, the U.S. seafood processing industry, imports and exports of fish-related products, and domestic supply and per capita consumption of fisheries products. Within the aquaculture chapter, the mass of production for catfish, striped bass, tilapia, trout, crawfish, salmon and shrimp are reported. While some of these fisheries are produced on land and some in open water cages within coastal wetlands, all have data on the quantity of food stock produced, which is the activity data that is applied to the IPCC Tier 1 default emissions factor to estimate emissions of N_2O from aquaculture. It is not apparent from the data as to the amount of aquaculture occurring above the extent of high tides on river floodplains. While some aquaculture occurs on coastal lowland floodplains, this is likely a minor component of tidal aquaculture production because of the need for a regular source of water for pond flushing. The estimation of N_2O emissions from aquaculture is not sensitive to salinity using IPCC approaches, and as such, the location of aquaculture ponds within the boundaries of coastal wetlands does not influence the calculations.

Other open water shellfisheries for which no food stock is provided, and thus no additional N inputs, are not applicable for estimating N_2O emissions (e.g., clams, mussels, and oysters) and have not been included in the analysis. The IPCC Tier 1 default emissions factor of 0.00169 kg N_2O-N per kg of fish/shellfish produced is applied to the activity data to calculate total N_2O emissions.

Methodological recalculations were applied to the entire time series to ensure time-series consistency from 1990 through 2022.

Uncertainty

Uncertainty estimates are based upon the Tier 1 default 95 percent confidence interval provided in Table 4.15, chapter 4 of the *Wetlands Supplement* for N_2O emissions and on expert judgment of the NOAA *Fisheries of the United States* fisheries production data. Given the overestimate of fisheries production from coastal wetland areas

[65] See https://www.fisheries.noaa.gov/resource/document/fisheries-united-states-2020; accessed September August 2023.

due to the inclusion of fish production in non-coastal wetland areas, this is a reasonable initial first approximation for an uncertainty range.

Uncertainty estimates for N_2O emissions from aquaculture production are presented in Table 6-79 for N_2O emissions. The combined uncertainty is 116 percent above and below the estimate of 0.13 MMT CO_2 Eq. In 2022, the total flux was 0.13 MMT CO_2 Eq., with lower and upper estimates of 0.00 and 0.29 MMT CO_2 Eq.

Table 6-79: Approach 1 Quantitative Uncertainty Estimates for N_2O Emissions from Aquaculture Production in Coastal Wetlands in 2022 (MMT CO_2 Eq. and Percent)

Source	2022 Emissions Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emissions Estimate[a] (MMT CO_2 Eq.)		(%)	
		Lower Bound	Upper Bound	Lower Bound	Upper Bound
Combined Uncertainty for N_2O Emissions for Aquaculture Production in Coastal Wetlands	0.13	0.00	0.29	-116%	+116%

[a] Range of emission estimates predicted by Monte Carlo stochastic simulation for a 95 percent confidence interval.

QA/QC and Verification

NOAA provided internal QA/QC review of reported fisheries data. The coastal wetlands inventory team consulted with the coordinating lead authors of the coastal wetlands chapter of the *Wetlands Supplement* to assess which fisheries production data to include in estimating emissions from aquaculture. It was concluded that N_2O emissions estimates should be applied to any fish production to which food supplement is supplied be they pond or coastal open water and that salinity conditions were not a determining factor in production of N_2O emissions.

Recalculations Discussion

No recalculations were performed for the current *Inventory*.

Flooded Land Remaining Flooded Land

Flooded lands are defined as water bodies where human activities have 1) caused changes in the amount of surface area covered by water, typically through water level regulation (e.g., constructing a dam), 2) waterbodies where human activities have changed the hydrology of existing natural waterbodies thereby altering water residence times and/or sedimentation rates, in turn causing changes to the natural emission of greenhouse gases, and 3) waterbodies that have been created by excavation, such as canals, ditches and ponds (IPCC 2019). Flooded lands include waterbodies with seasonally variable degrees of inundation, but these waterbodies would be expected to retain some inundated area throughout the year under normal conditions.

Flooded lands are broadly classified as "reservoirs" or "other constructed waterbodies" (IPCC 2019). Other constructed waterbodies include canals/ditches and ponds (flooded land <8 ha surface area). Reservoirs are defined as flooded land greater than 8 ha. IPCC guidance (IPCC 2019) provides default emission factors for reservoirs, ponds, and canals/ditches.

Land that has been flooded for greater than 20 years is defined as flooded land remaining flooded land and land flooded for 20 years or less is defined as land converted to flooded land. The distinction is based on literature reports that CH_4 and CO_2 emissions are high immediately following flooding, but decline to a steady background level approximately 20 years after flooding (Abril et al. 2005; Barros et al. 2011; Teodoru et al. 2012). Emissions of CH_4 are estimated for flooded land remaining flooded land, but CO_2 emissions are not included as they are

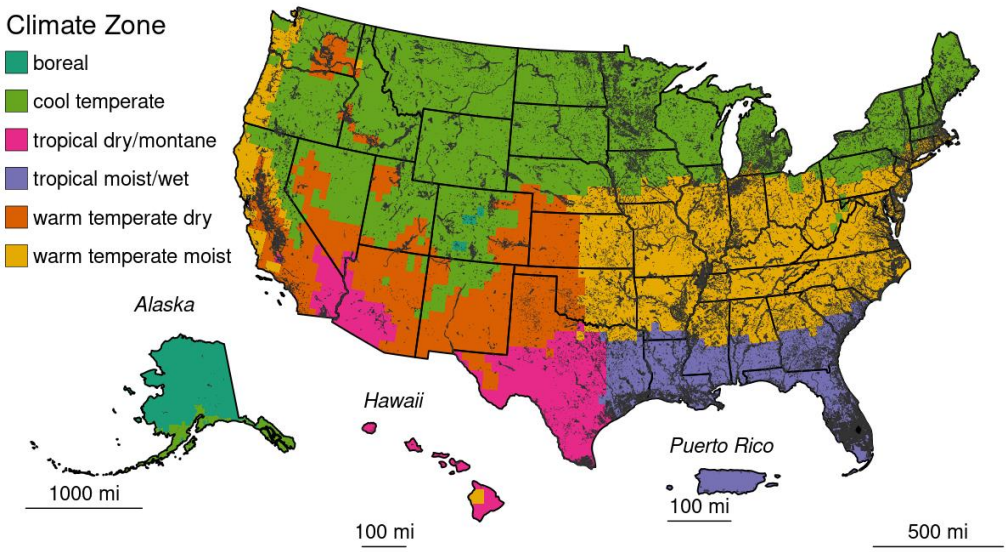
primarily the result of decomposition of organic matter entering the waterbody from the catchment or contained in inundated soils and are captured in Chapter 6, Land Use, Land-Use Change, and Forestry.

Nitrous oxide emissions from flooded lands are largely related to input of organic or inorganic nitrogen from the watershed. These inputs from runoff/leaching/deposition are largely driven by anthropogenic activities such as land-use change, wastewater disposal or fertilizer application in the watershed or application of fertilizer or feed in aquaculture. These emissions are not included here to avoid double-counting of N_2O emissions which are captured in other source categories, such as indirect N_2O emissions from managed soils (Section 5.4, Agricultural Soil Management) and wastewater management (Section 7.2, Wastewater Treatment and Discharge).

Emissions from Flooded Land Remaining Flooded Land–Reservoirs

Reservoirs are designed to store water for a wide range of purposes including hydropower, flood control, drinking water, and irrigation. In 2022, the United States and Puerto Rico hosted 10.2 million ha of reservoir surface area in the flooded land remaining flooded land category (see Methodology and Time-Series Consistency below for calculation details). These reservoirs are distributed across all six of the aggregated climate zones used to define flooded land emission factors (Figure 6-10) (IPCC 2019).

Figure 6-10: U.S. Reservoirs (black polygons) in the Flooded Land Remaining Flooded Land Category in 2022



Note: Colors represent climate zone used to derive IPCC default emission factors.

Methane is produced in reservoirs through the microbial breakdown of organic matter. Per unit area, CH_4 emission rates tend to scale positively with temperature and system productivity (i.e., abundance of algae), but negatively with system size (i.e., depth, surface area). Methane produced in reservoirs can be emitted from the reservoir surface or exported from the reservoir when CH_4-rich water passes through the dam. This exported CH_4 can be released to the atmosphere as the water passes through hydropower turbines or the downstream river channel. Methane emitted to the atmosphere via this pathway is referred to as "downstream emissions."

Table 6-80 and Table 6-81 below summarize nationally aggregated CH_4 emissions from reservoirs. The increase in CH_4 emissions through the time series is attributable to reservoirs matriculating from the land converted to flooded land category into the flooded land remaining flooded land category.

Table 6-80: CH_4 Emissions from Flooded Land Remaining Flooded Land—Reservoirs (MMT CO_2 Eq.)

Source	1990	2005	2018	2019	2020	2021	2022
Reservoirs							
Surface Emission	26.2	27.7	27.9	27.9	27.9	27.9	27.9
Downstream Emission	2.4	2.5	2.5	2.5	2.5	2.5	2.5
Total	**28.6**	**30.2**	**30.4**	**30.4**	**30.4**	**30.4**	**30.4**

Note: Totals may not sum to due independent rounding.

Table 6-81: CH_4 Emissions from Flooded Land Remaining Flooded Land—Reservoirs (kt CH_4)

Source	1990	2005	2018	2019	2020	2021	2022
Reservoirs							
Surface Emission	937	989	997	997	997	997	997
Downstream Emission	84	89	90	90	90	90	90
Total	**1,022**	**1,078**	**1,086**	**1,086**	**1,087**	**1,087**	**1,087**

Note: Totals may not sum to due independent rounding.

Methane emissions from reservoirs in Texas, Florida, and Louisiana (Figure 6-11, Table 6-82) compose 34 percent of national CH_4 emissions from reservoirs in 2022. Emissions from these states are particularly high due to 1) the large expanse of reservoirs in these states (Table 6-85) and 2) the high CH_4 emission factor for the tropical dry/montane and topical moist climate zones which encompass a majority of the flooded land area in these states (Figure 6-10, Table 6-83).

Methane emissions from reservoirs in flooded land remaining flooded land increased 6.4 percent from 1990 to 2022 due to the matriculation of reservoirs in land converted to flooded land to flooded land remaining flooded land.

Figure 6-11: Total CH_4 Emissions (Downstream + Surface) from Reservoirs in Flooded Land Remaining Flooded Land in 2022 (kt CH_4)

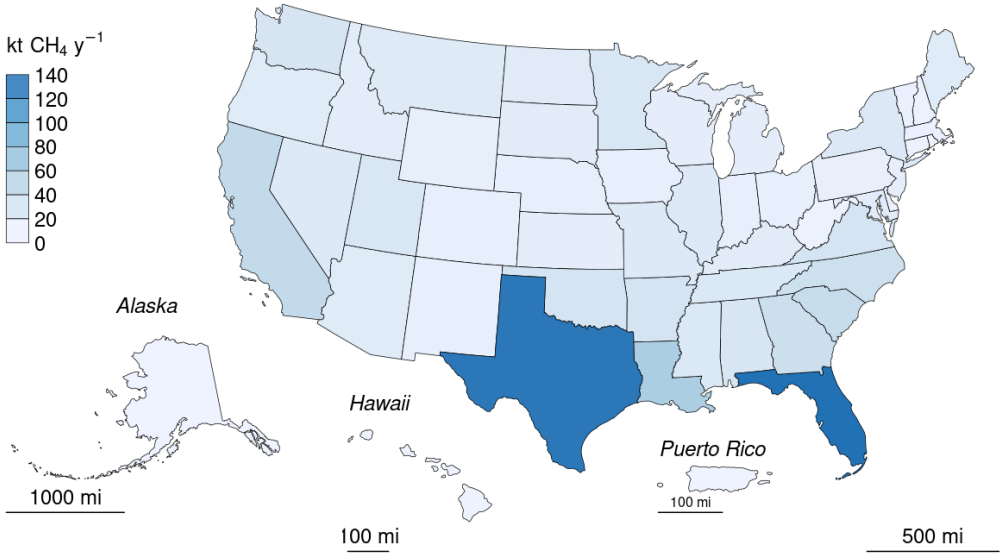


Table 6-82: Surface and Downstream CH_4 Emissions from Reservoirs in Flooded Land Remaining Flooded Land in 2022 (kt CH_4)

State	Surface	Downstream	Total
Alabama	22	2	24
Alaska	1	+	1
Arizona	14	1	16
Arkansas	25	2	27
California	42	4	46
Colorado	7	1	7
Connecticut	3	+	3
Delaware	3	+	3
District of Columbia	+	+	+
Florida	143	13	155
Georgia	35	3	38
Hawaii	1	+	1
Idaho	12	1	13
Illinois	17	2	19
Indiana	7	1	7
Iowa	7	1	7
Kansas	10	1	11
Kentucky	13	1	14
Louisiana	58	5	64
Maine	14	1	15
Maryland	13	1	14
Massachusetts	5	+	5
Michigan	9	1	10
Minnesota	21	2	23
Mississippi	20	2	21
Missouri	17	1	18
Montana	16	1	17
Nebraska	7	1	7
Nevada	17	2	19
New Hampshire	3	+	4
New Jersey	9	1	9
New Mexico	7	1	7
New York	18	2	20
North Carolina	33	3	36
North Dakota	14	1	15
Ohio	7	1	7
Oklahoma	26	2	28
Oregon	14	1	16
Pennsylvania	7	1	8
Puerto Rico	+	+	+
Rhode Island	1	+	1
South Carolina	38	3	41
South Dakota	12	1	14
Tennessee	20	2	21
Texas	138	12	150
Utah	21	2	23
Vermont	5	+	5
Virginia	25	2	27
Washington	23	2	25
West Virginia	3	+	3
Wisconsin	10	1	11
Wyoming	7	1	8

+ Indicates values less than 0.5 kt.

Methodology and Time-Series Consistency

Estimates of CH_4 emission for reservoirs in flooded land remaining flooded land follow the Tier 1 methodology in the *2019 Refinement to the 2006 IPCC Guidelines* (IPCC 2019). Methane emissions from the surface of these flooded lands are calculated as the product of flooded land surface area and a climate-specific emission factor (Table 6-83). Downstream emissions are calculated as nine percent of the surface emission (Tier 1 default). Total CH_4 emissions from reservoirs are calculated as the sum of surface and downstream emissions. National emissions are calculated as the sum of state emissions.

The IPCC default surface emission factors used in the Tier 1 methodology are derived from model-predicted (G-res model, Prairie et al. 2017) emission rates for all reservoirs in the Global Reservoir and Dam (GRanD) database (Lehner et al. 2011). Predicted emission rates were aggregated by the 11 IPCC climate zones (IPCC 2019, Table 7A.2) which were collapsed into six climate zones using a regression tree approach. All six aggregated climate zones are present in the United States.

Table 6-83: IPCC (2019) Default CH_4 Emission Factors for Surface Emission from Reservoirs in Flooded Land Remaining Flooded Land

Climate	Surface emission factor (MT CH_4 ha^{-1} y^{-1})
Boreal	0.0136
Cool Temperate	0.054
Warm Temperate Dry	0.1509
Warm Temperate Moist	0.0803
Tropical Dry/Montane	0.2837
Tropical Moist/Wet	0.1411

Note: downstream CH_4 emissions are calculated as 9 percent of surface emissions. Downstream emissions are not calculated for CO_2.

Area estimates

U.S. reservoirs were identified from the NHDWaterbody layer in the National Hydrography Dataset Plus V2 (NHD),[66] the National Inventory of Dams (NID),[67] the National Wetlands Inventory (NWI),[68] the Navigable Waterways (NW) network,[69] and the EPA's Safe Drinking Water Information System (SDWIS).[70] The NHD only covers the conterminous U.S., whereas the NID, NW and NWI also include Alaska, Hawaii, and Puerto Rico.

Waterbodies in the NHDWaterbody layer that were greater than or equal to 8 ha in surface area, not identified as canal/ditch in NHD, and met any of the following criteria were considered reservoirs: 1) the waterbody was classified as "Reservoir" in the NHDWaterbody layer, 2) the waterbody name in the NHDWaterbody layer included "Reservoir", 3) the waterbody in the NHDWaterbody layer was located in close proximity (up to 100 m) to a dam in the NID, 4) the NHDWaterbody GNIS name was similar to a nearby NID feature (between 100 m to 1000 m), 5) the waterbody intersected a public drinking water intake.

[66] See https://www.usgs.gov/core-science-systems/ngp/national-hydrography.

[67] See https://nid.sec.usace.army.mil.

[68] See https://www.fws.gov/program/national-wetlands-inventory/data-download.

[69] See https://hifld-geoplatform.opendata.arcgis.com/maps/aaa3767c7d2b41f69e7528f99cf2fb76_0/about.

[70] See https://www.epa.gov/enviro/sdwis-overview. Not publicly available due to security concerns.

EPA assumes that all features included in the NW network are subject to water-level management to maintain minimum water depths required for navigation and are therefore managed flooded lands. Navigable Waterway features greater than 8 ha in surface area are defined as reservoirs.

NWI features were considered "managed" if they had a Special Modifier value indicating the presence of management activities (Figure 6-12). To be included in the flooded lands inventory, the managed flooded land had to be wet or saturated for at least one season per year (see "Water Regime" in Figure 6-12). NWI features that met these criteria, were greater than 8 ha in surface area, and were not a canal/ditch (see emissions from land converted to flooded land – other constructed waterbodies) were defined as reservoirs.

Any NWI or NHD feature that intersected a drinking water intake point from SDWIS was assumed to be "managed." The rational being that a waterbody used as a source for public drinking water is typically managed in some capacity - by flow and/or volume control.

Surface areas for identified flooded lands were taken from the NHD, NWI or NW. If features from the NHD, NWI, or NW datasets overlapped, duplicated areas were erased. The first step was to take the final NWI flooded lands features and use it to identify overlapping NHD features. If the NHD feature had its center in a NWI feature, it was removed from analysis. Next, remaining NHD features were erased from any remaining overlapping NWI features. Final selections of NHD and NWI features were used to erase any overlapping NW waterbodies.

Reservoir age was determined by assuming the waterbody was created the same year as a nearby (up to 100 m) NID feature. If no nearby NID feature was identified, it was assumed the waterbody was greater than 20-years old throughout the time series.

Figure 6-12: Selected Features from NWI that Meet Flooded Lands Criteria

MODIFIERS

In order to more adequately describe the wetland and deepwater habitats, one each of the water regime, water chemistry, soil, or special modifiers may be applied at the class or lower level in the hierarchy.

Water Regime			Special Modifiers	Water Chemistry		Soil
Nontidal	**Saltwater Tidal**	**Freshwater Tidal**		**Halinity/Salinity**	**pH Modifiers for Fresh Water**	
A Temporarily Flooded	L Subtidal	Q Regularly Flooded-Fresh Tidal	b Beaver	1 Hyperhaline / Hypersaline	a Acid	g Organic
B Seasonally Saturated	M Irregularly Exposed	R Seasonally Flooded-Fresh Tidal	d Partly Drained/Ditched	2 Euhaline / Eusaline	t Circumneutral	n Mineral
C Seasonally Flooded	N Regularly Flooded	S Temporarily Flooded- Fresh Tidal	f Farmed	3 Mixohaline / M ixosaline (Brackish)	i Alkaline	
D Continuously Saturated	P Irregularly Flooded	T Semipermanently Flooded-Fresh Tidal	m Managed	4 Polyhaline		
E Seasonally Flooded / Saturated		V Permanently Flooded-Fresh Tidal	h Diked/Impounded	5 Mesohaline		
F Semipermanently Flooded			r Artificial Substrate	6 Oligohaline		
G Intermittently Exposed			s Spoil	0 Fresh		
H Permanently Flooded			x Excavated			
J Intermittently Flooded						
K Artificially Flooded						

Must also meet one selected special modifier (red box) to be included in the flooded lands inventory

Included in the flooded lands inventory if it meets water regime qualifier (gold box)

Source (modified): https://www.fws.gov/sites/default/files/documents/wetlands-and-deepwater-map-code-diagram.pdf

IPCC (2019) allows for the exclusion of managed waterbodies from the inventory if the water surface area or residence time was not substantially changed by the construction of the dam. The guidance does not quantify what constitutes a "substantial" change, but here EPA excludes the U.S. Great Lakes from the inventory based on expert judgment that neither the surface area nor water residence time was substantially altered by their associated dams.

Reservoirs were disaggregated by state (using boundaries from the 2016 U.S. Census Bureau[71]) and climate zone. Downstream and surface emissions for cross-state reservoirs were allocated to states based on the surface area that the reservoir occupied in each state. Only the U.S. portion of reservoirs that cross country borders were included in the inventory.

[71] See https://www.census.gov/geographies/mapping-files/time-series/geo/carto-boundary-file.html.

The surface area of reservoirs in flooded land remaining flooded land increased by approximately 6 percent from 1990 to 2022 (Table 6-84) due to reservoirs matriculating into flooded land remaining flooded land when they reached 20 years of age.

Table 6-84: National Totals of Reservoir Surface Area in Flooded Land Remaining Flooded Land (millions of ha)

Surface Area (millions of ha)	1990	2005	2018	2019	2020	2021	2022
Reservoir	9.6	10.1	10.2	10.2	10.2	10.2	10.2

Table 6-85: State Breakdown of Reservoir Surface Area in Flooded Land Remaining Flooded Land (millions of ha)

State	1990	2005	2018	2019	2020	2021	2022
Alabama	0.22	0.23	0.23	0.23	0.23	0.23	0.23
Alaska	0.02	0.02	0.02	0.02	0.02	0.02	0.02
Arizona	0.06	0.06	0.06	0.06	0.06	0.06	0.06
Arkansas	0.28	0.29	0.29	0.29	0.29	0.29	0.29
California	0.37	0.39	0.39	0.39	0.39	0.39	0.39
Colorado	0.08	0.09	0.09	0.09	0.09	0.09	0.09
Connecticut	0.03	0.03	0.04	0.04	0.04	0.04	0.04
Delaware	0.03	0.03	0.03	0.03	0.03	0.03	0.03
District of Columbia	+	+	+	+	+	+	+
Florida	0.98	1.01	1.01	1.01	1.01	1.01	1.01
Georgia	0.27	0.29	0.29	0.29	0.29	0.29	0.29
Hawaii	+	+	+	+	+	+	+
Idaho	0.17	0.19	0.19	0.19	0.19	0.19	0.19
Illinois	0.17	0.18	0.22	0.22	0.22	0.22	0.22
Indiana	0.07	0.08	0.08	0.08	0.08	0.08	0.08
Iowa	0.08	0.09	0.10	0.10	0.10	0.10	0.10
Kansas	0.09	0.11	0.11	0.11	0.11	0.11	0.11
Kentucky	0.16	0.16	0.16	0.16	0.16	0.16	0.16
Louisiana	0.40	0.41	0.41	0.41	0.41	0.41	0.41
Maine	0.25	0.26	0.26	0.26	0.26	0.26	0.26
Maryland	0.16	0.16	0.16	0.16	0.16	0.16	0.16
Massachusetts	0.07	0.07	0.07	0.07	0.07	0.07	0.07
Michigan	0.16	0.17	0.17	0.17	0.17	0.17	0.17
Minnesota	0.38	0.38	0.39	0.39	0.39	0.39	0.39
Mississippi	0.18	0.19	0.19	0.19	0.19	0.19	0.19
Missouri	0.19	0.21	0.21	0.21	0.21	0.21	0.21
Montana	0.27	0.29	0.29	0.29	0.29	0.29	0.29
Nebraska	0.07	0.08	0.08	0.08	0.08	0.08	0.08
Nevada	0.09	0.09	0.09	0.09	0.09	0.09	0.09
New Hampshire	0.06	0.06	0.06	0.06	0.06	0.06	0.06
New Jersey	0.11	0.11	0.11	0.11	0.11	0.11	0.11
New Mexico	0.05	0.05	0.05	0.05	0.05	0.05	0.05
New York	0.31	0.32	0.32	0.32	0.32	0.32	0.32
North Carolina	0.39	0.41	0.41	0.41	0.41	0.41	0.41
North Dakota	0.10	0.25	0.26	0.26	0.26	0.26	0.26
Ohio	0.08	0.09	0.09	0.09	0.09	0.09	0.09
Oklahoma	0.24	0.27	0.27	0.27	0.27	0.27	0.27
Oregon	0.20	0.20	0.20	0.20	0.20	0.20	0.20
Pennsylvania	0.09	0.11	0.11	0.11	0.11	0.11	0.11
Puerto Rico	+	+	+	+	+	+	+
Rhode Island	0.02	0.02	0.02	0.02	0.02	0.02	0.02
South Carolina	0.31	0.32	0.33	0.33	0.33	0.33	0.33

South Dakota	0.23	0.23	0.23	0.23	0.23	0.23	0.23
Tennessee	0.18	0.24	0.24	0.24	0.24	0.24	0.24
Texas	0.63	0.70	0.71	0.71	0.71	0.71	0.71
Utah	0.18	0.18	0.18	0.18	0.18	0.18	0.18
Vermont	0.09	0.09	0.09	0.09	0.09	0.09	0.09
Virginia	0.30	0.31	0.31	0.31	0.31	0.31	0.31
Washington	0.24	0.24	0.24	0.24	0.24	0.24	0.24
West Virginia	0.03	0.03	0.04	0.04	0.04	0.04	0.04
Wisconsin	0.18	0.18	0.18	0.18	0.18	0.18	0.18
Wyoming	0.12	0.13	0.14	0.14	0.14	0.14	0.14
Total	**9.47**	**10.10**	**10.20**	**10.20**	**10.20**	**10.20**	**10.20**

+ Indicates values less than 0.005 million ha.

Note: Totals may not sum due to independent rounding.

Uncertainty

Uncertainty in estimates of CH_4 emissions from reservoirs in flooded land remaining flooded land (Table 6-86) are developed using Monte Carlo simulations (IPCC Approach 2) and include uncertainty in the default emission factors and land areas. Each iteration of the simulation draws surface and downstream emission factors from a statistical distribution based on the mean and variance in the *2019 Refinement to the 2006 IPCC Guidelines* (IPCC 2019). The CH_4 emission factors for surface and downstream emissions are modeled using normal and lognormal distributions, respectively. The 2019 IPCC Refinement does not contain sufficient information to define a normal distribution for the CO_2 emission factor and a uniform distribution bounded by the 95% confidence internal of the mean is assumed. Uncertainties in the spatial data include 1) uncertainty in area estimates from the NHD, NWI, and NW, and 2) uncertainty in the location of dams in the NID and drinking water intakes in SDWIS. Overall uncertainties in these spatial datasets are unknown, but uncertainty for remote sensing products is assumed to be ± 10 - 15 percent based on IPCC guidance (IPCC 2003). An uncertainty range of ± 15 percent for the reservoir area estimates is assumed and is based on expert judgment. Each iteration of the simulation draws a surface area for each waterbody from a uniform distribution bounded by ± 15 percent of the estimated surface area.

Table 6-86: Approach 2 Quantitative Uncertainty Estimates for CH_4 Emissions from Reservoirs in Flooded Land Remaining Flooded Land

Source	Gas	2022 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Reservoir						
Surface	CH_4	27.9	27.4	28.4	-1.7%	+1.7%
Downstream	CH_4	2.5	2.4	3.1	-5.6%	+22.4%
Total	**CH_4**	**30.4**	**29.9**	**31.3**	**-1.6%**	**+2.9%**

[a] Range of emission estimates predicted by Monte Carlo stochastic simulation for a 95 percent confidence interval.

QA/QC and Verification

The National Hydrography Data (NHD) is managed by the USGS in collaboration with many other federal, state, and local entities. Extensive QA/QC procedures are incorporated into the curation of the NHD. The National Inventory of Dams (NID) is maintained by the U.S. Army Corps of Engineers (USACE) in collaboration with the Federal Emergency Management Agency (FEMA) and state regulatory offices. USACE resolves duplicative and conflicting data from 68 data sources, which helps obtain the more complete, accurate, and updated NID. The Navigable Waterways (NW) dataset is part of the U.S. Department of Transportation (USDOT)/Bureau of Transportation Statistics (BTS) National Transportation Atlas Database (NTAD). The NW is a comprehensive network database of the nation's navigable waterways updated on a continuing basis. U.S. Fish and Wildlife Service is the principal agency in charge of wetland mapping including the National Wetlands Inventory (NWI). Quality and consistency of

the Wetlands Layer is supported by federal wetlands mapping and classification standards, which were developed under the oversight of the Federal Geographic Data Committee (FGDC) with input by the FGDC Wetlands Subcommittee. This dataset is part of the FGDC Water-Inland Theme, which is co-chaired by the FWS and the U.S. Geological Survey. The EPA's Safe Drinking Water Information System (SDWIS) tracks information on drinking water contamination levels as required by the 1974 Safe Drinking Water Act and its 1986 and 1996 amendments.

General QA/QC procedures were applied to activity data, documentation, and emission calculations consistent with the U.S. Inventory QA/QC plan, which is in accordance with Vol. 1 Chapter 6 of the *2006 IPCC Guidelines* (see Annex 8 for more details). All calculations were executed independently in Excel and R. Ten percent of state and national totals were randomly selected for comparison between the two approaches to ensure there were no computational errors.

Recalculations Discussion

The EPA's SDWIS is a new data source used in the current (1990 through 2022) *Inventory*. The assumption is that any waterbody used as a public drinking water source is managed in some capacity - by flow and/or volume control. This data source added 418 reservoirs totaling 736,344 ha.

The National Inventory of Dams (NID) data are updated regularly. The version of NID used for the current *Inventory* contains 47 new dams and updated values for "year of dam completion" for 975 dams relative to the previous (1990 through 2021) *Inventory* data. Similarly, the National Wetlands Inventory (NWI) is periodically updated. The NWI version used for the current *Inventory* has major updates for MS, ND, NM, and MT.

The net effect of these recalculations was an average annual increase in CH_4 emission estimates from reservoirs of 1.23 MMT CO_2 Eq., or 4 percent, over the time series from 1990 to 2021 compared to the previous *Inventory*.

Planned Improvements

The EPA recently completed a survey of greenhouse gas emissions from 108 reservoirs in the conterminous United States.[72] The data will be used to develop country-specific emission factors for U.S. reservoirs to be used in the 1990 through 2024 *Inventory* submission.

Emissions from Flooded Land Remaining Flooded Land–Other Constructed Waterbodies

The IPCC (IPCC 2019) provides emission factors for several types of "other constructed waterbodies" including freshwater ponds and canals/ditches. IPCC (2019) describes ponds as waterbodies that are "…constructed by excavation and/or construction of walls to hold water in the landscape for a range of uses, including agricultural water storage, access to water for livestock, recreation, and aquaculture." Furthermore, the IPCC "Decision tree for types of Flooded Land" (IPCC 2019, Fig. 7.2) defines a size threshold of 8 ha to distinguish reservoirs from "other constructed waterbodies." For this *Inventory*, ponds are defined as managed flooded land that are 1) less than 8 ha in surface area, and 2) not categorized as canals/ditches. IPCC (2019) further distinguishes saline versus brackish ponds, with the former supporting lower CH_4 emissions than the latter. Activity data on pond salinity are not uniformly available for the conterminous United States and all ponds in the inventory are assumed to be freshwater. Ponds often receive high organic matter and nutrient loadings, may have low oxygen levels, and are often sites of substantial CH_4 emissions from anaerobic sediments.

Canals and ditches (terms are used interchangeably) are linear water features constructed to transport water (i.e., stormwater drainage, aqueduct), to irrigate or drain land, to connect two or more bodies of water, or to serve as a

[72] See https://www.epa.gov/air-research/research-emissions-us-reservoirs.

waterway for watercraft. The geometry and construction of canals and ditches varies widely and includes narrow earthen channels (<1 m wide) and concrete lined aqueducts in excess of 50 m wide. Canals and ditches can be extensive in many agricultural, forest and settlement areas, and may also be significant sources of emissions in some circumstances.

Methane emissions from freshwater ponds in flooded land remaining flooded land increased by approximately 1 percent from 1990 to 2022. Methane emissions from canals and ditches have remained constant throughout the time series because age data are not available for canals and ditches, thus they are assumed to be greater than 20-years old in 1990 and are included in flooded land remaining flooded land throughout the time series. Overall, CH_4 emissions from other constructed waterbodies have remained fairly constant since 1990 (Table 6-87 and Table 6-88).

Table 6-87: CH_4 Emissions from Other Constructed Waterbodies in Flooded Land Remaining Flooded Land (MMT CO_2 Eq.)

Source	1990	2005	2018	2019	2020	2021	2022
Other Constructed Waterbodies							
Canals and Ditches	2.3	2.3	2.3	2.3	2.3	2.3	2.3
Freshwater Ponds	11.4	11.5	11.5	11.5	11.5	11.5	11.5
Total	**13.7**	**13.8**	**13.8**	**13.8**	**13.8**	**13.8**	**13.8**

Note: Totals may not sum due to independent rounding.

Table 6-88: CH_4 Emissions from Other Constructed Waterbodies in Flooded Land Remaining Flooded Land (kt CH_4)

Source	1990	2005	2018	2019	2020	2021	2022
Other Constructed Waterbodies							
Canals and Ditches	80.9	80.9	80.9	80.9	80.9	80.9	80.9
Freshwater Ponds	406.6	411.0	411.7	411.8	411.8	411.8	411.9
Total	**487.5**	**491.9**	**492.6**	**492.6**	**492.7**	**492.7**	**492.7**

Note: Totals may not sum due to independent rounding.

Florida and Louisiana have the greatest methane emissions from canals and ditches in the United States (Figure 6-13, Table 6-89). Presumably, most of these canals serve to drain the extensive wetland complexes in these states (Davis, 1973). California has the third greatest methane emissions from canals and ditches. Canals and ditches in California primarily serve to convey water from the mountains to urban and agricultural areas. Michigan and Minnesota have the fourth and fifth largest methane emissions from canals and ditches. These systems serve to drain historic wetlands to facilitate row-crop agriculture. Texas, Florida, and Georgia have the greatest methane emissions from freshwater ponds, although states throughout the eastern United States make significant contributions to the national total. These patterns of emissions are in accordance with the distribution of other constructed waterbodies in the United States.

Table 6-89: CH_4 Emissions from Other Constructed Waterbodies in Flooded Land Remaining Flooded Land in 2022 (kt CH_4)

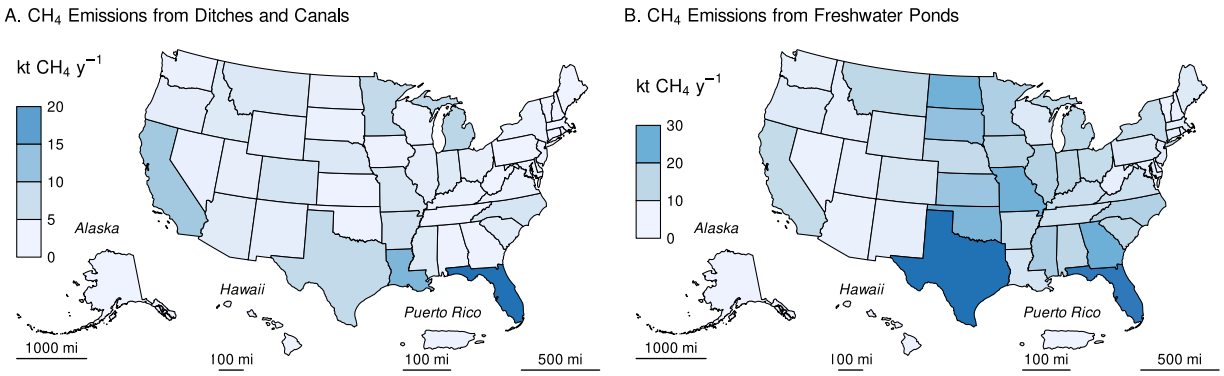
State	Canals and Ditches	Freshwater Ponds	Total
Alabama	+	10.5	10.6
Alaska	+	+	+
Arizona	1.5	1.0	2.4
Arkansas	3.1	9.4	12.4
California	7.0	9.2	16.2
Colorado	2.9	4.8	7.7
Connecticut	+	1.8	1.8
Delaware	+	0.9	0.9
District of Columbia	+	+	+

Florida	15.6	30.7	46.2
Georgia	+	21.0	21.2
Hawaii	+	+	0.5
Idaho	1.7	2.4	4.1
Illinois	1.0	11.7	12.8
Indiana	1.7	10.6	12.3
Iowa	+	11.2	11.6
Kansas	+	15.4	15.5
Kentucky	+	7.7	7.9
Louisiana	9.4	5.9	15.3
Maine	+	3.5	3.5
Maryland	+	2.3	2.7
Massachusetts	+	2.3	2.3
Michigan	5.4	10.0	15.4
Minnesota	4.7	12.7	17.3
Mississippi	1.6	13.4	15.1
Missouri	2.4	20.7	23.1
Montana	2.0	10.5	12.5
Nebraska	2.0	9.1	11.1
Nevada	0.7	0.8	1.5
New Hampshire	+	1.0	1.1
New Jersey	+	3.0	3.4
New Mexico	0.8	2.1	2.9
New York	+	8.3	8.7
North Carolina	2.6	12.2	14.8
North Dakota	0.8	20.6	21.3
Ohio	0.8	8.9	9.7
Oklahoma	+	19.3	19.4
Oregon	1.0	3.6	4.6
Pennsylvania	+	4.1	4.1
Puerto Rico	+	+	+
Rhode Island	+	+	+
South Carolina	1.3	10.4	11.7
South Dakota	+	16.6	16.9
Tennessee	+	6.7	6.8
Texas	4.6	32.1	36.8
Utah	0.8	2.0	2.8
Vermont	+	0.8	0.8
Virginia	0.5	7.3	7.9
Washington	+	2.0	2.5
West Virginia	+	1.5	1.5
Wisconsin	+	3.8	4.2
Wyoming	0.9	4.8	5.7
Total	**80.9**	**411.9**	**492.7**

+ Indicates values less than 0.5 kt.

Note: Totals may not sum due to independent rounding.

Figure 6-13: 2022 CH_4 Emissions from A) Ditches and Canals and B) Freshwater Ponds in Flooded Land Remaining Flooded Land (kt CH_4)



Methodology and Time-Series Consistency

Estimates of CH_4 emissions for other constructed waterbodies in flooded land remaining flooded Land follow the Tier 1 methodology in IPCC (2019). All calculations are performed at the state level and summed to obtain national estimates. Based on IPCC guidance, methane emissions from the surface of these flooded lands are calculated as the product of flooded land surface area and an emission factor (Table 6-90). Although literature data on greenhouse gas emissions from canals and ditches is relatively sparse, they have the highest default emission factor of all flooded land types (Table 6-90). Default emission factors for freshwater ponds are on the higher end of those for reservoirs. There are insufficient data to support climate-specific emission factors for ponds or canals and ditches. Downstream emissions are not inventoried for other constructed waterbodies because 1) many of these systems are not associated with dams (e.g., excavated ponds and ditches), and 2) there are insufficient data to derive downstream emission factors for other constructed waterbodies that are associated with dams (IPCC 2019).

Table 6-90: IPCC (2019) Default CH_4 Emission Factors for Surface Emissions from Other Constructed Waterbodies in Flooded Land Remaining Flooded Land

Other Constructed Waterbody	Surface emission factor (MT CH_4 ha^{-1} y^{-1})
Freshwater ponds	0.183
Canals and ditches	0.416

Area estimates

Other constructed waterbodies were identified from the NHDWaterbody layer in the National Hydrography Dataset Plus V2 (NHD),[73] the National Inventory of Dams (NID),[74] the National Wetlands Inventory (NWI),[75] the Navigable Waterways (NW) network,[76] and the EPA's Safe Drinking Water Information System (SDWIS).[77] The NHD

[73] See https://www.usgs.gov/core-science-systems/ngp/national-hydrography.

[74] See https://nid.sec.usace.army.mil.

[75] See https://www.fws.gov/program/national-wetlands-inventory/data-download.

[76] See https://hifld-geoplatform.opendata.arcgis.com/maps/aaa3767c7d2b41f69e7528f99cf2fb76_0/about.

[77] See https://www.epa.gov/enviro/sdwis-overview. Not publicly available due to security concerns.

only covers the conterminous United States, whereas the NID, NW and NWI also include Alaska, Hawaii, District of Columbia, and Puerto Rico. The following paragraphs present the criteria used to identify other constructed waterbodies in the NHD, NW, and NWI.

Waterbodies in the NHDWaterbody layer that were greater than 20-years old, less than 8 ha in surface area, not identified as canal/ditch in NHD, and met any of the following criteria were considered freshwater ponds in flooded land remaining flooded land: 1) the waterbody was classified "Reservoir" in the NHDWaterbody layer, 2) the waterbody name in the NHDWaterbody layer included "Reservoir", 3) the waterbody in the NHDWaterbody layer was located in close proximity (up to 100 m) to a dam in the NID, 4) the NHDWaterbody GNIS name was similar to nearby NID feature (between 100 m to 1000 m), the waterbody intersected a drinking water intake.

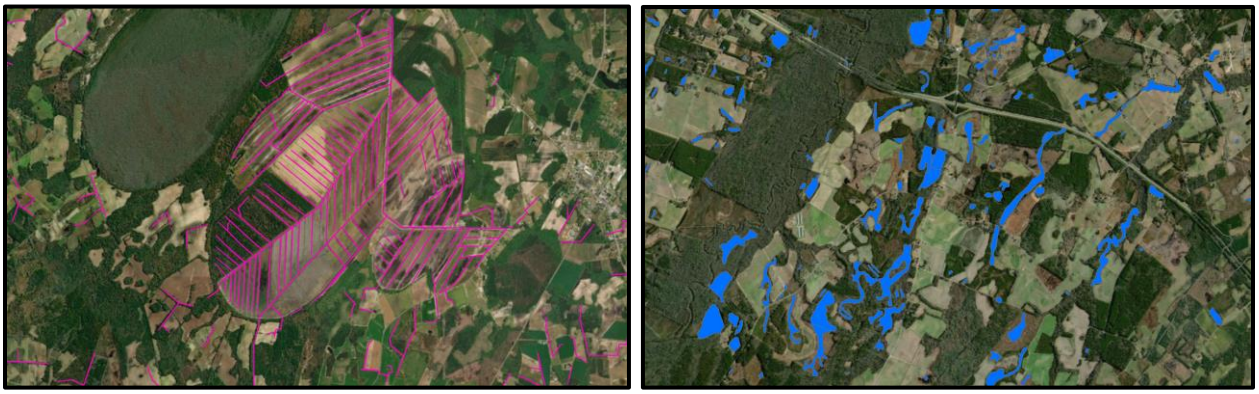
EPA assumes that all features included in the NW are subject to water-level management to maintain minimum water depths required for navigation and are therefore managed flooded lands. NW features that were less than 8 ha in surface area and not identified as canals/ditch (see below) were considered freshwater ponds. Only 2.1 percent of NW features met these criteria, and they were primarily associated with larger navigable waterways, such as lock chambers on impounded rivers.

NWI features were considered "managed" if they had a special modifier value indicating the presence of management activities (Figure 6-12). To be included in the flooded lands inventory, the managed flooded land had to be wet or saturated for at least one season per year (see "Water Regime" in Figure 6-12). NWI features that met these criteria, were less than 8 ha in surface area, and were not a canal/ditch (see below) were defined as freshwater ponds.

Any NWI or NHD feature that intersected a drinking water intake point from SDWIS was assumed to be "managed." The rational being that a waterbody used as a source for public drinking water is typically managed in some capacity - by flow and/or volume control.

Canals and ditches, a subset of other constructed waterbodies, were identified in the NWI by their morphology. Unlike a natural water body, canals and ditches are typically narrow, linear features with abrupt angular turns. Figure 6-14 contrasts the unique shape of ditches/canals vs more natural water features.

Figure 6-14: Left: NWI Features Identified as Canals/Ditches (pink) by Unique Narrow, Linear/Angular Morphology. Right: Non-Canal/Ditches with More Natural Morphology (blue)



This morphology was identified systematically using shape attributes in a decision tree model. A training set of 752 features were identified as either "ditch" or "not ditch" using expert judgment. The training set was used to train a decision tree which was used to categorize millions of NWI features based on three shape attribute ratios (Figure 6-12).

Table 6-91: Predictors used in Decision Tree to Identify Canal/Ditches

Shape Length : # of Shape Vertices
Shape Area : Shape Length
Shape Area : # of Shape Vertices

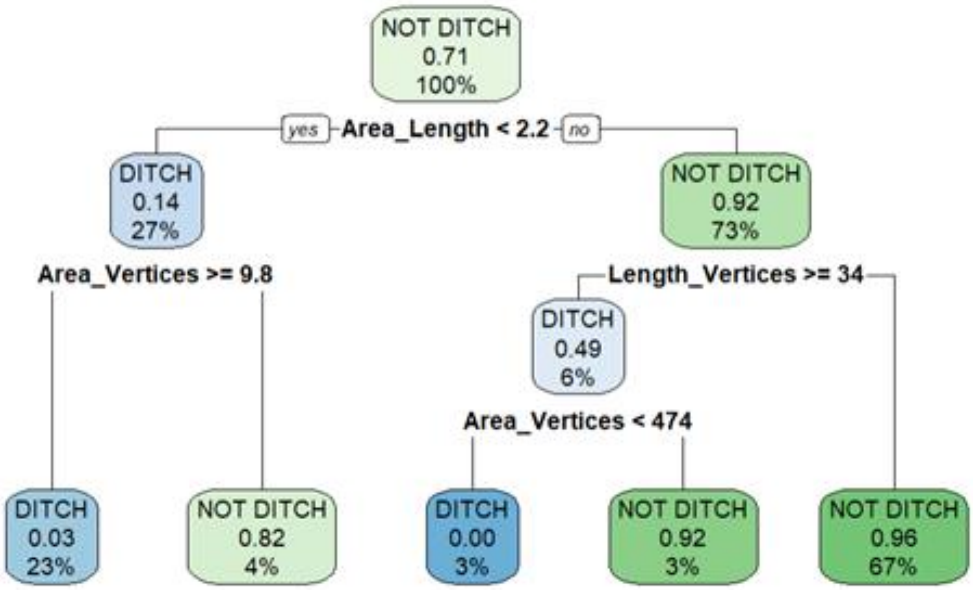
The decision tree built a model using 80 percent of the 752 training features and used the 20 percent to validate the model. The model was 93.1 percent accurate. Below are the validation results (Table 6-92).

Table 6-92: Validation Results for Ditch/Canal Classification Decision Tree

	Truth	
Prediction	Ditch/Canal	Not Ditch/Canal
Ditch/Canal	49	5
Not Ditch/Canal	8	27

The decision tree model was then applied to the entire NWI dataset using the following shape attribute ratios (Figure 6-15).

Figure 6-15: Structure of Decision Tree Used to Identify Canals/Ditches



Surface areas for other constructed waterbodies were taken from NHD, NWI or the NW. If features from the NHD, NWI, or the NW datasets overlapped, these areas were erased. The first step was to take the final NWI flooded lands features and use it to identify overlapping NHD features. If the NHD feature had its center in a NWI feature, it was removed from analysis. Next, remaining NHD features were erased from any remaining overlapping NWI features. Final selections of NHD and NWI features were used to erase any overlapping NW waterbodies.

The age of other constructed waterbody features was determined by assuming the waterbody was created the same year as a nearby (up to 100 m) NID feature. If no nearby NID feature was identified, it was assumed the waterbody was greater than 20-years old throughout the time series. No canal/ditch features were associated with a nearby dam, therefore all canal/ditch features were assumed to be greater than 20-years old through the time series.

For the year 2022, this *Inventory* contains 2,250,662 ha of freshwater ponds and 194,412 ha of canals and ditches in flooded land remaining flooded land (Table 6-93). The surface area of freshwater ponds increased by 28,632 ha (1.3 percent) from 1990 to 2022 due to flooded lands matriculating from land converted to flooded land to flooded land remaining flooded land. All canals and ditches were assumed to be greater than 20-years old throughout the time series, thus the surface area of these flooded lands is constant throughout the time series.

Table 6-93: National Surface Area Totals in Flooded Land Remaining Flooded Land - Other Constructed Waterbodies (ha)

	1990	2005	2018	2019	2020	2021	2022
Canals and ditches	194,412	194,412	194,412	194,412	194,412	194,412	194,412
Freshwater ponds	2,222,030	2,245,881	2,249,672	2,250,007	2,250,337	2,250,540	2,250,662
Total	**2,416,442**	**2,440,292**	**2,444,084**	**2,444,418**	**2,444,749**	**2,444,951**	**2,445,074**

Note: Totals may not sum due to independent rounding.

Canals and ditches in the conterminous United States are most abundant in the Gulf Coast states and California (Figure 6-16A, Table). Florida contains 19 percent of all U.S. canal and ditch surface area, most of which were constructed in the early 1900s for drainage, flood protection, and water storage purposes. Freshwater ponds are more widely distributed across the United States (Figure 6-16B, Table 6-95). Texas has the greatest surface area of freshwater ponds, equivalent to 8 percent of all freshwater pond surface area in the United States, closely followed by Florida.

Figure 6-16: 2022 Surface Area of A) Ditches and Canals and B) Freshwater Ponds in Flooded Land Remaining Flooded Land (ha)

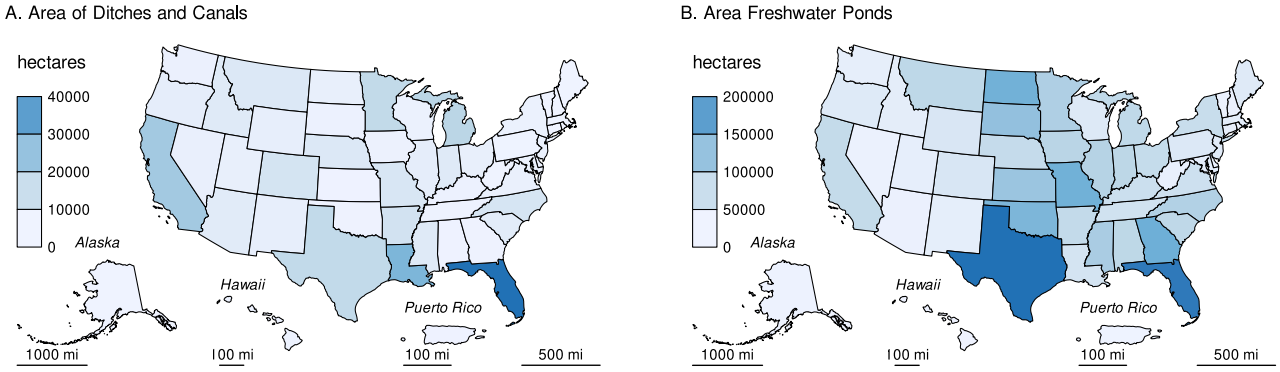


Table 6-94: State Totals of Surface Area in Flooded Land Remaining Flooded Land— Canals and Ditches (ha)

State	1990	2005	2018	2019	2020	2021	2022
Alabama	228	228	228	228	228	228	228
Alaska	115	115	115	115	115	115	115
Arizona	3,536	3,536	3,536	3,536	3,536	3,536	3,536
Arkansas	7,349	7,349	7,349	7,349	7,349	7,349	7,349
California	16,725	16,725	16,725	16,725	16,725	16,725	16,725
Colorado	6,874	6,874	6,874	6,874	6,874	6,874	6,874
Connecticut	28	28	28	28	28	28	28
Delaware	130	130	130	130	130	130	130
District of Columbia	1	1	1	1	1	1	1
Florida	37,482	37,482	37,482	37,482	37,482	37,482	37,482
Georgia	352	352	352	352	352	352	352

Hawaii	538	538	538	538	538	538	538
Idaho	4,027	4,027	4,027	4,027	4,027	4,027	4,027
Illinois	2,489	2,489	2,489	2,489	2,489	2,489	2,489
Indiana	4,064	4,064	4,064	4,064	4,064	4,064	4,064
Iowa	867	867	867	867	867	867	867
Kansas	258	258	258	258	258	258	258
Kentucky	672	672	672	672	672	672	672
Louisiana	22,565	22,565	22,565	22,565	22,565	22,565	22,565
Maine	56	56	56	56	56	56	56
Maryland	967	967	967	967	967	967	967
Massachusetts	132	132	132	132	132	132	132
Michigan	12,897	12,897	12,897	12,897	12,897	12,897	12,897
Minnesota	11,235	11,235	11,235	11,235	11,235	11,235	11,235
Mississippi	3,936	3,936	3,936	3,936	3,936	3,936	3,936
Missouri	5,670	5,670	5,670	5,670	5,670	5,670	5,670
Montana	4,740	4,740	4,740	4,740	4,740	4,740	4,740
Nebraska	4,864	4,864	4,864	4,864	4,864	4,864	4,864
Nevada	1,587	1,587	1,587	1,587	1,587	1,587	1,587
New Hampshire	103	103	103	103	103	103	103
New Jersey	944	944	944	944	944	944	944
New Mexico	2,002	2,002	2,002	2,002	2,002	2,002	2,002
New York	925	925	925	925	925	925	925
North Carolina	6,321	6,321	6,321	6,321	6,321	6,321	6,321
North Dakota	1,819	1,819	1,819	1,819	1,819	1,819	1,819
Ohio	1,819	1,819	1,819	1,819	1,819	1,819	1,819
Oklahoma	278	278	278	278	278	278	278
Oregon	2,498	2,498	2,498	2,498	2,498	2,498	2,498
Pennsylvania	143	143	143	143	143	143	143
Puerto Rico	249	249	249	249	249	249	249
Rhode Island	1	1	1	1	1	1	1
South Carolina	3,226	3,226	3,226	3,226	3,226	3,226	3,226
South Dakota	703	703	703	703	703	703	703
Tennessee	442	442	442	442	442	442	442
Texas	11,152	11,152	11,152	11,152	11,152	11,152	11,152
Utah	1,875	1,875	1,875	1,875	1,875	1,875	1,875
Vermont	95	95	95	95	95	95	95
Virginia	1,306	1,306	1,306	1,306	1,306	1,306	1,306
Washington	1,125	1,125	1,125	1,125	1,125	1,125	1,125
West Virginia	28	28	28	28	28	28	28
Wisconsin	887	887	887	887	887	887	887
Wyoming	2,086	2,086	2,086	2,086	2,086	2,086	2,086
Total	**194,412**	**194,412**	**194,412**	**194,412**	**194,412**	**194,412**	**194,412**

Table 6-95: State Totals of Surface Area in Flooded Land Remaining Flooded Land—Freshwater Ponds (ha)

State	1990	2005	2018	2019	2020	2021	2022
Alabama	57,034	57,342	57,355	57,355	57,355	57,355	57,355
Alaska	2,367	2,370	2,370	2,370	2,370	2,370	2,370
Arizona	5,199	5,236	5,249	5,249	5,253	5,253	5,253
Arkansas	50,880	51,211	51,211	51,211	51,211	51,211	51,211
California	50,219	50,426	50,499	50,504	50,511	50,513	50,519
Colorado	26,174	26,448	26,478	26,479	26,480	26,480	26,494
Connecticut	9,630	9,697	9,699	9,699	9,699	9,699	9,699
Delaware	4,717	4,721	4,721	4,721	4,721	4,721	4,721
District of Columbia	16	16	16	16	16	16	16
Florida	167,317	167,453	167,496	167,502	167,502	167,508	167,508

Georgia	113,254	114,898	114,969	114,972	114,972	114,972	114,972
Hawaii	1,580	1,592	1,595	1,595	1,595	1,595	1,595
Idaho	13,220	13,352	13,359	13,359	13,359	13,360	13,360
Illinois	63,516	64,044	64,144	64,149	64,159	64,160	64,169
Indiana	57,593	58,065	58,170	58,175	58,175	58,175	58,185
Iowa	57,450	59,612	60,745	60,929	61,051	61,147	61,168
Kansas	81,828	83,900	83,976	83,985	83,985	84,002	84,004
Kentucky	41,427	41,808	41,837	41,837	41,837	41,837	41,837
Louisiana	32,085	32,210	32,221	32,221	32,226	32,226	32,226
Maine	19,102	19,149	19,159	19,159	19,159	19,159	19,159
Maryland	12,569	12,739	12,810	12,810	12,812	12,815	12,818
Massachusetts	12,359	12,413	12,457	12,464	12,470	12,472	12,476
Michigan	54,525	54,672	54,701	54,701	54,709	54,709	54,709
Minnesota	68,801	69,082	69,173	69,176	69,202	69,210	69,220
Mississippi	72,832	73,209	73,336	73,343	73,363	73,375	73,383
Missouri	109,573	112,993	113,068	113,071	113,073	113,077	113,079
Montana	56,860	57,246	57,263	57,268	57,269	57,269	57,269
Nebraska	48,051	49,380	49,649	49,667	49,697	49,706	49,709
Nevada	4,452	4,455	4,508	4,509	4,512	4,512	4,515
New Hampshire	5,427	5,526	5,585	5,585	5,586	5,587	5,587
New Jersey	16,192	16,232	16,253	16,253	16,253	16,253	16,253
New Mexico	11,379	11,394	11,398	11,401	11,401	11,401	11,406
New York	45,224	45,485	45,590	45,592	45,592	45,598	45,598
North Carolina	66,205	66,661	66,744	66,744	66,747	66,750	66,751
North Dakota	112,310	112,384	112,469	112,475	112,485	112,489	112,492
Ohio	48,028	48,393	48,591	48,605	48,637	48,651	48,656
Oklahoma	103,243	105,224	105,288	105,304	105,318	105,324	105,333
Oregon	19,304	19,487	19,532	19,534	19,539	19,539	19,539
Pennsylvania	22,018	22,256	22,289	22,289	22,289	22,289	22,289
Puerto Rico	708	708	708	708	708	708	708
Rhode Island	2,204	2,213	2,220	2,220	2,220	2,220	2,220
South Carolina	55,794	56,456	56,673	56,682	56,686	56,686	56,686
South Dakota	90,237	90,447	90,504	90,515	90,516	90,521	90,521
Tennessee	35,927	36,307	36,332	36,337	36,343	36,344	36,344
Texas	172,580	175,497	175,569	175,574	175,575	175,575	175,575
Utah	10,703	10,764	10,772	10,772	10,773	10,773	10,773
Vermont	4,316	4,381	4,392	4,392	4,392	4,392	4,392
Virginia	39,938	39,996	40,000	40,000	40,000	40,000	40,000
Washington	10,943	11,081	11,119	11,119	11,122	11,123	11,123
West Virginia	8,027	8,156	8,166	8,166	8,166	8,166	8,166
Wisconsin	20,845	20,989	21,003	21,003	21,003	21,003	21,003
Wyoming	25,851	26,106	26,243	26,243	26,244	26,246	26,250
Total	**2,222,030**	**2,245,881**	**2,249,672**	**2,250,007**	**2,250,337**	**2,250,540**	**2,250,662**

Uncertainty

Uncertainty in estimates of CH_4 emissions from other constructed waterbodies (ponds, canals/ditches) in flooded land remaining flooded land (Table 6-96) are estimated using IPCC Approach 2 and include uncertainty in the default emission factors and the flooded land area inventory. Uncertainty in default emission factors is provided in the *2019 Refinement to the 2006 IPCC Guidelines* (IPCC 2019). Uncertainties in the spatial data include 1) uncertainty in area estimates from the NHD, NWI, and NW, and 2) uncertainty in the location of dams in the NID. Overall uncertainties in these spatial datasets are unknown, but uncertainty for remote sensing products is assumed to be ± 10 to 15 percent based on IPCC guidance (IPCC 2003). An uncertainty range of ± 15 percent for the flooded land area estimates is assumed and is based on expert judgment.

Table 6-96: Approach 2 Quantitative Uncertainty Estimates for CH_4 Emissions from Other Constructed Waterbodies in Flooded Land Remaining Flooded Land

Source	Gas	2022 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (MMT CO_2 Eq.)		Uncertainty Range Relative to Emission Estimate[a] (%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Canals and ditches	CH_4	2.3	2.1	2.4	-5.1%	+7.0%
Freshwater pond	CH_4	11.5	11.5	11.5	-0.04%	+0.04%
Total	**CH_4**	**13.8**	**13.7**	**13.9**	**-0.8%**	**+1.0%**

[a] Range of emission estimates predicted by Monte Carlo stochastic simulation for a 95 percent confidence interval.

QA/QC and Verification

The National Hydrography Data (NHD) is managed by the USGS in collaboration many other federal, state, and local entities. Extensive QA/QC procedures are incorporated into the curation of the NHD. The National Inventory of Dams (NID) is maintained by the U.S. Army Corps of Engineers (USACE) in collaboration with the Federal Emergency Management Agency (FEMA) and state regulatory offices. USACE resolves duplicative and conflicting data from 68 data sources, which helps obtain the more complete, accurate, and updated NID.[78] The Navigable Waterways (NW) dataset is part of the U.S. Department of Transportation (USDOT)/Bureau of Transportation Statistics (BTS) National Transportation Atlas Database (NTAD). The NW is a comprehensive network database of the nation's navigable waterways updated on a continuing basis. U.S. Fish and Wildlife Service is the principal agency in charge of wetland mapping including the National Wetlands Inventory (NWI). Quality and consistency of the Wetlands Layer is supported by federal wetlands mapping and classification standards, which were developed under the oversight of the Federal Geographic Data Committee (FGDC) with input by the FGDC Wetlands Subcommittee. This dataset is part of the FGDC Water-Inland Theme, which is co-chaired by the FWS and the U.S. Geological Survey. The EPA's Safe Drinking Water Information System (SDWIS) tracks information on drinking water contamination levels as required by the 1974 Safe Drinking Water Act and its 1986 and 1996 amendments.

General QA/QC procedures were applied to activity data, documentation, and emission calculations consistent with the U.S. Inventory QA/QC plan, which is in accordance with Vol. 1 Chapter 6 of *2006 IPCC Guidelines* (see Annex 8 for more details). All calculations were executed independently in Excel and R. Ten percent of state and national totals were randomly selected for comparison between the two approaches to ensure there were no computational errors.

Recalculations Discussion

The EPA's SDWIS is a new data source used in the current (1990 through 2022) *Inventory*. The assumption is that any waterbody used as a public drinking water source is managed in some capacity—by flow and/or volume control. This data source added 54 features totaling 173 ha of other constructed waterbodies.

The National Inventory of Dams (NID) data are updated regularly. The version of NID used for the current (1990 through 2022) *Inventory* contains 47 new dams and updated values for "year of dam completion" for 975 dams relative to the previous (1990 through 2021) *Inventory* data. Similarly, the National Wetlands Inventory (NWI) is periodically updated. The NWI version used for the current *Inventory* has major updates for MS, ND, NM, and MT.

The net effect of these recalculations was an average annual decrease in CH_4 emission estimates from other constructed waterbodies of 2.7 MMT CO_2 Eq., or 17 percent, over the time series from 1990 to 2021 compared to the previous *Inventory*.

[78] See https://www.epa.gov/national-aquatic-resource-surveys/national-lakes-assessment-2017-quality-assurance-project-plan.

Planned Improvements

Default emission factors for canals/ditches were derived from a global dataset that include few measurements from U.S. systems. The EPA plans to conduct a literature survey to determine if sufficient data are available to derive a country-specific emission factor for the 1990 through 2024 *Inventory* submission.

Canal and ditch surface area included here may overlap with ditches and canals included in CH_4 emission estimates for ditches draining inland organic soils (IPCC 2013, section 2.2.2.1). EPA plans to reconcile ditch/canal surface areas between the two managed land types (flooded land vs drained inland organic soils) in the next (i.e., 1990 through 2023) *Inventory*.

Features less than 8 ha in the NW that were not identified as Canal/Ditch were defined as freshwater ponds. Many of these features are lock chambers connected to an upstream reservoir. These systems likely have emission rates more similar to a reservoir than freshwater pond. In the next (1990 through 2023) *Inventory* these systems will be classified as reservoirs.

6.9 Land Converted to Wetlands (CRT Source Category 4D2)

Emissions and Removals from Land Converted to Vegetated Coastal Wetlands

Land converted to vegetated coastal wetlands occurs as a result of inundation of unprotected low-lying coastal areas with gradual sea-level rise, flooding of previously drained land behind hydrological barriers, and through active restoration and creation of coastal wetlands through removal of hydrological barriers. Based upon NOAA C-CAP, wetlands are subdivided into freshwater (Palustrine) and saline (Estuarine) classes and further subdivided into emergent marsh, scrub shrub and forest classes All other land categories (i.e., forest land, cropland, grassland, settlements and other lands) are identified as having some area converting to vegetated coastal wetlands. This *Inventory* does not include land converted to unvegetated open water coastal wetlands (see Planned Improvements section below). Between 1990 and 2022 the rate of annual transition for land converted to vegetated coastal wetlands ranged from 0 to 2,650 ha per year, depending on the type of land converted.[79] Conversion rates from forest land were relatively consistent between 1990 and 2010 (ranging between 2,409 and 2,650 ha) and decreased to 625 ha starting in 2011; the majority of these conversions resulted in increases in the area of palustrine wetlands, which also initiates CH_4 emissions when lands are inundated with fresh water.[80] Little to no conversion of cropland, grassland, settlement, or other lands to vegetated coastal wetlands occurred during the reporting period, with converted areas ranging from 0 to 25 ha per year.[81]

[79] Data from C-CAP; see https://coast.noaa.gov/digitalcoast/tools/. Accessed October 2023.

[80] Currently, the C-CAP dataset categorizes coastal wetlands as either palustrine (fresh water) or estuarine (presence of saline water). This classification does not differentiate between estuarine wetlands with salinity ≤ 18 ppt (when methanogenesis begins to occur) and those that are >18 ppt (where negligible to no CH_4 is produced); therefore, it is not possible at this time to account for CH_4 emissions from estuarine wetlands in the *Inventory*.

[81] At the present stage of *Inventory* development, coastal wetlands are not explicitly shown in the land representation analysis (Section 6.1) while work continues harmonizing data from NOAA's Coastal Change Analysis Program (C-CAP) with NRI, FIA and NLDC data used to compile the land representation (NOAA OCM 2020).

Conversion to coastal wetlands resulted in a biomass carbon stock loss of 0.2 MMT CO_2 Eq. (0.03 MMT C) in 2022 (Table 6-97 and Table 6-98). Loss of forest biomass through conversion of forest lands to vegetated coastal wetlands is the primary driver behind biomass carbon stock change being a source rather than a sink across the time series. Conversion of cropland, grassland, settlement and other lands result in a net increase in biomass stocks. Conversion of lands to vegetated coastal wetlands resulted in a DOM loss of 0.03 MMT CO_2 Eq. (0.008 MMT C) in 2022 (Table 6-97 and Table 6-98), which is driven by the loss of DOM when forest land is converted to vegetated coastal wetlands. This is likely an overestimate of loss because wetlands inherently preserve dead organic material. Conversion of cropland, grassland, settlement and other land results in a net increase in DOM Across all time periods, soil carbon accumulation resulting from lands converted to vegetated coastal wetlands is a carbon sink and has ranged between -0.14 and -0.3 MMT CO_2 Eq. (-0.04 and -0.07 MMT C; Table 6-97 and Table 6-98). Conversion of lands to coastal wetlands resulted in CH_4 emissions of 0.17 MMT CO_2 Eq. (6.1 kt CH_4) in 2022 (Table 6-99). Methane emissions due to the conversion of lands to vegetated coastal wetlands are largely the result of forest land converting to palustrine emergent and scrub shrub coastal wetlands in warm temperate climates. Emissions were the highest between 1990 and 2002 (0.28 MMT CO_2 Eq., 10.0 kt CH_4) and have continually decreased to current levels. This decrease was driven by a reduction in the rate of conversion of forest land to palustrine scrub-shrubs and emergent wetlands.

Table 6-97: Net CO_2 Flux from Carbon Stock Changes in Land Converted to Vegetated Coastal Wetlands (MMT CO_2 Eq.)

Land Use/Carbon Pool	1990	2005	2018	2019	2020	2021	2022
Cropland Converted to Vegetated Coastal Wetlands	**(+)**	**(+)**	**(+)**	**(+)**	**(+)**	**(+)**	**(+)**
Biomass C Stock	(+)	(+)	(+)	(+)	(+)	(+)	(+)
Soil C Stock	(+)	(+)	(+)	(+)	(+)	(+)	(+)
Forest Land Converted to Vegetated Coastal Wetlands	**0.49**	**0.50**	**(+)**	**0.01**	**0.02**	**0.03**	**0.04**
Biomass C Stock	0.62	0.62	0.13	0.13	0.13	0.13	0.13
Dead Organic Matter C Flux	0.11	0.12	0.03	0.03	0.03	0.03	0.03
Soil C Stock	(0.24)	(0.24)	(0.16)	(0.15)	(0.14)	(0.13)	(0.12)
Grassland Converted to Vegetated Coastal Wetlands	**(+)**	**(+)**	**(+)**	**(+)**	**(+)**	**(+)**	**(+)**
Biomass C Stock	(+)	(+)	(+)	(+)	(+)	(+)	(+)
Soil C Stock	(+)	(+)	(+)	(+)	(+)	(+)	(+)
Other Land Converted to Vegetated Coastal Wetlands	**(0.03)**	**(0.03)**	**(0.02)**	**(0.02)**	**(0.02)**	**(0.02)**	**(0.02)**
Biomass C Stock	(0.01)	(0.02)	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)
Soil C Stock	(0.02)	(0.02)	(0.02)	(0.02)	(0.02)	(0.02)	(0.02)
Settlements Converted to Vegetated Coastal Wetlands	**(+)**	**(+)**	**(+)**	**(+)**	**(+)**	**(+)**	**(+)**
Biomass C Stock	(+)	(+)	(+)	(+)	(+)	(+)	(+)
Soil C Stock	(+)	(+)	(+)	(+)	(+)	(+)	(+)
Total Biomass Flux	**0.60**	**0.60**	**0.12**	**0.12**	**0.12**	**0.12**	**0.12**
Total Dead Organic Matter Flux	**0.11**	**0.12**	**0.03**	**0.03**	**0.03**	**0.03**	**0.03**
Total Soil C Flux	**(0.25)**	**(0.25)**	**(0.18)**	**(0.17)**	**(0.16)**	**(0.15)**	**(0.14)**
Total Flux	**0.46**	**0.47**	**(0.02)**	**(0.02)**	**(0.01)**	**0.00**	**0.01**

+ Absolute value does not exceed 0.005 MMT CO_2 Eq.

Note: Totals may not sum due to independent rounding. Parentheses indicate net sequestration.

Table 6-98: Net CO_2 Flux from Carbon Stock Changes in Land Converted to Vegetated Coastal Wetlands (MMT C)

Land Use/Carbon Pool	1990	2005	2018	2019	2020	2021	2022
Cropland Converted to Vegetated Coastal	**(+)**	**(+)**	**(+)**	**(+)**	**(+)**	**(+)**	**(+)**

Wetlands							
Biomass C Stock	(+)	(+)	(+)	(+)	(+)	(+)	(+)
Soil C Stock	(+)	(+)	(+)	(+)	(+)	(+)	(+)
Forest Land Converted to Vegetated Coastal Wetlands	**0.13**	**0.14**	**+**	**+**	**0.006**	**0.008**	**0.01**
Biomass C Stock	0.17	0.17	0.04	0.04	0.04	0.04	0.04
Dead Organic Matter C Flux	0.03	0.03	0.01	0.01	0.01	0.01	0.01
Soil C Stock	(0.06)	(0.06)	(0.04)	(0.04)	(0.04)	(0.04)	(0.03)
Grassland Converted to Vegetated Coastal Wetlands	**(+)**	**(+)**	**(+)**	**(+)**	**(+)**	**()**	**(+)**
Biomass C Stock	(+)	(+)	(+)	(+)	(+)	(+)	(+)
Soil C Stock	(+)	(+)	(+)	(+)	(+)	(+)	(+)
Other Land Converted to Vegetated Coastal Wetlands	**(0.01)**	**(0.01)**	**(0.01)**	**(0.01)**	**(0.01)**	**(0.01)**	**(0.01)**
Biomass C Stock	(+)	(0.01)	(+)	(+)	(+)	(+)	(+)
Soil C Stock	(+)	(0.01)	(+)	(+)	(+)	(+)	(+)
Settlements Converted to Vegetated Coastal Wetlands	**(+)**	**(+)**	**(+)**	**(+)**	**(+)**	**(+)**	**(+)**
Biomass C Stock	(+)	(+)	(+)	(+)	(+)	(+)	(+)
Soil C Stock	(+)	(+)	(+)	(+)	(+)	(+)	(+)
Total Biomass Flux	**0.16**	**0.16**	**0.03**	**0.03**	**0.03**	**0.03**	**0.03**
Total Dead Organic Matter Flux	**0.03**	**0.03**	**0.01**	**0.01**	**0.01**	**0.01**	**0.01**
Total Soil C Flux	**(0.07)**	**(0.07)**	**(0.05)**	**(0.05)**	**(0.04)**	**(0.04)**	**(0.04)**
Total Flux	**0.13**	**0.13**	**(0.01)**	**(+)**	**(+)**	**+**	**+**

+ Absolute value does not exceed 0.005 MMT C.

Notes: Totals may not sum due to independent rounding. Parentheses indicate net sequestration.

Table 6-99: CH_4 Emissions from Land Converted to Vegetated Coastal Wetlands (MMT CO_2 Eq. and kt CH_4)

Land Use/Carbon Pool	1990	2005	2018	2019	2020	2021	2022
Cropland Converted to Vegetated Coastal Wetlands							
CH_4 Emissions (MMT CO_2 Eq.)	+	+	+	+	+	+	+
CH_4 Emissions (kt CH_4)	+	0.01	0.04	0.04	0.05	0.05	0.05
Forest Land Converted to Vegetated Coastal Wetlands							
CH_4 Emissions (MMT CO_2 Eq.)	0.28	0.27	0.19	0.18	0.17	0.16	0.15
CH_4 Emissions (kt CH_4)	9.88	9.74	6.85	6.48	6.10	5.76	5.41
Grassland Converted to Vegetated Coastal Wetlands							
CH_4 Emissions (MMT CO_2 Eq.)	+	+	+	+	+	+	+
CH_4 Emissions (kt CH_4)	0.01	0.01	0.07	0.07	0.08	0.08	0.09
Other Land Converted to Vegetated Coastal Wetlands							
CH_4 Emissions (MMT CO_2 Eq.)	+	+	0.01	0.01	0.01	0.01	0.02
CH_4 Emissions (kt CH_4)	0.08	0.14	0.43	0.47	0.50	0.52	0.54
Settlements Converted to Vegetated Coastal Wetlands							
CH_4 Emissions (MMT CO_2 Eq.)	+	+	+	+	+	+	+
CH_4 Emissions (kt CH_4)	0.01	+	+	+	+	+	+
Total CH_4 Emissions (MMT CO_2 Eq.)	**0.28**	**0.28**	**0.21**	**0.20**	**0.19**	**0.18**	**0.17**
Total CH_4 Emissions (kt CH_4)	**9.98**	**9.91**	**7.39**	**7.06**	**6.73**	**6.41**	**6.09**

+ Absolute value does not exceed 0.005 MMT CO_2 Eq. or 0.005 kt CH_4.

Note: Totals may not sum due to independent rounding.

Methodology and Time-Series Consistency

The following section provides a description of the methodology used to estimate changes in biomass, dead organic matter and soil carbon stocks and CH_4 emissions for land converted to vegetated coastal wetlands. Methodological recalculations were applied to the entire time series to ensure time-series consistency from 1990 through 2022.

Biomass Carbon Stock Changes

Biomass carbon stocks for land converted to vegetated coastal wetlands are estimated for palustrine and estuarine marshes for land below the elevation of high tides (taken to be mean high water spring tide elevation) and as far seawards as the extent of intertidal vascular plants within the U.S. land representation according to the national LiDAR dataset, the national network of tide gauges and land use histories recorded in the 1996, 2001, 2005, 2011, and 2016 NOAA C-CAP surveys (NOAA OCM 2020). Both federal and non-federal lands are represented. Delineating vegetated coastal wetlands from ephemerally flooded upland grasslands represents a particular challenge in remote sensing. Moreover, at the boundary between wetlands and uplands, which may be gradual on low lying coastlines, the presence of wetlands may be ephemeral depending upon weather and climate cycles and as such, impacts on the emissions and removals will vary over these time frames. Trends in land cover change are extrapolated to 1990 and 2021 from these datasets using the C-CAP change data closest in date to a given year. Biomass is not sensitive to soil organic content. Aboveground biomass carbon stocks for non-forested coastal wetlands are derived from a national assessment combining field plot data and aboveground biomass mapping by remote sensing (Byrd et al. 2017; Byrd et al. 2018; Byrd et al. 2020). Aboveground biomass carbon removal data for all subcategories are not available and thus assumptions were applied using expert judgment about the most appropriate assignment to a disaggregation of a community class. The aboveground biomass carbon stock for estuarine forested wetlands (dwarf mangroves that are not classified as forests due to their stature) is derived from a meta-analysis by Lu and Megonigal (2017[82]). Root to shoot ratios from the *Wetlands Supplement* were used to account for belowground biomass, which were multiplied by the aboveground carbon stock (IPCC 2014) and summed with aboveground biomass to obtain total biomass carbon stocks. Aboveground biomass carbon stocks for forest land, cropland, and grassland that are lost with the conversion to vegetated coastal wetlands were derived from Tier 1 default values (IPCC 2006; IPCC 2019). Biomass carbon stock changes are calculated by subtracting the biomass carbon stock values of each land use category (i.e., forest land, cropland, and grassland) from those of vegetated coastal wetlands in each climate zone and multiplying that value by the corresponding C-CAP derived area gained that year in each climate zone. The difference between the stocks is reported as the stock change under the assumption that the change occurred in the year of the conversion. The total coastal wetland biomass carbon stock change is accounted for during the year of conversion; therefore, no interannual changes are calculated during the remaining years it is in the category.

Dead Organic Matter

Dead organic matter (DOM) carbon stocks, which include litter and dead wood stocks, are accounted for in subtropical estuarine forested wetlands for lands converted to vegetated coastal wetlands across all years. Tier 1 estimates of mangrove DOM carbon stocks were used for subtropical estuarine forested wetlands (IPCC 2014). Neither Tier 1 or 2 data on DOM are currently available for either palustrine or estuarine scrub/shrub wetlands for any climate zone or estuarine forested wetlands in climates other than subtropical climates. Tier 1 DOM C stocks for forest land converted to vegetated coastal wetlands were derived from IPCC (2019) to account for the loss of DOM that occurs with conversion. Changes in DOM are assumed to be negligible for other land use conversions (i.e., other than forest land) to coastal wetlands based on the Tier 1 method in IPCC (2006). Trends in land cover change are derived from the NOAA C-CAP dataset and extrapolated to cover the entire 1990 through 2022 time series. Dead organic matter removals are calculated by multiplying the C-CAP derived area gained that year by the

[82] See https://github.com/Smithsonian/Coastal-Wetland-NGGI-Data-Public; accessed October 2023.

difference between Tier 1 DOM carbon stocks for vegetated coastal wetlands and forest land. The difference between the stocks is reported as the stock change under the assumption that the change occurred in the year of the conversion. The coastal wetland DOM stock is assumed to be in steady state once established in the year of conversion; therefore, no interannual changes are calculated.

Soil Carbon Stock Changes

Soil carbon removals are estimated for land converted to vegetated coastal wetlands across all years. Soil carbon stock changes, stratified by climate zones and wetland classes, are derived from a synthesis of peer-reviewed literature[83] (Lynch 1989; Orson et al. 1990; Kearny & Stevenson 1991; Thom et al. 1992; Roman et al. 1997; Craft et al. 1998; Orson et al. 1998; Merrill 1999; Weis et al. 2001; Hussein et al. 2004; Church et al. 2006; Köster et al. 2007; Drexler et al. 2009; Boyd 2012; Callaway et al. 2012 a & b; Bianchi et al. 2013; Drexler et al. 2013; Watson and Byrne 2013; Breithaupt et al. 2014; Crooks et al. 2014; Weston et al. 2014; Smith et al. 2015; Villa & Mitsch 2015; Boyd and Sommerfield 2016; Marchio et al. 2016; Noe et al. 2016; Arriola and Cable 2017; Boyd et al. 2017; Gerlach et al. 2017; Giblin and Forbrich 2018; Krauss et al. 2018; Abbott et al. 2019; Drexler et al. 2019; Poppe and Rybczyk 2019; Ensign et al. 2020; Kemp et al. 2020; Lagomasino et al. 2020; Luk et al. 2020; McTigue et al. 2020; Peck et al. 2020; Vaughn et al. 2020; Weston et al. 2020; Arias-Ortiz et al. 2021; Baustian et al. 2021; Allen et al. 2022; Miller et al. 2022). To estimate soil carbon stock changes, no differentiation is made for soil type (i.e., mineral, organic). Soil C removal data for all subcategories are not available and thus assumptions were applied using expert judgment about the most appropriate assignment to a disaggregation of a community class.

As per IPCC (2014) guidance, land converted to vegetated coastal wetlands is assumed to remain in this category for up to 20 years before transitioning to vegetated coastal wetlands remaining vegetated coastal wetlands. Tier 2 level estimates of soil carbon stock changes associated with annual soil carbon accumulation from land converted to vegetated coastal wetlands were developed using country-specific soil carbon removal factors multiplied by activity data of land area for land converted to vegetated coastal wetlands for a given year in addition to the previous 19-year cumulative area. Guidance from the *Wetlands Supplement* allows for the rate of soil carbon accumulation to be instantaneously equivalent to that in natural settings and that soil carbon accumulation is initiated when natural vegetation becomes established; this is assumed to occur in the first year of conversion. No loss of soil carbon as a result of land conversion to coastal wetlands is assumed to occur. Since the C-CAP coastal wetland area dataset begins in 1996, the area converted prior to 1996 is assumed to be the same as in 1996. Similarly, the coastal wetland area data for 2017 through 2022 is assumed to be the same as in 2016. The methodology follows Eq. 4.7, Chapter 4 of the *IPCC Wetlands Supplement* (IPCC 2014) and is applied to the area of land converted to vegetated coastal wetlands on an annual basis.

Soil Methane Emissions

Tier 1 estimates of CH_4 emissions for land converted to vegetated coastal wetlands are derived from the same wetland map used in the analysis of wetland soil carbon fluxes for palustrine wetlands, and are produced from C-CAP, LiDAR and tidal data, in combination with default CH_4 emission factors provided in Table 4.14 of the *IPCC Wetlands Supplement.* The methodology follows Eq. 4.9, Chapter 4 of the *IPCC Wetlands Supplement* and a global warming potential of 28 is used (IPCC 2013). Because land converted to vegetated coastal wetlands is held in this category for up to 20 years before transitioning to vegetated coastal wetlands remaining to vegetated coastal wetlands, CH_4 emissions in a given year represent the cumulative area held in this category for that year and the prior 19 years.

Uncertainty

Underlying uncertainties in estimates of soil carbon removal factors, biomass change, DOM, and CH_4 emissions

[83] Coastal Carbon Network (2023). Database: Coastal Carbon Library (Version 1.0.0). Smithsonian Environmental Research Center. Dataset. https://doi.org/10.25573/serc.21565671. Accessed October 2023

include error in uncertainties associated with Tier 2 literature values of soil carbon removal estimates, biomass stocks, DOM, and IPCC default CH_4 emission factors, uncertainties linked to interpretation of remote sensing data, as well as assumptions that underlie the methodological approaches applied.

Uncertainty specific to coastal wetlands include differentiation of palustrine and estuarine community classes, which determines what flux is applied. Because mean soil and biomass carbon removal for each available community class are in a fairly narrow range, the same overall uncertainty was assigned to each, respectively (i.e., applying approach for asymmetrical errors, the largest uncertainty for any soil carbon stock value should be applied in the calculation of error propagation; IPCC 2000). Uncertainties for CH_4 flux are the Tier 1 default values reported in the *Wetlands Supplement*. Overall uncertainty of the NOAA C-CAP remote sensing product is 15 percent. This is in the range of remote sensing methods (±10 to 15 percent; IPCC 2003). However, there is significant uncertainty in salinity ranges for tidal and non-tidal estuarine wetlands and activity data used to estimate the CH_4 flux (e.g., delineation of an 18 ppt boundary), which will need significant improvement to reduce uncertainties. The combined uncertainty was calculated by summing the squared uncertainty for each individual source (C-CAP, soil, biomass, and DOM) and taking the square root of that total.

Uncertainty estimates are presented in Table 6-100 for each carbon pool and the CH_4 emissions. The combined uncertainty is 42.6 percent above and below the estimate of 0.17 MMT CO_2 Eq. In 2022, the total flux was 0.17 MMT CO_2 Eq., with lower and upper estimates of 0.10 and 0.24 MMT CO_2 Eq.

Table 6-100: Approach 1 Quantitative Uncertainty Estimates for Carbon Stock Changes occurring within Land Converted to Vegetated Coastal Wetlands in 2022 (MMT CO_2 Eq. and Percent)

Source	2022 Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Estimate[a] (MMT CO_2 Eq.)		(%)	
		Lower Bound	Upper Bound	Lower Bound	Upper Bound
Biomass C Stock Flux	0.12	0.1	0.15	-20.0%	20.0%
Dead Organic Matter Flux	0.03	0.02	0.03	-25.8%	25.8%
Soil C Stock Flux	(0.14)	(0.2)	(0.1)	-17.7%	17.7%
Methane Emissions	0.17	0.12	0.22	-29.9%	29.9%
Total Uncertainty	**0.18**	**0.11**	**0.26**	**-42.2%**	**42.2%**

[a] Range of flux estimates based on error propagation at 95 percent confidence interval.
Notes: Totals may not sum due to independent rounding. Parentheses indicate net sequestration.

QA/QC and Verification

NOAA provided National LiDAR Dataset, tide data, and C-CAP land cover and land cover change mapping, all of which are subject to agency internal mandatory QA/QC assessment (McCombs et al. 2016). QA/QC and verification of soil carbon stock dataset has been provided by the Smithsonian Environmental Research Center and coastal wetland inventory team leads. Biomass carbon stocks are derived from peer-review literature, reviewed by U.S. Geological Survey prior to publishing, by the peer-review process during publishing, and by the coastal wetland inventory team leads prior to inclusion in the *Inventory* and from IPCC reports. As a QC step, a check was undertaken confirming that coastal wetlands recognized by C-CAP represent a subset of wetlands recognized by the NRI for marine coastal states. A team of two evaluated and verified there were no computational errors within the calculation worksheets. Soil carbon stock, emissions/removals data are based upon peer-reviewed literature and CH_4 emission factors are derived from the *Wetlands Supplement*.

Recalculations Discussion

A recalculation of emission factors for soil carbon accretion rates was performed using the same methodology and criteria as in Lu and Megonigal (2017) and described above. This new analysis incorporated data published since

2016 and other relevant data that were not previously included. The updated synthesis resulted in a general increase in soil carbon accumulation rates for estuarine emergent and scrub/shrub wetlands, which resulted in a minimal annual average increase (0.001 MMT CO_2 Eq.) for the entire time series.

Planned Improvements

Currently, the only coastal wetland conversion that is reported in the *Inventory* is lands converted to vegetated coastal wetlands. The next (1990 through 2023) *Inventory* submission is expected to include carbon stock change data for lands converted to unvegetated open water coastal wetlands.

Land Converted to Flooded Land

Flooded lands are defined as water bodies where human activities have 1) caused changes in the amount of surface area covered by water, typically through water level regulation (e.g., constructing a dam), 2) waterbodies where human activities have changed the hydrology of existing natural waterbodies thereby altering water residence times and/or sedimentation rates, in turn causing changes to the natural production of greenhouse gases, and 3) waterbodies that have been created by excavation, such as canals, ditches and ponds (IPCC 2019). Flooded lands include waterbodies with seasonally variable degrees of inundation but would be expected to retain some inundated area throughout the year under normal conditions.

Flooded lands are broadly classified as "reservoirs" or "other constructed waterbodies" (IPCC 2019). Reservoirs are defined as flooded land greater than 8 ha and includes the seasonally flooded land on the perimeter of permanently flooded land (i.e., inundation areas). IPCC guidance (IPCC 2019) provides default emission factors for reservoirs and several types of "other constructed waterbodies" including freshwater ponds and canals/ditches.

Land that has been flooded for 20 years or greater is defined as flooded land remaining flooded land and land flooded for less than 20 years is defined as land converted to flooded land. The distinction is based on literature reports that CO_2 and CH_4 emissions are high immediately following flooding as labile organic matter is rapidly degraded but decline to a steady background level approximately 20 years after flooding (Abril et al. 2005, Barros et al. 2011, Teodoru et al. 2012). Both CO_2 and CH_4 emissions are estimated for land converted to flooded land.

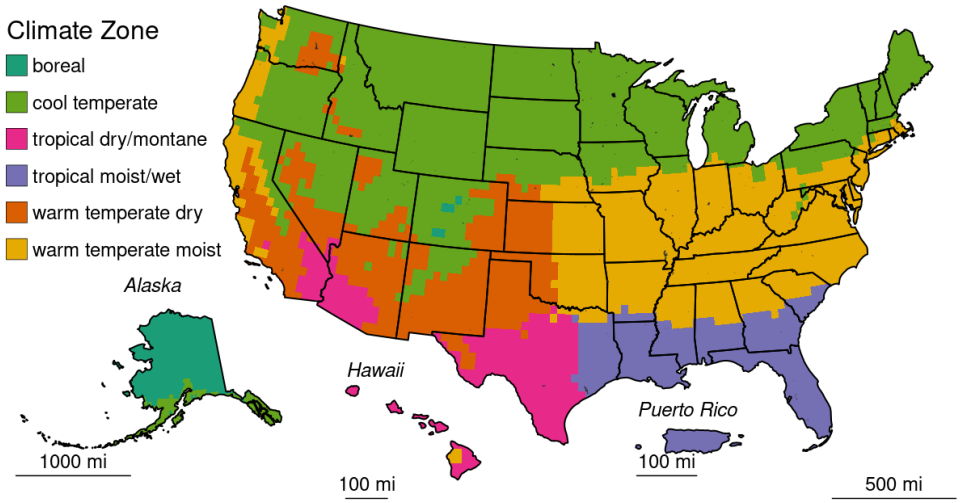
Nitrous oxide emissions from flooded lands are largely related to inputs of organic or inorganic nitrogen from the watershed. These inputs from runoff/leaching/deposition are largely driven by anthropogenic activities such as land-use change, wastewater disposal or fertilizer application in the watershed or application of fertilizer or feed in aquaculture. These emissions are not included here to avoid double-counting N_2O emissions which are captured in other source categories, such as indirect N_2O emissions from managed soils (Section 5.4, Agricultural Soil Management) and wastewater management (Section 7.2, Wastewater Treatment and Discharge).

Reservoirs are designed to store water for a wide range of purposes including hydropower, flood control, drinking water, and irrigation. The permanently wetted portion of reservoirs are typically surrounded by periodically inundated land referred to as a "drawdown zone" or "inundation area." Greenhouse gas emissions from inundation areas are considered significant and similar per unit area to the emissions from the water surface and are therefore included in the total reservoir surface area when estimating greenhouse gas emissions from flooded land. Lakes converted into reservoirs without substantial changes in water surface area or water residence times are not considered to be managed flooded land (see Area Estimates below) (IPCC 2019).

In 2022, the United States and Puerto Rico contained 72,461 ha of reservoir surface area in land converted to flooded land (see Methodology and Time-Series Consistency below for calculation details) distributed across all six of the aggregated climate zones used to define flooded land emission factors (Figure 6-17) (IPCC 2019).

Emissions from Land Converted to Flooded Land–Reservoirs

Figure 6-17: U.S. Reservoirs (black polygons) in the Land Converted to Flooded Land Category in 2022



Note: Colors represent climate zone used to derive IPCC default emission factors. Reservoirs (indicated by black polygons) are sparsely distributed across United States, but can be seen in MN, IL, and IN in this image.

Methane and CO_2 are produced in reservoirs through the natural breakdown of organic matter. Per unit area emission rates tend to scale positively with temperature and system productivity (i.e., abundance of algae). Greenhouse gases produced in reservoirs can be emitted directly from the water surface and inundation areas or as greenhouse gas-enriched water passes through the dam and the downstream river. Sufficient information exists to estimate downstream CH_4 emissions using Tier 1 IPCC guidance (IPCC 2019), but no guidance is provided for downstream CO_2 emissions. Table 6-101 and Table 6-102 below summarize nationally aggregated CH_4 and CO_2 emissions from reservoirs in land converted to flooded land. The decrease in CO_2 and CH_4 emissions through the time series is attributable to reservoirs matriculating from the land converted to flooded land category into the flooded land remaining flooded land category. Emissions have been stable since 2005, reflecting the low rate of new flooded land creation over the past 17 years.

Table 6-101: CH_4 Emissions from Land Converted to Flooded Land—Reservoirs (MMT CO_2 Eq.)

Source	1990	2005	2018	2019	2020	2021	2022
Reservoirs							
Surface Emissions	2.5	0.4	0.2	0.2	0.2	0.2	0.2
Downstream Emissions	0.2	+	+	+	+	+	+
Total	**2.7**	**0.4**	**0.2**	**0.2**	**0.2**	**0.2**	**0.2**

+Indicates values less than 0.05 MMT CO_2

Note: Totals may not sum due to independent rounding.

Table 6-102: CH_4 Emissions from Land Converted to Flooded Land—Reservoirs (kt CH_4)

Source	1990	2005	2018	2019	2020	2021	2022
Reservoirs							
Surface Emissions	90	14	7	7	7	7	7
Downstream Emissions	8	1	1	1	1	1	1
Total	**98**	**15**	**8**	**8**	**8**	**7**	**7**

Note: Totals may not sum due to independent rounding.

Table 6-103: CO_2 Emissions from Land Converted to Flooded Land—Reservoirs (MMT CO_2)

Source	1990	2005	2018	2019	2020	2021	2022
Reservoir	3.5	0.6	0.3	0.3	0.3	0.3	0.3

Table 6-104: CO_2 Emissions from Land Converted to Flooded Land—Reservoirs (MMT C)

Source	1990	2005	2018	2019	2020	2021	2022
Reservoir	0.9	0.2	0.1	0.1	0.1	0.1	0.1

Methane and CO_2 emissions from reservoirs in Minnesota were 8-fold greater than from any other state (Figure 6-18 and Table 6-105). This is attributed to nineteen reservoirs created in Minnesota after 2001 which impound 54,064 ha of water, 96 percent of which is located in Mille Lacs Lake.

North Dakota is the second largest source of CO_2 and CH_4 from reservoirs in land converted to flooded land. Over ninety-nine percent of land converted to flooded land reservoir surface area in North Dakota is attributed to Devils Lake. Both Mille Lacs and Devils Lakes are natural waterbodies provisioned with dams for water level management.

Figure 6-18: 2022 A) CH_4 and B) CO_2 Emissions from U.S. Reservoirs in Land Converted to Flooded Land

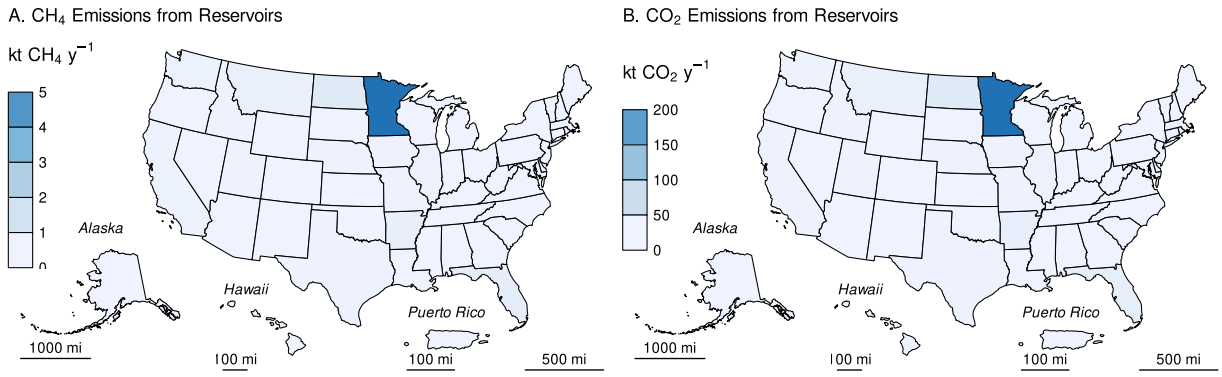


Table 6-105: Methane and CO_2 Emissions from Reservoirs in Land Converted to Flooded Land in 2022 (kt CH_4; kt CO_2)

	CH_4			CO_2[a]
State	Surface	Downstream	Total	Surface
Alabama	0	0	0	0
Alaska	0	0	0	0
Arizona	0	0	0	0
Arkansas	+	+	+	9
California	+	+	+	3
Colorado	+	+	+	1
Connecticut	+	+	+	+
Delaware	0	0	0	0
District of Columbia	0	0	0	0
Florida	+	+	+	13
Georgia	+	+	+	1
Hawaii	0	0	0	0
Idaho	+	+	+	2

Illinois	+	+	+	4
Indiana	+	+	+	+
Iowa	+	+	+	2
Kansas	+	+	+	+
Kentucky	0	0	0	0
Louisiana	+	+	+	+
Maine	+	+	+	+
Maryland	+	+	+	+
Massachusetts	+	+	+	5
Michigan	+	+	+	+
Minnesota	5	+	5	202
Mississippi	+	+	+	+
Missouri	+	+	+	2
Montana	+	+	+	8
Nebraska	+	+	+	1
Nevada	+	+	+	+
New Hampshire	+	+	+	1
New Jersey	0	0	0	0
New Mexico	+	+	+	1
New York	+	+	+	+
North Carolina	+	+	+	1
North Dakota	+	+	1	22
Ohio	+	+	+	1
Oklahoma	0	0	0	0
Oregon	+	+	+	1
Pennsylvania	+	+	+	1
Puerto Rico	0	0	0	0
Rhode Island	0	0	0	0
South Carolina	0	0	0	0
South Dakota	+	+	+	+
Tennessee	+	+	+	1
Texas	+	+	+	3
Utah	+	+	+	1
Vermont	0	0	0	0
Virginia	0	0	0	0
Washington	+	+	+	3
West Virginia	+	+	+	+
Wisconsin	+	+	+	1
Wyoming	+	+	+	1

+ Indicates values greater than zero and less than 0.5 kt.

[a] CO_2: Only surface CO_2 emissions are included in the *Inventory.*

Methodology and Time-Series Consistency

Estimates of CH_4 and CO_2 emissions for reservoirs in land converted to flooded land follow the Tier 1 methodology in the IPCC guidance (IPCC 2019). All calculations are performed at the state level and summed to obtain national estimates. Emissions from the surface of these flooded lands are calculated as the product of flooded land surface area and a climate-specific emission factor (Table 6-106). Downstream CH_4 emissions are calculated as 9 percent of the surface CH_4 emission (Tier 1 default). The IPCC guidance (IPCC 2019) does not address downstream CO_2 emissions, presumably because there are insufficient data in the literature to estimate this emission pathway.

The IPCC default surface emission factors are derived from model-predicted (G-res model, Prairie et al. 2017) emission rates for all reservoirs in the Global Reservoir and Dam (GRanD) database (Lehner et al. 2011). Predicted emission rates were aggregated by the 11 IPCC climate zones (IPCC 2019, Table 7A.2) which were collapsed into six climate zones using a regression tree approach. All six aggregated climate zones are present in the United States.

Table 6-106: IPCC (2019) Default CH_4 and CO_2 Emission Factors for Surface Emissions from Reservoirs in Land Converted to Flooded Land

	Surface emission factor	
Climate	**MT CH_4 ha^{-1} y^{-1}**	**MT CO_2 ha^{-1} y^{-1}**
Boreal	0.0277	3.45
Cool Temperate	0.0847	3.74
Warm Temperate Dry	0.1956	6.23
Warm Temperate Moist	0.1275	5.35
Tropical Dry/Montane	0.3923	10.82
Tropical Moist/Wet	0.2516	10.16

Note: Downstream CH_4 emissions are calculated as 9 percent of surface emissions. Downstream emissions are not calculated for CO_2.

Area estimates

U.S. reservoirs were identified from the NHDWaterbody layer in the National Hydrography Dataset Plus V2 (NHD),[84] the National Inventory of Dams (NID),[85] the National Wetlands Inventory (NWI),[86] and the Navigable Waterways (NW) network,[87] and the EPA's Safe Drinking Water Information System (SDWIS).[88] The NHD only covers the conterminous United States, whereas the NID, NW and NWI also include Alaska, Hawaii, and Puerto Rico. The following paragraphs present the criteria used to identify other constructed waterbodies in the NHD, NW, and NWI.

Waterbodies in the NHDWaterbody layer that were less than or equal to 20-years old, greater than or equal to 8 ha in surface area, not identified as canal/ditch in NHD, and met any of the following criteria were considered reservoirs in land converted to flooded land: 1) the waterbody was classified "Reservoir" in the NHDWaterbody layer, 2) the waterbody name in the NHDWaterbody layer included "Reservoir", 3) the waterbody in the NHDWaterbody layer was located in close proximity (up to 100 m) to a dam in the NID, 4) the NHDWaterbody GNIS name was similar to nearby NID feature (between 100 m to 1000 m).

EPA assumes that all features included in the NW are subject to water-level management to maintain minimum water depths required for navigation and are therefore managed flooded lands. NW features greater than 8 ha in surface area are defined as reservoirs.

NWI features were considered "managed" if they had a special modifier value indicating the presence of management activities (Figure 6-19). To be included in the flooded lands inventory, the managed flooded land had to be wet or saturated for at least one season per year (see 'Water Regime' in Figure 6-19). NWI features that met these criteria, were greater than 8 ha in surface area, and were not a canal/ditch (see emissions from land converted to flooded land–other constructed waterbodies) were defined as reservoirs.

Any NWI or NHD feature that intersected a drinking water intake point from SDWIS was assumed to be "managed." The rational being that a waterbody used as a source for public drinking water is typically managed in some capacity - by flow and/or volume control.

Surface areas for identified flooded lands were taken from NHD, NWI or the NW. If features from the NHD, NWI, or the NW datasets overlapped, duplicate areas were erased. The first step was to take the final NWI flooded lands

[84] See https://www.usgs.gov/core-science-systems/ngp/national-hydrography.

[85] See https://nid.sec.usace.army.mil.

[86] See https://www.fws.gov/program/national-wetlands-inventory/data-download.

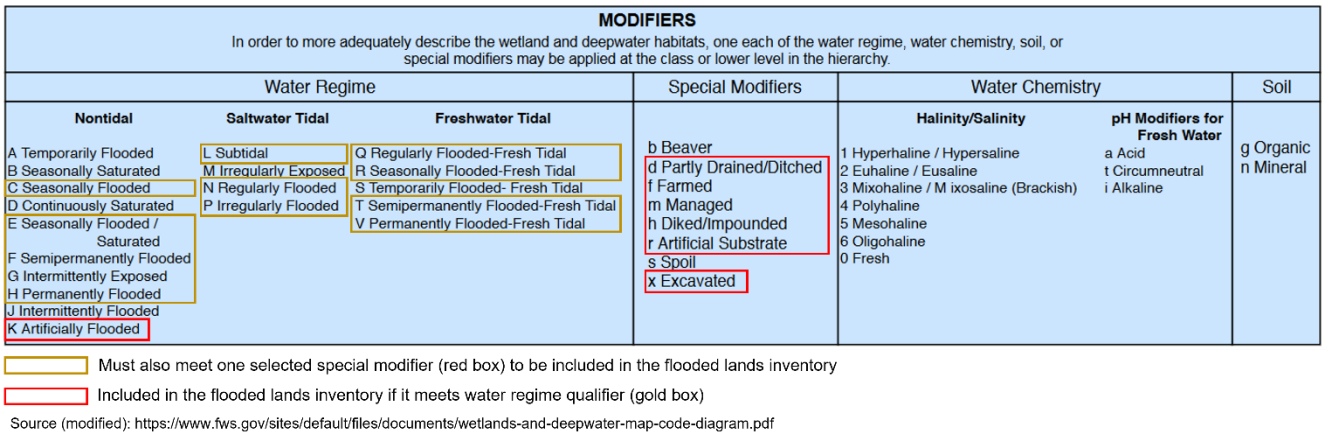
[87] See https://www.census.gov/geographies/mapping-files/time-series/geo/carto-boundary-file.html.

[88] See https://www.epa.gov/enviro/sdwis-overview. Not publicly available due to security concerns.

features and use it to identify overlapping NHD features. If the NHD feature had its center in a NWI feature, it was removed from analysis. Next, remaining NHD features were erased from any remaining overlapping NWI features. Final selections of NHD and NWI features were used to erase any overlapping NW waterbodies.

Reservoir age was determined by assuming they were created the same year as a nearby (up to 100 m) NID feature. If no nearby NID feature was identified, it was assumed the feature was greater than 20-years old throughout the time series. Only reservoirs less than or equal to 20-years old are included in land converted to flooded land.

Figure 6-19: Selected Features from NWI that meet Flooded Lands Criteria



IPCC (2019) allows for the exclusion of managed waterbodies from the inventory if the water surface area or residence time was not substantially changed by the construction of the dam. The guidance does not quantify what constitutes a "substantial" change, but here EPA excludes the U.S. Great Lakes from the inventory based on expert judgment that neither the surface area nor water residence time was substantially altered by their associated dams.

Reservoirs were disaggregated by state (using boundaries from the 2016 U.S. Census Bureau[89]) and climate zone. Downstream and surface emissions for cross-state reservoirs were allocated to states based on the surface area that the reservoir occupied in each state. Only the U.S. portion of reservoirs that cross country borders were included in the *Inventory*.

The surface area of reservoirs in land converted to flooded land decreased by nearly 90 percent from 1990 to 2022 (Table 6-107). This is due to reservoirs that were less than 20-years old at the beginning of time series entering the flooded land remaining flooded land category when they exceeded 20 years of age. The rate at which flooded land has aged out of the land converted to flooded land category has outpaced the rate of new dam construction. New dam construction has slowed considerably during the time series with only nine new dams constructed in 2022,[90] versus 552 in 1990 (Figure 6-20).

Table 6-107: National Totals of Reservoir Surface Area in Land Converted to Flooded Land (thousands of ha)

Surface Area (thousands of ha)	1990	2005	2018	2019	2020	2021	2022
Reservoir	566	115	78	77	75	74	73

[89] See https://www.census.gov/geographies/mapping-files/time-series/geo/carto-boundary-file.html.

[90] See https://nid.sec.usace.army.mil.

Figure 6-20: Number of Dams Built per Year from 1990 through 2022

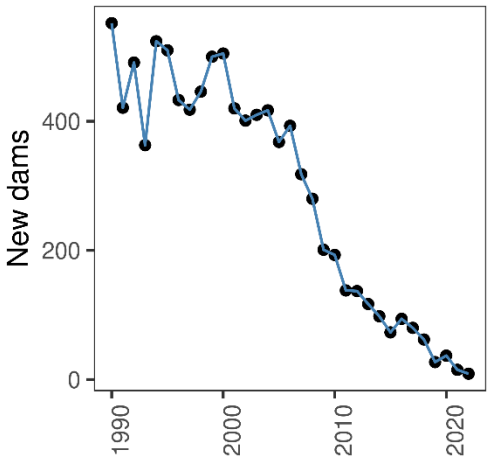


Table 6-108: State Breakdown of Reservoir Surface Area in Land Converted to Flooded Land (thousands of ha)

State	1990	2005	2018	2019	2020	2021	2022
Alabama	7.5	0.0	0.0	0.0	0.0	0.0	0.0
Alaska	0.6	0.0	0.0	0.0	0.0	0.0	0.0
Arizona	0.0	0.1	0.0	0.0	0.0	0.0	0.0
Arkansas	10.1	2.9	1.8	1.8	1.8	1.8	1.8
California	19.6	2.1	0.5	0.5	0.5	0.5	0.5
Colorado	5.9	1.3	0.3	0.3	0.3	0.3	0.3
Connecticut	2.3	2.2	0.0	0.0	0.0	0.0	0.0
Delaware	0.0	0.0	0.0	0.0	0.0	0.0	0.0
District of Columbia	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Florida	25.7	3.8	1.5	1.5	1.4	1.2	1.2
Georgia	20.6	4.9	0.1	0.1	0.1	0.1	0.1
Hawaii	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Idaho	17.7	1.2	0.5	0.5	0.5	0.5	0.5
Illinois	49.2	39.4	1.4	1.3	1.3	0.8	0.8
Indiana	10.6	0.3	0.1	0.1	0.1	0.1	0.1
Iowa	12.3	3.1	1.0	1.0	0.7	0.7	0.5
Kansas	19.6	0.4	0.2	0.2	0.1	0.1	0.0
Kentucky	1.3	0.1	0.0	0.0	0.0	0.0	0.0
Louisiana	9.4	0.2	0.0	0.0	0.0	0.0	0.0
Maine	10.9	4.4	0.0	0.0	0.0	0.0	0.0
Maryland	0.8	0.1	0.1	0.1	0.1	0.1	0.1
Massachusetts	1.6	0.5	1.5	1.5	1.4	1.4	1.2
Michigan	11.6	0.9	0.1	0.1	0.1	0.1	0.1
Minnesota	9.9	6.4	54.6	54.6	54.3	54.2	54.1
Mississippi	6.2	0.6	0.1	0.1	0.1	0.1	0.1
Missouri	16.4	0.5	0.4	0.4	0.4	0.4	0.4
Montana	14.4	3.9	2.1	2.1	2.1	2.1	2.1
Nebraska	5.8	1.7	0.6	0.6	0.3	0.3	0.3
Nevada	1.6	1.1	0.1	0.1	0.1	0.1	0.1
New Hampshire	0.4	0.2	0.1	0.1	0.1	0.1	0.1
New Jersey	0.7	0.6	0.0	0.0	0.0	0.0	0.0
New Mexico	1.3	0.1	0.1	0.1	0.1	0.1	0.1
New York	4.2	2.6	0.1	0.1	0.1	0.1	0.1

North Carolina	19.7	0.7	0.3	0.2	0.2	0.2	0.2
North Dakota	7.5	3.5	6.3	6.3	6.3	6.2	5.9
Ohio	7.2	1.3	0.3	0.3	0.2	0.2	0.1
Oklahoma	28.7	0.2	0.0	0.0	0.0	0.0	0.0
Oregon	6.2	0.4	0.2	0.2	0.2	0.1	0.1
Pennsylvania	12.6	1.3	0.1	0.1	0.1	0.1	0.1
Puerto Rico	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Rhode Island	0.1	0.0	0.0	0.0	0.0	0.0	0.0
South Carolina	18.5	5.8	0.0	0.0	0.0	0.0	0.0
South Dakota	0.5	3.9	0.8	0.8	0.0	0.0	0.0
Tennessee	58.7	0.0	0.1	0.1	0.1	0.1	0.1
Texas	74.8	0.9	0.3	0.3	0.2	0.2	0.2
Utah	1.9	0.1	0.3	0.3	0.3	0.3	0.3
Vermont	0.2	0.1	0.0	0.0	0.0	0.0	0.0
Virginia	5.8	0.4	0.0	0.0	0.0	0.0	0.0
Washington	5.3	1.6	0.9	0.9	0.5	0.5	0.5
West Virginia	3.1	1.6	0.1	0.0	0.0	0.0	0.0
Wisconsin	1.9	0.4	0.2	0.2	0.2	0.2	0.2
Wyoming	15.1	6.5	0.4	0.2	0.2	0.2	0.2
Total	**565.8**	**114.6**	**77.6**	**77.1**	**74.7**	**73.7**	**72.5**

Uncertainty

Uncertainty in estimates of CH_4 and CO_2 emissions from reservoirs on land converted to flooded land were developed using IPCC Approach 2 and include uncertainty in the default emission factors and the flooded land area inventory (Table 1-105). Uncertainty in emission factors is provided in the *2019 Refinement to the 2006 IPCC Guidelines* (IPCC 2019). Uncertainties in the spatial data include 1) uncertainty in area estimates from the NHD, NWI, and NW, and 2) uncertainty in the location of dams in the NID and drinking water intakes in SDWIS. Overall uncertainties in these spatial datasets are unknown, but uncertainty for remote sensing products is assumed to be ± 10 to 15 percent based on IPCC guidance (IPCC 2003). An uncertainty range of ± 15 percent for the flooded land area estimates is assumed and is based on expert judgment.

Table 6-109: Approach 2 Quantitative Uncertainty Estimates for CH_4 and CO_2 Emissions from Reservoirs in Land Converted to Flooded Land

Source	Gas	2022 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (MMT CO_2 Eq.)		Uncertainty Range Relative to Emission Estimate[a] (%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Reservoir						
Surface	CH_4	0.19	0.17	0.21	-11.5%	+11.9%
Surface	CO_2	0.2	0.26	0.33	-11.7%	+12.4%
Downstream	CH_4	+	+	0.08	-54.1%	+397.0%
Total		**0.5**	**0.44**	**0.59**	**-12.2%**	**+18.8%**

+ Indicates values less than 0.05 MMT CO_2 Eq.

[a] Range of emission estimates predicted by Monte Carlo stochastic simulation for a 95 percent confidence interval.

QA/QC and Verification

The National Hydrography Data (NHD) is managed by the USGS in collaboration many other federal, state, and local entities. Extensive QA/QC procedures are incorporated into the curation of the NHD. The National Inventory of Dams (NID) is maintained by the U.S. Army Corps of Engineers (USACE) in collaboration with the Federal Emergency Management Agency (FEMA) and state regulatory offices. USACE resolves duplicative and conflicting data from 68 data sources, which helps obtain the more complete, accurate, and updated NID. The Navigable Waterways (NW) dataset is part of the U.S. Department of Transportation (USDOT)/Bureau of Transportation

Statistics (BTS) National Transportation Atlas Database (NTAD). The NW is a comprehensive network database of the nation's navigable waterways updated on a continuing basis. U.S. Fish and Wildlife Service is the principal agency in charge of wetland mapping including the National Wetlands Inventory (NWI). Quality and consistency of the Wetlands Layer is supported by federal wetlands mapping and classification standards, which were developed under the oversight of the Federal Geographic Data Committee (FGDC) with input by the FGDC Wetlands Subcommittee. This dataset is part of the FGDC Water-Inland Theme, which is co-chaired by the FWS and the U.S. Geological Survey. The EPA's Safe Drinking Water Information System (SDWIS) tracks information on drinking water contamination levels as required by the 1974 Safe Drinking Water Act and its 1986 and 1996 amendments.

General QA/QC procedures were applied to activity data, documentation, and emission calculations consistent with the U.S. Inventory QA/QC plan, which is in accordance with Vol. 1 Chapter 6 of the *2006 IPCC Guidelines* (see Annex 8 for more details). All calculations were executed independently in Excel and R. Ten percent of state and national totals were randomly selected for comparison between the two approaches to ensure there were no computational errors.

Recalculations Discussion

The EPA's SDWIS is a new data source used in the current (1990 through 2022) *Inventory*. The assumption is that any waterbody used as a public drinking water source is managed in some capacity—by flow and/or volume control. This data source added 418 reservoirs totaling 736,344 ha.

The National Inventory of Dams (NID) data are updated regularly. The version of NID used for the current *Inventory* contains 47 new dams and updated values for "year of dam completion" for 975 dams relative to the previous (1990 through 2021) *Inventory* data. Similarly, the National Wetlands Inventory (NWI) is periodically updated. The NWI version used for the current 1990 through 2022 *Inventory* has major updates for MS, ND, NM, and MT.

Overall, the recalculations resulted in substantial increases in methane and carbon dioxide emissions in the first few years of the time series (e.g., increase of 3.8 MMT CO_2 Eq. in 1990), but the differences were minor by 2008 through 2021 (<0.1 MMT CO_2 Eq.).

Planned Improvements

The EPA recently completed a survey of greenhouse gas emissions from 108 reservoirs in the conterminous United States.[91] The data will be used to develop country-specific emission factors for U.S. reservoirs to be used in the 1990 through 2024 *Inventory* submission.

Emissions from Land Converted to Flooded Land–Other Constructed Waterbodies

Freshwater ponds are the only type of flooded lands within the "other constructed waterbodies" subcategory of land converted to flooded land that are included in this *Inventory* (see Methodology for details) because age data are not available for canals and ditches. All canals and ditches are assumed to be greater than 20-years old throughout the time series and are included in flooded land remaining flooded land.

IPCC (2019) describes ponds as waterbodies that are "…constructed by excavation and/or construction of walls to hold water in the landscape for a range of uses, including agricultural water storage, access to water for livestock, recreation, and aquaculture." The IPCC "Decision tree for types of Flooded Land" (IPCC 2019, Fig. 7.2) elaborates on this description by defining waterbodies less than 8 ha as a subset of "other constructed waterbodies." For this *Inventory*, ponds are defined as managed flooded land not identified as "canal/ditch" (see Methods below) with

[91] See https://www.epa.gov/air-research/research-emissions-us-reservoirs.

surface area less than 8 ha. IPCC (2019) further distinguishes saline versus brackish ponds, with the former supporting lower CH_4 emission rates than the latter. Activity data on pond salinity is not uniformly available for the United States and all ponds in land converted to flooded land are assumed to be freshwater. Ponds often receive high organic matter and nutrient loadings, may have low oxygen levels, and are sites of substantial CH_4 and CO_2 emissions from anaerobic sediments.

Methane and CO_2 emissions from freshwater ponds decreased 95 percent from 1990 to 2022 due to flooded land matriculating from land converted to flooded land to flooded land remaining flooded land. In 2022, states in the Great Plains region generally had the greatest CO_2 and CH_4 emissions from freshwater ponds in land converted to flooded land (Table 6-110 through Table 6-114, Figure 6-21). Mississippi had the second greatest emissions of all states, partly due to the relatively high CO_2 emission factor for the tropical moist/wet climate zone (Figure 6-17, Table 6-115).

Table 6-110: CH_4 Emissions from Other Constructed Waterbodies in Land Converted to Flooded Land (MMT CO_2 Eq.)

Source	1990	2005	2018	2019	2020	2021	2022
Freshwater Ponds	0.1	+	+	+	+	+	+

+ Indicates values less than 0.05 MMT CO_2 Eq.

Table 6-111: CH_4 Emissions from Other Constructed Waterbodies in Land Converted to Flooded Land (kt CH_4)

Source	1990	2005	2018	2019	2020	2021	2022
Freshwater Ponds	5	1	+	+	+	+	+

+ Indicates values less than 0.5 kt.

Table 6-112: CO_2 Emissions from Other Constructed Waterbodies in Land Converted to Flooded Land (MMT CO_2 Eq.)

Source	1990	2005	2018	2019	2020	2021	2022
Freshwater Ponds	+	+	+	+	+	+	+

+ Indicates values less than 0.05 MMT C.

Table 6-113: CO_2 Emissions from Other Constructed Waterbodies in Land Converted to Flooded Land (MMT C)

Source	1990	2005	2018	2019	2020	2021	2022
Freshwater Ponds	0.04	0.01	+	+	+	+	+

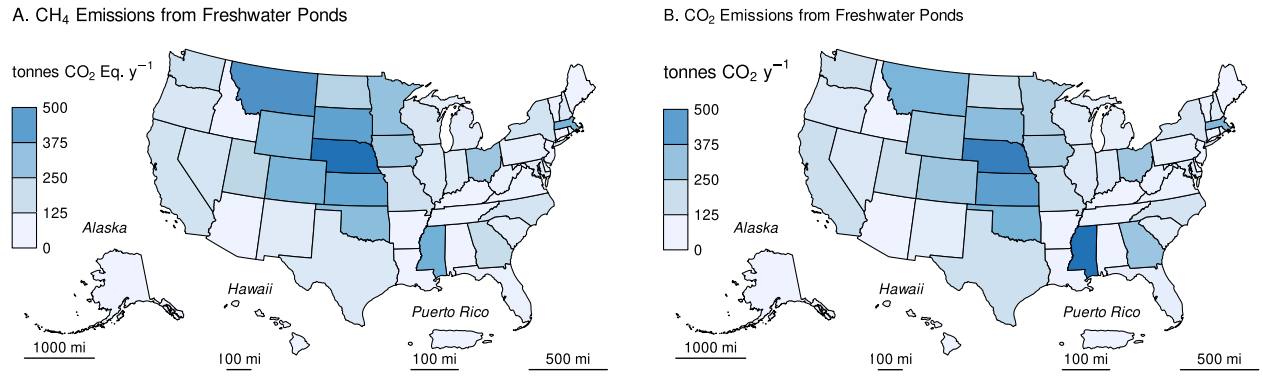
+ Indicates values less than 0.005 MMT C.

Table 6-114: CH_4 and CO_2 Emissions from Other Constructed Waterbodies in Land Converted to Flooded Land in 2022 (MT CO_2 Eq.)

	Freshwater Ponds		
State	CH_4	CO_2	Total
Alabama	0	0	0
Alaska	0	0	0
Arizona	0	0	0
Arkansas	1	1	3
California	126	146	272
Colorado	382	290	672
Connecticut	0	0	0
Delaware	0	0	1
District of Columbia	0	0	0
Florida	18	37	55
Georgia	164	293	457

Hawaii	0	0	0
Idaho	0	0	0
Illinois	83	74	157
Indiana	66	69	135
Iowa	282	254	535
Kansas	435	456	891
Kentucky	3	3	5
Louisiana	3	6	10
Maine	1	1	2
Maryland	58	60	118
Massachusetts	381	358	738
Michigan	41	30	71
Minnesota	317	232	549
Mississippi	400	612	1,012
Missouri	133	139	271
Montana	509	371	880
Nebraska	620	567	1,186
Nevada	103	80	183
New Hampshire	80	59	139
New Jersey	0	0	0
New Mexico	57	46	103
New York	120	96	215
North Carolina	107	112	219
North Dakota	229	167	396
Ohio	289	285	574
Oklahoma	339	378	717
Oregon	89	71	161
Pennsylvania	29	25	54
Puerto Rico	0	0	0
Rhode Island	0	0	0
South Carolina	47	49	95
South Dakota	455	332	788
Tennessee	11	11	22
Texas	83	138	222
Utah	207	151	359
Vermont	15	11	26
Virginia	10	11	21
Washington	140	132	272
West Virginia	19	19	38
Wisconsin	93	68	162
Wyoming	369	269	639
Total	**6,917**	**6,510**	**13,427**

Figure 6-21: 2022 A) CH_4 and B) CO_2 Emissions from Other Constructed Waterbodies (Freshwater Ponds) in Land Converted to Flooded Land (MT CO_2 Eq.)



Methodology and Time-Series Consistency

Estimates of CH_4 and CO_2 emissions for other constructed waterbodies in land converted to flooded land follow the Tier 1 methodology in IPCC (2019). All calculations are performed at the state level and summed to obtain national estimates. Greenhouse gas emissions from the surface of these flooded lands are calculated as the product of flooded land surface area and an emission factor (Table 6-115). Due to a lack of empirical data on CO_2 emissions from recently created ponds, IPCC (2019) states "For all types of ponds created by damming, the methodology described above to estimate CO_2 emissions from land converted to reservoirs may be used." This *Inventory* uses IPCC default CO_2 emission factors for land converted to reservoirs when estimating CO_2 emissions from land converted to freshwater ponds. IPCC guidance also states that "there is insufficient information available to derive separate CH_4 emission factors for recently constructed ponds…" and allows for the use of IPCC default CH_4 emission factors for land remaining flooded land. Downstream emissions are not inventoried for other constructed waterbodies because 1) many of these systems are not associated with dams (e.g., excavated ponds and ditches), and 2) there are insufficient data to derive downstream emission factors for other constructed waterbodies that are associated with dams (IPCC 2019).

Table 6-115: IPCC Default Methane and CO_2 Emission Factors for Other Constructed Waterbodies in Land Converted to Flooded Land

		Emission Factor	
Other Constructed Waterbody	**Climate Zone**	**MT CH_4 ha^{-1} y^{-1}**	**MT CO_2 ha^{-1} y^{-1}**
Freshwater ponds	Boreal	0.183	3.45
Freshwater ponds	Cool Temperate	0.183	3.74
Freshwater ponds	Warm Temperate Dry	0.183	6.23
Freshwater ponds	Warm Temperate Moist	0.183	5.35
Freshwater ponds	Tropical Dry/Montane	0.183	10.82
Freshwater ponds	Tropical Moist/Wet	0.183	10.16

Area Estimates

Other constructed waterbodies were identified from the NHDWaterbody layer in the National Hydrography Dataset Plus V2 (NHD),[92] the National Inventory of Dams (NID),[93] the National Wetlands Inventory (NWI),[94] and the Navigable Waterways (NW) network[95], and the EPA's Safe Drinking Water Information System (SDWIS)[96]. The NHD only covers the conterminous United States, whereas the NID, NW and NWI also include Alaska, Hawaii, and Puerto Rico.

Waterbodies in the NHDWaterbody layer that were less than or equal to 20-years old, less than 8 ha in surface area, not identified as canal/ditch in NHD, and met any of the following criteria were considered freshwater ponds in land converted to flooded land: 1) the waterbody was classified "Reservoir" in the NHDWaterbody layer, 2) the waterbody name in the NHDWaterbody layer included "Reservoir", 3) the waterbody in the NHDWaterbody layer was located in close proximity (up to 100 m) to a dam in the NID, 4) the NHDWaterbody GNIS name was similar to nearby NID feature (between 100 m to 1000 m).

EPA assumes that all features included in the NW are subject to water-level management to maintain minimum water depths required for navigation and are therefore managed flooded lands. NW features that were less than 8 ha in surface area and not identified as canals/ditch (see below) were considered freshwater ponds. Only 2.1 percent of NW features met these criteria, and they were primarily associated with larger navigable waterways, such as lock chambers on impounded rivers.

NWI features were considered "managed" if they had a special modifier value indicating the presence of management activities (Figure 6-19). To be included in the flooded lands inventory, the managed flooded land had to be wet or saturated for at least one season per year (see 'Water Regime' in Figure 6-19). NWI features that met these criteria, were less than 8 ha in surface area, and were not a canal/ditch were defined as freshwater ponds.

Any NWI or NHD feature that intersected a drinking water intake point from SDWIS was assumed to be "managed". The rational being that a waterbody used as a source for public drinking water is typically managed in some capacity - by flow and/or volume control.

Surface areas for other constructed waterbodies were taken from NHD, NWI or the NW. If features from the NHD, NWI, or the NW datasets overlapped, duplicate areas were erased. The first step was to take the final NWI flooded lands features and use it to identify overlapping NHD features. If the NHD feature had its center in a NWI feature, it was removed from analysis. Next, remaining NHD features were erased from any remaining overlapping NWI features. Final selections of NHD and NWI features were used to erase any overlapping NW waterbodies.

The age of other constructed waterbody features was determined by assuming the waterbody was created the same year as a nearby (up to 100 m) NID feature. If no nearby NID feature was identified, it was assumed the waterbody was greater than 20-years old throughout the time series. No canal/ditch features were associated with a nearby dam, therefore all canal/ditch features were assumed to be greater than 20-years old through the time series.

For the year 2022, this *Inventory* contains 1,350 ha of freshwater ponds in land converted to flooded land. The surface area of freshwater ponds decreased by 95 percent from 1990 to 2022 due to flooded lands aging out of land converted to flooded land more quickly than new flooded lands entered the category. The greatest reduction in freshwater pond surface area occurred in Iowa, Kansas, and Georgia (Table 6-117). Freshwater ponds in the 2021 inventory are most abundant in Nebraska, Montana, and Kansas (Figure 6-22).

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[92] See https://www.usgs.gov/core-science-systems/ngp/national-hydrography.

[93] See https://nid.sec.usace.army.mil.

[94] See https://www.fws.gov/program/national-wetlands-inventory/data-download.

[95] See https://hifld-geoplatform.opendata.arcgis.com/datasets/geoplatform::navigable-waterway-network-lines-1/about.

[96] Not publicly available due to security concerns.

Table 6-116: National Surface Area Totals of Other Constructed Waterbodies in Land Converted to Flooded Land (ha)

Other Constructed Waterbodies	1990	2005	2018	2019	2020	2021	2022
Freshwater Ponds	25,492	5,357	2,604	2,317	1,983	1,673	1,472

Figure 6-22: Surface Area of Other Constructed Waterbodies in Land Converted to Flooded Land (ha) in 2022

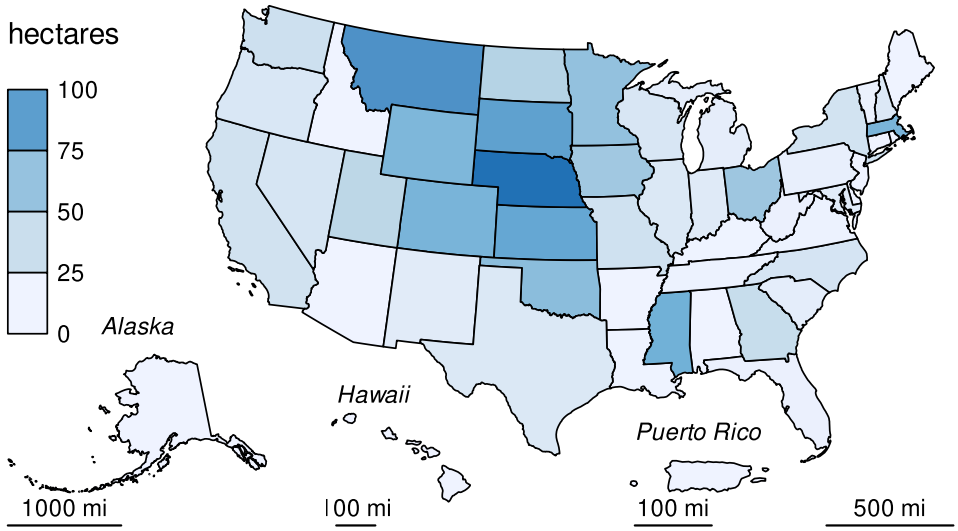


Table 6-117: State Surface Area Totals of Other Constructed Waterbodies in Land Converted to Flooded Land (ha)

State	1990	2005	2018	2019	2020	2021	2022
Alabama	317	13	0	0	0	0	0
Alaska	3	0	0	0	0	0	0
Arizona	39	16	4	4	0	0	0
Arkansas	331	0	0	0	0	0	0
California	263	103	45	40	33	31	25
Colorado	279	71	79	78	89	89	75
Connecticut	67	2	0	0	0	0	0
Delaware	4	0	0	0	0	0	0
District of Columbia	0	0	0	0	0	0	0
Florida	154	58	15	10	10	4	4
Georgia	1,686	83	35	32	32	32	32
Hawaii	11	4	0	0	0	0	0
Idaho	133	8	1	1	1	0	0
Illinois	557	133	42	37	27	26	16
Indiana	494	133	28	23	23	23	13
Iowa	2,592	1,580	474	290	172	76	55
Kansas	2,099	147	113	104	103	87	85
Kentucky	394	30	1	1	1	1	1
Louisiana	130	17	7	7	1	1	1
Maine	51	10	0	0	0	0	0
Maryland	226	81	20	20	18	15	11

Massachusetts	68	79	93	86	80	78	74
Michigan	162	37	16	16	8	8	8
Minnesota	344	142	103	101	79	71	62
Mississippi	414	200	124	117	98	85	78
Missouri	3,451	104	38	34	32	29	26
Montana	400	109	105	100	99	99	99
Nebraska	1,427	374	182	164	133	125	121
Nevada	21	64	26	26	22	22	20
New Hampshire	154	61	17	17	16	16	16
New Jersey	50	21	0	0	0	0	0
New Mexico	14	14	19	17	17	17	11
New York	312	124	31	29	29	24	23
North Carolina	498	92	28	28	25	22	21
North Dakota	90	135	67	61	51	48	45
Ohio	431	293	121	107	75	60	56
Oklahoma	2,008	147	111	95	81	75	66
Oregon	220	69	25	22	18	17	17
Pennsylvania	255	33	6	6	6	6	6
Puerto Rico	0	0	0	0	0	0	0
Rhode Island	9	7	0	0	0	0	0
South Carolina	826	230	22	13	9	9	9
South Dakota	227	98	105	94	93	89	89
Tennessee	389	37	14	9	2	2	2
Texas	2,950	89	21	16	17	16	16
Utah	68	19	42	42	40	40	40
Vermont	70	11	3	3	3	3	3
Virginia	58	4	2	2	2	2	2
Washington	153	57	31	31	28	27	27
West Virginia	130	10	4	4	4	4	4
Wisconsin	146	21	18	18	18	18	18
Wyoming	316	190	79	79	78	75	72
Total	**25,492**	**5,357**	**2,317**	**1,983**	**1,673**	**1,472**	**1,350**

Uncertainty

Uncertainty in estimates of CO_2 and CH_4 emissions from land converted to flooded land–other constructed water bodies include uncertainty in the default emission factors and the flooded land area inventory. Uncertainty in emission factors is provided in the *2019 Refinement to the 2006 IPCC Guidelines* (IPCC 2019). Uncertainties in the spatial data include 1) uncertainty in area estimates from the NHD and NW, and 2) uncertainty in the location of dams in the NID and drinking water intakes in SDWIS. Overall uncertainties in the NHD, NWI, NID, and NW are unknown, but uncertainty for remote sensing products is ±10 to 15 percent (IPCC 2003). EPA assumes an uncertainty of ± 15 percent for the flooded land area inventory based on expert judgment. These uncertainties do not include the underestimate of pond surface area discussed above.

Table 6-118: Approach 2 Quantitative Uncertainty Estimates for CH_4 and CO_2 Emissions from Other Constructed Waterbodies in Land Converted to Flooded Land

Source	Gas	2022 Emission Estimate (kt CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (kt CO_2 Eq.)		Uncertainty Range Relative to Emission Estimate[a] (%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Freshwater ponds	CH_4	6.90	6.80	7.10	-2.3%	+2.7%
Freshwater ponds	CO_2	6.51	6.38	6.62	-2.0%	+1.8%
Total		**13.42**	**13.18**	**13.70**	**-1.8%**	**+2.1%**

[a] Range of emission estimates predicted by Monte Carlo stochastic simulation for a 95 percent confidence interval.
Note: Totals may not sum due to independent rounding.

QA/QC and Verification

The National Hydrography Data (NHD) is managed by the USGS with collaboration from many other federal, state, and local entities. Extensive QA/QC procedures are incorporated into the curation of the NHD. The National Inventory of Dams (NID) is maintained by the U.S. Army Corps of Engineers (USACE) in collaboration with the Federal Emergency Management Agency (FEMA) and state regulatory offices. USACE resolves duplicative and conflicting data from 68 data sources, which helps obtain the more complete, accurate, and updated NID. The Navigable Waterways (NW) dataset is part of the U.S. Department of Transportation (USDOT)/Bureau of Transportation Statistics (BTS) National Transportation Atlas Database (NTAD). The NW is a comprehensive network database of the nation's navigable waterways updated on a continuing basis. U.S. Fish and Wildlife Service is the principal agency in charge of wetland mapping including the National Wetlands Inventory. Quality and consistency of the Wetlands Layer is supported by federal wetlands mapping and classification standards, which were developed under the oversight of the Federal Geographic Data Committee (FGDC) with input by the FGDC Wetlands Subcommittee. This dataset is part of the FGDC Water-Inland Theme, which is co-chaired by the FWS and the U.S. Geological Survey. The EPA's Safe Drinking Water Information System (SDWIS) tracks information on drinking water contamination levels as required by the 1974 Safe Drinking Water Act and its 1986 and 1996 amendments.

General QA/QC procedures were applied to activity data, documentation, and emission calculations consistent with the U.S. Inventory QA/QC plan, which is in accordance with Vol. 1 Chapter 6 of the *2006 IPCC Guidelines* (see Annex 8 for more details). All calculations were executed independently in Excel and R. Ten percent of state and national totals were randomly selected for comparison between the two approaches to ensure there were no computational errors.

Recalculations Discussion

The EPA's SDWIS is a new data source used in the current (1990 through 2022) *Inventory.* The assumption is that any waterbody used as a public drinking water source is managed in some capacity - by flow and/or volume control. This data source added 54 features totaling 173 ha of other constructed waterbodies.

The National Inventory of Dams (NID) data are updated regularly. The version of NID used for the current *Inventory* contains 47 new dams and updated values for “year of dam completion” for 975 dams relative to the previous (1990 through 2021) *Inventory* data. Similarly, the National Wetlands Inventory (NWI) is periodically updated. The NWI version used for the current *Inventory* has major updates for MS, ND, NM, and MT.

The net effect of these recalculations was an average annual increase in CH_4 and CO_2 emissions from other constructed waterbodies of 0.03 MMT CO_2 Eq., or 51 percent, over the time series from 1990 to 2021 compared to the previous *Inventory*.

Planned Improvements

Features < 8 ha in the NW that were not identified as canal/ditch were defined as freshwater ponds. Many of these features are lock chambers connected to an upstream reservoir. These systems likely have emission rates more similar to a reservoir than freshwater pond. In the next (i.e., 1990 through 2023) *Inventory* these systems will be classified as reservoirs.

6.10 Settlements Remaining Settlements (CRT Category 4E1)

Soil Carbon Stock Changes (CRT Category 4E1)

Soil organic C stock changes for settlements remaining settlements occur in both mineral and organic soils. However, the United States does not estimate changes in soil organic C stocks for mineral soils in settlements remaining settlements. This approach is consistent with the assumption of the Tier 1 method in the 2006 *IPCC Guidelines* (IPCC 2006) that inputs equal outputs, and therefore the soil organic C stocks do not change in this land use category. This assumption may be re-evaluated in the future if funding and resources are available to conduct an analysis of soil organic C stock changes for mineral soils in settlements remaining settlements.

Drainage of organic soils is common when wetland areas have been developed for settlements. Organic soils, also referred to as *Histosols*, include all soils with more than 12 to 20 percent organic carbon by weight, depending on clay content (NRCS 1999; Brady and Weil 1999). The organic layer of these soils can be very deep (i.e., several meters), and form under inundated conditions that results in minimal decomposition of plant residues. Drainage of organic soils leads to aeration of the soil that accelerates decomposition rate and CO_2 emissions.[97] Due to the depth and richness of the organic layers, carbon loss from drained organic soils can continue over long periods of time, which varies depending on climate and composition (i.e., decomposability) of the organic matter (Armentano and Menges 1986).

Settlements remaining settlements includes all areas that have been settlements for a continuous time period of at least 20 years according to the 2017 United States Department of Agriculture (USDA) National Resources Inventory (NRI) (USDA-NRCS 2020)[98] or according to the National Land Cover Dataset (NLCD) for federal lands (Yang et al. 2018; Fry et al. 2011; Homer et al. 2007, 2015). There are discrepancies between the current land representation (see Section 6.1) and the area data that have been used in the *Inventory* for settlements remaining settlements. Specifically, Alaska and the small amount of settlements on federal lands are not included in this *Inventory* even though these areas are part of the U.S. managed land base. There is a planned improvement to include CO_2 emissions from drainage of organic soils in settlements of Alaska and federal lands as part of a future *Inventory* (see Planned Improvements section).

CO_2 emissions from drained organic soils in settlements are 15.4 MMT CO_2 Eq. (4.2 MMT C) in 2022 (see Table 6-119 and Table 6-120). Although the flux is relatively small, the amount has increased by 56 percent since 1990 due to an increase in area of drained organic soils in settlements.

Table 6-119: Net CO_2 Flux from Soil C Stock Changes in Settlements Remaining Settlements (MMT CO_2 Eq.)

Soil Type	1990	2005	2018	2019	2020	2021	2022
Organic Soils	9.9	10.1	14.4	14.6	15.1	15.4	15.4

[97] N_2O emissions from drained organic soils are included in the N_2O Emissions from Settlement Soils section.

[98] NRI survey locations are classified according to land use histories starting in 1979, and consequently the classifications are based on less than 20 years from 1990 to 1998. This may have led to an overestimation of Settlements Remaining Settlements in the early part of the time series to the extent that some areas are converted to settlements between 1971 and 1978.

Table 6-120: Net CO_2 Flux from Soil C Stock Changes in Settlements Remaining Settlements (MMT C)

Soil Type	1990	2005	2018	2019	2020	2021	2022
Organic Soils	2.7	2.7	3.9	4.0	4.1	4.2	4.2

Methodology and Time-Series Consistency

An IPCC Tier 2 method is used to estimate soil organic C stock changes for organic soils in settlements remaining settlements (IPCC 2006). Organic soils in settlements remaining settlements are assumed to be losing C at a rate similar to croplands due to deep drainage, and therefore emission rates are based on country-specific values for cropland (Ogle et al. 2003).

The land area designated as settlements is based primarily on the 2017 NRI (USDA-NRCS 2020) with additional information from the NLCD to the extend the time series through 2020 (Yang et al. 2018). Soils are classified as organic using data from the Soil Survey Geographic Database (SSURGO) (Soil Survey Staff 2020). The areas have been modified through a process in which the Forest Inventory and Analysis (FIA) survey data are harmonized with the NRI data (Nelson et al. 2020). This process ensures that the land use areas are consistent across all land use categories (see Section 6.1 for more information). All settlements occurring on organic soil are assumed to be drained for the purposes of approximating greenhouse gas emissions. The area of drained organic soils is estimated from the NRI spatial weights and aggregated to the country (Table 6-121). The area of land on organic soils in settlements remaining settlements has increased from 216 thousand hectares in 1990 to over 327 thousand hectares in 2020.

Table 6-121: Thousands of Hectares of Drained Organic Soils in Settlements Remaining Settlements

	1990	2005	2014	2015	2016	2017	2018	2019	2020	2021	2022
Area (Thousand Hectares)	216	219	276	283	291	302	311	317	327	*	*

NRI data have not been incorporated into the *Inventory* after 2020, designated with asterisks (*).

To estimate CO_2 emissions from drained organic soils across the time series from 1990 to 2020, the area of organic soils by climate (i.e., cool temperate, warm temperate, subtropical) in settlements remaining settlements is multiplied by the appropriate country-specific emission factors for cropland remaining cropland under the assumption that there is deep drainage of the soils. The emission factors are 11.2 MT C per ha in cool temperate regions, 14.0 MT C per ha in warm temperate regions, and 14.3 MT C per ha in subtropical regions (see Annex 3.12 for more information).

In order to ensure time-series consistency, the same methods are applied from 1990 to 2020, and a linear extrapolation method is used to approximate emissions for the remainder of the 2021 to 2020 time series (see Box 6-4 in cropland remaining cropland). The extrapolation is based on a linear regression model with moving-average (ARMA) errors using the 1990 to 2020 emissions data, and is a standard data splicing method for imputing missing emissions data in a time series (IPCC 2006). The Tier 2 method described previously will be applied in future inventories to recalculate the estimates beyond 2020 as new activity data are integrated into the analysis.

Uncertainty

The total uncertainty was quantified with two variance components (Ogle et al. 2010) that are combined using simple error propagation methods provided by the IPCC (2006), i.e., by taking the square root of the sum of the squares of the standard deviations of the uncertain quantities. The first variance component is associated with uncertainty in the emission factor, and the second variance component is associated with scaling of the data from the NRI survey to the entire area of drained organic soils in settlements remaining settlements, and is computed using a standard variance estimator for a two-stage sample design (Särndal et al. 1992). There is also additional uncertainty associated with the fit of the linear regression model for the data splicing methods that was

incorporated into the analysis for the latter part of the time series. Soil carbon losses from drained organic soils in settlements remaining settlements for 2022 are estimated to be between 7.7 and 23.2 MMT CO_2 Eq. at a 95 percent confidence level (Table 6-115). This indicates a range of 50 percent below and 50 percent above the 2022 emission estimate of 15.4 MMT CO_2 Eq.

Table 6-122: Uncertainty Estimates for CO_2 Emissions from Drained Organic Soils in Settlements Remaining Settlements (MMT CO_2 Eq. and Percent)

Source	Gas	2022 Emission Estimate	Uncertainty Range Relative to Emission Estimate[a] (MMT CO_2 Eq.)		(%)	
		(MMT CO_2 Eq.)	Lower Bound	Upper Bound	Lower Bound	Upper Bound
Organic Soils	CO_2	15.4	7.7	23.2	-50%	+50%

[a] Range of emission estimates is a 95 percent confidence interval.

QA/QC and Verification

Quality control measures included checking input data, model scripts, and results to ensure data are properly handled throughout the inventory process consistent with the U.S. *Inventory* QA/QC plan, which is in accordance with Volume 1, Chapter 6 of the *2006 IPCC Guidelines* (see Annex 8 for more details). Inventory reporting forms and text are reviewed and revised as needed to correct transcription errors. No errors were found in this *Inventory*.

Recalculations Discussion

Recalculations are associated with updated land areas for drainage of organic soils in settlements remaining settlements, and update that was made by incorporating new USDA-NRCS NRI data through 2017 and extending the time series using NLCD. As a result of this change, CO_2-equivalent emissions changed annually with an average annual decrease of 1.8 MMT CO_2 Eq., or 14 percent, over the time series from 1990 to 2021 compared to the previous *Inventory*.

Planned Improvements

A key improvement is to estimate CO_2 emissions from drainage of organic soils in settlements of Alaska and federal lands. This improvement will resolve most of the differences between the managed land base for settlements remaining settlements and amount of area currently included in this *Inventory* as settlements remaining settlements (see Table 6-123). This improvement will be made pending prioritization of resources to expand the inventory for this source category.

Table 6-123: Area of Managed Land in Settlements Remaining Settlements that is not included in the current *Inventory* (Thousand Hectares)

Year	Area (Thousand Hectares)		
	SRS Managed Land Area (Section 6.1)	SRS Area Included in Inventory	Difference
1990	30,548	30,366	182
1991	30,545	30,364	182
1992	30,543	30,361	182
1993	30,470	30,288	182
1994	30,385	30,203	182
1995	30,322	30,141	182
1996	30,263	30,081	182
1997	30,193	30,011	182
1998	30,127	29,945	182
1999	30,073	29,891	182
2000	30,015	29,834	182
2001	29,963	29,781	182
2002	29,956	29,774	182
2003	30,479	30,298	182
2004	30,973	30,791	182
2005	31,432	31,250	182
2006	31,940	31,758	182
2007	32,397	32,215	182
2008	33,015	32,833	182
2009	33,591	33,410	182
2010	34,166	33,984	182
2011	34,731	34,549	182
2012	35,302	35,120	182
2013	36,224	36,042	182
2014	37,159	36,977	182
2015	38,026	37,844	182
2016	38,938	38,756	182
2017	39,861	39,679	182
2018	40,756	40,574	182
2019	41,602	41,420	182
2020	42,452	42,270	182
2021	43,175	*	*
2022	43,734	*	*

NRI data have not been incorporated into the *Inventory* after 2020, designated with asterisks (*).

Changes in Carbon Stocks in Settlement Trees (CRT Category 4E1)

Settlements are land uses where human populations and activities are concentrated. In these areas, the anthropogenic impacts on tree growth, stocking and mortality are particularly pronounced (Nowak 2012) in comparison to forest lands where non-anthropogenic forces can have more significant impacts. Estimates included in this section include net CO_2 and carbon flux from trees on settlements remaining settlements and land converted to settlements as it is not possible to report on these separately at this time.

Trees in settlement areas of the United States are estimated to account for an average annual net sequestration of 118.2 MMT CO_2 Eq. (32.2 MMT C) over the period from 1990 through 2022. Net carbon sequestration from settlement trees in 2022 is estimated to be 138.5 MMT CO_2 Eq. (37.8 MMT C) (Table 6-124). Dominant factors affecting carbon flux trends for settlement trees are changes in the amount of settlement area (increasing

sequestration due to more land and trees) and net changes in tree cover (e.g., tree losses versus tree gains through planting and natural regeneration), with percent tree cover trending downward recently. In addition, changes in species composition, tree sizes and tree densities affect base carbon flux estimates. Annual sequestration increased by 43 percent between 1990 and 2022 due to increases in settlement area and changes in total tree cover.

Trees in settlements often grow faster than forest trees because of their relatively open structure (Nowak and Crane 2002). Because tree density in settlements is typically much lower than in forested areas, the carbon storage per hectare of land is in fact smaller for settlement areas than for forest areas. Also, percent tree cover in settlement areas is less than in forests and this urban tree cover varies significantly across the United States (e.g., Nowak and Greenfield 2018a). To quantify the carbon stored in settlement trees, the methodology used here requires analysis per unit area of tree cover, rather than per unit of total land area (as is done for forest lands).

Table 6-124: Net Flux from Trees in Settlements Remaining Settlements (MMT CO_2 Eq. and MMT C)[a]

Year	1990	2005	2018	2019	2020	2021	2022
MMT CO_2 Eq.	(96.6)	(117.0)	(134.4)	(135.6)	(136.7)	(137.8)	(138.5)
MMT C	(26.3)	(31.9)	(36.7)	(37.0)	(37.3)	(37.6)	(37.8)

[a] These estimates include net CO_2 and C flux from trees on settlements remaining settlements and land converted to settlements as it is not possible to report on these separately at this time.

Note: Parentheses indicate net sequestration.

Methodology and Time-Series Consistency

To estimate net carbon sequestration in settlement areas, three types of data are required for each state:

1. Settlement area
2. Percent tree cover in settlement areas
3. Carbon sequestration density per unit of tree cover

Settlement Area

Settlement area is defined in Section 6.1 as a land-use category representing developed areas. The data used to estimate settlement area within Section 6.1 comes from the latest NRI as updated through 2017, with the extension of the time series through 2022 based on assuming the settlement area is the same as 2017. The NRI data is also harmonized with the FIA dataset, which is available through 2022, and the 2019 NLCD dataset. This process of combining the datasets extends the time series to ensure that there is a complete and consistent representation of land use data for all source categories in the LULUCF sector. Annual estimates of the net CO_2 flux (Table 6-124) were developed based on estimates of annual settlement area and tree cover derived from NLCD developed lands. Developed land, which was used to estimate tree cover in settlement areas, is about six percent higher than the area categorized as settlements in the representation of the U.S. land base developed for this report.

Percent Tree Cover in Settlement Areas

Percent tree cover in settlement area by state is needed to convert settlement land area to settlement tree cover area. Converting to tree cover area is essential as tree cover, and thus carbon estimates, can vary widely among states in settlement areas due to variations in the amount of tree cover (e.g., Nowak and Greenfield 2018a). However, since the specific geography of settlement area is unknown because they are based on NRI sampling methods, NLCD developed land was used to estimate the percent tree cover to be used in settlement areas. The NLCD developed land cover classes 21-24 (developed, open space (21), low intensity (22), medium intensity (23), and high intensity (24)) were used to estimate percent tree cover in settlement area by state (U.S. Department of Interior 2018; MRLC 2013).

a) "Developed, Open Space – areas with a mixture of some constructed materials, but mostly vegetation in the form of lawn grasses. Impervious surfaces account for less than 20 percent of total cover. These areas most commonly include large-lot single-family housing units, parks, golf courses, and vegetation planted in developed settings for recreation, erosion control, or aesthetic purposes." Plots designated as either park, recreation, cemetery, open space, institutional or vacant land were classified as "Developed, Open Space".

b) "Developed, Low Intensity – areas with a mixture of constructed materials and vegetation. Impervious surfaces account for 20 to 49 percent of total cover. These areas most commonly include single-family housing units." Plots designated as single family or low-density residential land were classified as "Developed, Low Intensity".

c) "Developed, Medium Intensity – areas with a mixture of constructed materials and vegetation. Impervious surfaces account for 50 to 79 percent of the total cover. These areas most commonly include single-family housing units." Plots designated as medium density residential, other urban or mixed urban were classified as "Developed, Medium Intensity".

d) "Developed High Intensity – highly developed areas where people reside or work in high numbers. Examples include apartment complexes, row houses and commercial/industrial. Impervious surfaces account for 80 to 100 percent of the total cover." Plots designated as either commercial, industrial, high density residential, downtown, multi-family residential, shopping, transportation or utility were classified as "Developed, High Intensity".

As NLCD is known to underestimate tree cover (Nowak and Greenfield 2010), photo-interpretation of tree cover within NLCD developed lands was conducted for the years of c. 2016 and 2020 using 1,000 random points to determine an average adjustment factor for NLCD tree cover estimates in developed land and determine recent tree cover changes. This photo-interpretation of change followed methods detailed in Nowak and Greenfield (2018b). Percent tree cover (%TC) in settlement areas by state was estimated as:

%TC in state = state NLCD %TC x national photo-interpreted %TC / national NLCD %TC

Percent tree cover in settlement areas by year was set as follows:

- 1990 to 2011: used 2011 NLCD tree cover adjusted with 2011 photo-interpreted values
- 2012 to 2015: used 2011 NLCD tree cover adjusted with photo-interpreted values, which were interpolated from values between 2011 and 2016
- 2016 to 2020: used 2016 NLCD tree cover adjusted with 2020 photo-interpreted values

Carbon Sequestration Density per Unit of Tree Cover

Methods for quantifying settlement tree biomass, carbon sequestration, and carbon emissions from tree mortality and decomposition were taken directly from Nowak et al. (2013), Nowak and Crane (2002), and Nowak (1994). In general, net carbon sequestration estimates followed three steps, each of which is explained further in the paragraphs below. First, field data from cities and urban areas within entire states were used to estimate carbon in tree biomass from field data on measured tree dimensions. Second, estimates of annual tree growth and biomass increment were generated from published literature and adjusted for tree condition, crown competition, and growing season to generate estimates of gross carbon sequestration in settlement trees for all 50 states and the District of Columbia. Third, estimates of carbon emissions due to mortality and decomposition were subtracted from gross carbon sequestration estimates to obtain estimates of net carbon sequestration. Carbon storage, gross and net sequestration estimates were standardized per unit tree cover based on tree cover in the study area.

Settlement tree carbon estimates are based on published literature (Nowak et al. 2013; Nowak and Crane 2002; Nowak 1994) as well as newer data from the i-Tree database[99] and U.S. Forest Service urban forest inventory data (e.g., Nowak et al. 2016, 2017) (Table 6-125). These data are based on collected field measurements in several U.S. cities between 1989 and 2017. Carbon storage and sequestration in these cities were estimated using the U.S. Forest Service's i-Tree Eco model (Nowak et al. 2008). This computer model uses standardized field data from randomly located plots, along with local hourly air pollution and meteorological data, to quantify urban forest structure, monetary values of the urban forest, and environmental effects, including total carbon stored and annual carbon sequestration (Nowak et al. 2013).

In each city, a random sample of plots were measured to assess tree stem diameter, tree height, crown height and crown width, tree location, species, and canopy condition. The data for each tree were used to estimate total dry-weight biomass using allometric models, a root-to-shoot ratio to convert aboveground biomass estimates to whole tree biomass, and wood moisture content. Total dry weight biomass was converted to carbon by dividing by two (50 percent carbon content). An adjustment factor of 0.8 was used for open grown trees to account for settlement trees having less aboveground biomass for a given stem diameter than predicted by allometric models based on forest trees (Nowak 1994). Carbon storage estimates for deciduous trees include only carbon stored in wood. Estimated carbon storage was divided by tree cover in the area to estimate carbon storage per square meter of tree cover.

Table 6-125: Carbon Storage (kg C/m² tree cover), Gross and Net Sequestration (kg C/m² tree cover/year) and Tree Cover (percent) among Sampled U.S. Cities (see Nowak et al. 2013)

			Sequestration						
City	Storage	SE	Gross	SE	Net	SE	Ratio[a]	Tree Cover	SE
Adrian, MI	12.17	1.88	0.34	0.04	0.13	0.07	0.36	22.1	2.3
Albuquerque, NM	5.61	0.97	0.24	0.03	0.20	0.03	0.82	13.3	1.5
Arlington, TX	6.37	0.73	0.29	0.03	0.26	0.03	0.91	22.5	0.3
Atlanta, GA	6.63	0.54	0.23	0.02	0.18	0.03	0.76	53.9	1.6
Austin, TX	3.57	0.25	0.17	0.01	0.13	0.01	0.73	30.8	1.1
Baltimore, MD	10.30	1.24	0.33	0.04	0.20	0.04	0.59	28.5	1.0
Boise, ID	7.33	2.16	0.26	0.04	0.16	0.06	0.64	7.8	0.2
Boston, MA	7.02	0.96	0.23	0.03	0.17	0.02	0.73	28.9	1.5
Camden, NJ	11.04	6.78	0.32	0.20	0.03	0.10	0.11	16.3	9.9
Casper, WY	6.97	1.50	0.22	0.04	0.12	0.04	0.54	8.9	1.0
Chester, PA	8.83	1.20	0.39	0.04	0.25	0.05	0.64	20.5	1.7
Chicago (region), IL	9.38	0.59	0.38	0.02	0.26	0.02	0.70	15.5	0.3
Chicago, IL	6.03	0.64	0.21	0.02	0.15	0.02	0.70	18.0	1.2
Corvallis, OR	10.68	1.80	0.22	0.03	0.20	0.03	0.91	32.6	4.1
El Paso, TX	3.93	0.86	0.32	0.05	0.23	0.05	0.72	5.9	1.0
Freehold, NJ	11.50	1.78	0.31	0.05	0.20	0.05	0.64	31.2	3.3
Gainesville, FL	6.33	0.99	0.22	0.03	0.16	0.03	0.73	50.6	3.1
Golden, CO	5.88	1.33	0.23	0.05	0.18	0.04	0.79	11.4	1.5
Grand Rapids, MI	9.36	1.36	0.30	0.04	0.20	0.05	0.65	23.8	2.0
Hartford, CT	10.89	1.62	0.33	0.05	0.19	0.05	0.57	26.2	2.0
Houston, TX	4.55	0.48	0.31	0.03	0.25	0.03	0.83	18.4	1.0
Indiana[b]	8.80	2.68	0.29	0.08	0.27	0.07	0.92	20.1	3.2
Jersey City, NJ	4.37	0.88	0.18	0.03	0.13	0.04	0.72	11.5	1.7
Kansas[b]	7.42	1.30	0.28	0.05	0.22	0.04	0.78	14.0	1.6
Kansas City (region), MO/KS	7.79	0.85	0.39	0.04	0.26	0.04	0.67	20.2	1.7

[99] See http://www.itreetools.org.

Lake Forest Park, WA	12.76	2.63	0.49	0.07	0.42	0.07	0.87	42.4	0.8
Las Cruces, NM	3.01	0.95	0.31	0.14	0.26	0.14	0.86	2.9	1.0
Lincoln, NE	10.64	1.74	0.41	0.06	0.35	0.06	0.86	14.4	1.6
Los Angeles, CA	4.59	0.51	0.18	0.02	0.11	0.02	0.61	20.6	1.3
Milwaukee, WI	7.26	1.18	0.26	0.03	0.18	0.03	0.68	21.6	1.6
Minneapolis, MN	4.41	0.74	0.16	0.02	0.08	0.05	0.52	34.1	1.6
Moorestown, NJ	9.95	0.93	0.32	0.03	0.24	0.03	0.75	28.0	1.6
Morgantown, WV	9.52	1.16	0.30	0.04	0.23	0.03	0.78	39.6	2.2
Nebraska[b]	6.67	1.86	0.27	0.07	0.23	0.06	0.84	15.0	3.6
New York, NY	6.32	0.75	0.33	0.03	0.25	0.03	0.76	20.9	1.3
North Dakota[b]	7.78	2.47	0.28	0.08	0.13	0.08	0.48	2.7	0.6
Oakland, CA	5.24	0.19	NA	NA	NA	NA	NA	21.0	0.2
Oconomowoc, WI	10.34	4.53	0.25	0.10	0.16	0.06	0.65	25.0	7.9
Omaha, NE	14.14	2.29	0.51	0.08	0.40	0.07	0.78	14.8	1.6
Philadelphia, PA	8.65	1.46	0.33	0.05	0.29	0.05	0.86	20.8	1.8
Phoenix, AZ	3.42	0.50	0.38	0.04	0.35	0.04	0.94	9.9	1.2
Roanoke, VA	9.20	1.33	0.40	0.06	0.27	0.05	0.67	31.7	3.3
Sacramento, CA	7.82	1.57	0.38	0.06	0.33	0.06	0.87	13.2	1.7
San Francisco, CA	9.18	2.25	0.24	0.05	0.22	0.05	0.92	16.0	2.6
Scranton, PA	9.24	1.28	0.40	0.05	0.30	0.04	0.74	22.0	1.9
Seattle, WA	9.59	0.98	0.67	0.06	0.55	0.05	0.82	27.1	0.4
South Dakota[b]	3.14	0.66	0.13	0.03	0.11	0.02	0.87	16.5	2.2
Syracuse, NY	9.48	1.08	0.30	0.03	0.22	0.04	0.72	26.9	1.3
Tennessee[b]	6.47	0.50	0.34	0.02	0.30	0.02	0.89	37.7	0.8
Washington, DC	8.52	1.04	0.26	0.03	0.21	0.03	0.79	35.0	2.0
Woodbridge, NJ	8.19	0.82	0.29	0.03	0.21	0.03	0.73	29.5	1.7

SE (Standard Error)
NA (Not Available)
[a] Ratio of net to gross sequestration
[b] Statewide assessment of urban areas

To determine gross sequestration rates, tree growth rates need to be estimated. Base growth rates were standardized for open-grown trees in areas with 153 days of frost-free length based on measured data on tree growth (Nowak et al. 2013). These growth rates were adjusted to local tree conditions based on length of frost-free season, crown competition (as crown competition increased, growth rates decreased), and tree condition (as tree condition decreased, growth rates decreased). Annual growth rates were applied to each sampled tree to estimate gross annual sequestration–that is, the difference in carbon storage estimates between year 1 and year (x + 1) represents the gross amount of carbon sequestered. These annual gross carbon sequestration rates for each tree were then scaled up to city estimates using tree population information. Total carbon sequestration was divided by total tree cover to estimate a gross carbon sequestration density (kg C/m^2 of tree cover/year). The area of assessment for each city or state was defined by its political boundaries; parks and other forested urban areas were thus included in sequestration estimates.

Where gross carbon sequestration accounts for all carbon sequestered, net carbon sequestration for settlement trees considers carbon emissions associated with tree death and removals. The third step in the methodology estimates net carbon emissions from settlement trees based on estimates of annual mortality, tree condition, and assumptions about whether dead trees were removed from the site. Estimates of annual mortality rates by diameter class and condition class were obtained from a study of street-tree mortality (Nowak 1986). Different decomposition rates were applied to dead trees left standing compared with those removed from the site. For removed trees, different rates were applied to the removed/aboveground biomass in contrast to the belowground biomass (Nowak et al. 2002). The estimated annual gross carbon emission rates for each plot were then scaled up to city estimates using tree population information.

The full methodology development is described in the underlying literature, and key details and assumptions were made as follows. The allometric models applied to the field data for the Nowak methodology for each tree were taken from the scientific literature (see Nowak 1994, Nowak et al. 2002), but if no allometric model could be found

for the particular species, the average result for the genus or botanical relative was used. The adjustment (0.8) to account for less live tree biomass in open-grown urban trees was based on information in Nowak (1994). Measured tree growth rates for street (Frelich 1992; Fleming 1988; Nowak 1994), park (deVries 1987), and forest (Smith and Shifley 1984) trees were standardized to an average length of growing season (153 frost free days) and adjusted for site competition and tree condition. Standardized growth rates of trees of the same species or genus were then compared to determine the average difference between standardized street tree growth and standardized park and forest growth rates. Crown light exposure (CLE) measurements (number of sides and/or top of tree exposed to sunlight) were used to represent forest, park, and open (street) tree growth conditions. Local tree base growth rates were then calculated as the average standardized growth rate for open-grown trees multiplied by the number of frost-free days divided by 153. Growth rates were then adjusted for CLE. The CLE-adjusted growth rate was then adjusted based on tree condition to determine the final growth rate. Assumptions for which dead trees would be removed versus left standing were developed specific to each land use and were based on expert judgment of the authors. Decomposition rates were based on literature estimates (Nowak et al. 2013).

Estimates of gross and net sequestration rates for each of the 50 states and the District of Columbia (Table 6-126) were compiled in units of carbon sequestration per unit area of tree canopy cover. These rates were used in conjunction with estimates of state settlement area and developed land percent tree cover data to calculate each state's annual net carbon sequestration by urban trees. This method was described in Nowak et al. (2013) and has been modified here to incorporate developed land percent tree cover data.

Net annual carbon sequestration estimates were obtained for all 50 states and the District of Columbia by multiplying the gross annual emission estimates by 0.73, the average ratio for net/gross sequestration (Table 6-126). However, state specific ratios were used where available.

State Carbon Sequestration Estimates

The gross and net annual carbon sequestration values for each state were multiplied by each state's settlement area of tree cover, which was the product of the state's settlement area and the state's tree cover percentage based on NLCD developed land. The model used to calculate the total carbon sequestration amounts for each state, can be written as follows:

Equation 6-1: Net State Annual Carbon Sequestration

$$\text{Net state annual C sequestration (t C/yr)} = \text{Gross state sequestration rate (t C/ha/yr)} \times \text{Net to Gross state sequestration ratio} \times \text{state settlement Area (ha)} \times \%\ \text{state tree cover in settlement area}$$

The results for all 50 states and the District of Columbia are given in Table 6-126. This approach is consistent with the default IPCC Gain-Loss methodology in IPCC (2006), although sufficient field data are not yet available to separately determine interannual gains and losses in carbon stocks in the living biomass of settlement trees. Instead, the methodology applied here uses estimates of net carbon sequestration based on modeled estimates of decomposition, as given by Nowak et al. (2013).

Table 6-126: Estimated Annual Carbon Sequestration, Tree Cover, and Annual Carbon Sequestration per Area of Tree Cover for settlement areas in the United States by State and the District of Columbia (2022)

State	Gross Annual Sequestration (Metric Tons C/Year)	Net Annual Sequestration (Metric Tons C/Year)	Tree Cover (Percent)	Gross Annual Sequestration per Area of Tree Cover (kg C/m²/Year)	Net Annual Sequestration per Area of Tree Cover (kg C/m²/Year)	Net: Gross Annual Sequestration Ratio
Alabama	2,268,736	1,653,170	53.1	0.376	0.274	0.73
Alaska	150,345	109,553	47.0	0.169	0.123	0.73

Arizona	165,494	120,591	4.5	0.388	0.283	0.73
Arkansas	1,316,764	959,492	48.5	0.362	0.264	0.73
California	2,015,461	1,468,615	16.8	0.426	0.311	0.73
Colorado	142,538	103,864	7.9	0.216	0.157	0.73
Connecticut	649,817	473,505	58.2	0.262	0.191	0.73
Delaware	101,819	74,193	24.2	0.366	0.267	0.73
DC	12,919	9,414	24.9	0.366	0.267	0.73
Florida	4,632,104	3,375,296	39.9	0.520	0.379	0.73
Georgia	3,886,939	2,832,313	55.9	0.387	0.282	0.73
Hawaii	302,023	220,076	41.4	0.637	0.464	0.73
Idaho	59,771	43,553	7.3	0.201	0.146	0.73
Illinois	669,891	488,132	15.4	0.310	0.226	0.73
Indiana	479,505	443,378	17.0	0.274	0.254	0.92
Iowa	177,874	129,612	8.5	0.263	0.191	0.73
Kansas	288,317	224,359	10.7	0.310	0.241	0.78
Kentucky	984,663	717,499	36.5	0.313	0.228	0.73
Louisiana	1,585,823	1,155,549	46.6	0.435	0.317	0.73
Maine	445,519	324,639	55.1	0.242	0.176	0.73
Maryland	857,152	624,585	39.8	0.353	0.257	0.73
Massachusetts	1,093,110	796,521	56.8	0.278	0.203	0.73
Michigan	1,410,284	1,027,638	34.4	0.241	0.175	0.73
Minnesota	325,047	236,853	13.0	0.251	0.183	0.73
Mississippi	1,630,583	1,188,165	56.9	0.377	0.275	0.73
Missouri	878,510	640,148	23.0	0.313	0.228	0.73
Montana	45,414	33,092	4.8	0.201	0.147	0.73
Nebraska	97,770	82,504	7.3	0.261	0.220	0.84
Nevada	35,783	26,074	4.8	0.226	0.165	0.73
New Hampshire	392,480	285,990	58.8	0.238	0.174	0.73
New Jersey	961,860	700,883	40.4	0.321	0.234	0.73
New Mexico	188,804	137,577	10.1	0.288	0.210	0.73
New York	1,606,981	1,170,966	39.6	0.263	0.192	0.73
North Carolina	3,457,794	2,519,606	53.7	0.341	0.249	0.73
North Dakota	18,730	8,900	1.7	0.244	0.116	0.48
Ohio	1,276,930	930,467	28.0	0.271	0.198	0.73
Oklahoma	718,922	523,860	21.9	0.364	0.265	0.73
Oregon	674,472	491,470	39.6	0.265	0.193	0.73
Pennsylvania	1,900,962	1,385,183	39.9	0.267	0.195	0.73
Rhode Island	127,720	93,066	49.6	0.283	0.206	0.73
South Carolina	2,052,656	1,495,718	53.3	0.370	0.269	0.73
South Dakota	29,351	25,453	2.8	0.258	0.224	0.87
Tennessee	1,678,890	1,501,125	40.8	0.332	0.297	0.89
Texas	4,416,309	3,218,052	28.2	0.403	0.294	0.73
Utah	119,794	87,291	11.6	0.235	0.172	0.73
Vermont	188,016	137,002	50.2	0.234	0.170	0.73
Virginia	2,111,293	1,538,445	52.5	0.321	0.234	0.73
Washington	1,139,218	830,119	37.3	0.282	0.206	0.73
West Virginia	774,594	564,427	63.6	0.264	0.192	0.73
Wisconsin	711,938	518,771	25.7	0.246	0.180	0.73
Wyoming	29,558	21,538	4.7	0.199	0.145	0.73
Total	**51,287,245**	**37,768,294**				

Uncertainty

Uncertainty associated with changes in carbon stocks in settlement trees includes the uncertainty associated with settlement area, percent tree cover in developed land and how well it represents percent tree cover in settlement areas, and estimates of gross and net carbon sequestration for each of the 50 states and the District of Columbia. A

ten percent uncertainty was associated with settlement area estimates based on expert judgment. Uncertainty associated with estimates of percent settlement tree coverage for each of the 50 states was based on standard error associated with the photo-interpretation of national tree cover in developed lands. Uncertainty associated with estimates of gross and net carbon sequestration for each of the 50 states and the District of Columbia was based on standard error estimates for each of the state-level sequestration estimates (Table 6-127). These estimates are based on field data collected in each of the 50 states and the District of Columbia, and uncertainty in these estimates increases as they are scaled up to the national level.

Additional uncertainty is associated with the biomass models, conversion factors, and decomposition assumptions used to calculate carbon sequestration and emission estimates (Nowak et al. 2002). These results also exclude changes in soil carbon stocks, and there is likely some overlap between the settlement tree carbon estimates and the forest tree carbon estimates (e.g., Nowak et al. 2013). Due to data limitations, settlement soil flux is not quantified as part of this analysis, while reconciliation of settlement tree and forest tree estimates will be addressed through the land-representation effort described in the Planned Improvements section of this chapter.

A Monte Carlo (Approach 2) uncertainty analysis was applied to estimate the overall uncertainty of the sequestration estimate in 2022. The results of this quantitative uncertainty analysis are summarized in Table 6-127. The change in carbon stocks in settlement trees in 2022 was estimated to be between -208.5 and -66.6 MMT CO_2 Eq. at a 95 percent confidence level. This analysis indicates a range of 51 percent more sequestration to 52 percent less sequestration than the 2022 flux estimate of -138.5 MMT CO_2 Eq.

Table 6-127: Approach 2 Quantitative Uncertainty Estimates for Net CO_2 Flux from Changes in Carbon Stocks in Settlement Trees (MMT CO_2 Eq. and Percent)

Source	Gas	2022 Flux Estimate	Uncertainty Range Relative to Flux Estimate[a] (MMT CO_2 Eq.)		Uncertainty Range Relative to Flux Estimate[a] (%)	
		(MMT CO_2 Eq.)	Lower Bound	Upper Bound	Lower Bound	Upper Bound
Changes in C Stocks in Settlement Trees	CO_2	(138.5)	(208.5)	(66.6)	-51%	+52%

[a] Range of C stock change estimates predicted by Monte Carlo stochastic simulation with a 95 percent confidence interval.

Note: Parentheses indicate negative values or net sequestration.

QA/QC and Verification

Tier 1 and Tier 2 QA/QC activities were conducted consistent with the U.S. QA/QC plan. Source-specific quality control measures for settlement trees included checking input data, documentation, and calculations to ensure data were properly handled through the inventory process. Errors that were found during this process were corrected as necessary.

Recalculations Discussion

The compilation methods remained the same in the latest *Inventory* relative to the previous *Inventory*. New data from the NRI and NLCD resulted in a small decrease in the settlement area for 2021, leading to no substantial change in the net carbon sequestration (Table 6-128).

Table 6-128: Recalculations of the Settlement Tree Categories

Category	2021 Estimate, Previous *Inventory*	2021 Estimate, Current *Inventory*	2022 Estimate, Current *Inventory*
Settlement Area (km^2)	469,705	469,600	471,851
Settlement Tree Coverage (km^2)	151,694	151,664	152,442
Net C Flux (MMT C)	(37.6)	(37.6)	(37.8)

Net CO_2 Flux MMT CO_2 Eq.	(137.8)	(137.8)	(138.5)

Planned Improvements

A consistent representation of the managed land base in the United States is discussed in Section 6.1, and discusses a planned improvement by the USDA Forest Service to reconcile the overlap between settlement trees and the forest land categories. Estimates for settlement trees are based on tree cover in settlement areas. Work is needed to clarify how much of this settlement area tree cover may also be accounted for in "forest" area assessments as some of these forests may be adjacent to settlement areas. For example, "forest" as defined by the USDA Forest Service Forest Inventory and Analysis (FIA) program fall within urban areas. Nowak et al. (2013) estimates that 1.5 percent of forest plots measured by the FIA program fall within land designated as Census urban, suggesting that approximately 1.5 percent of the carbon reported in the forest source category might also be counted in the urban areas. The potential overlap with settlement areas is unknown at this time but research is underway to develop spatially explicit and spatially continuous land representation products which will eliminate the potential for double counting. Future research may also enable more complete coverage of changes in the carbon stock of trees for all settlements land.

N_2O Emissions from Settlement Soils (CRT Source Category 4E1)

Of the synthetic N fertilizers applied to soils in the United States, approximately 1 to 2 percent are currently applied to lawns, golf courses, and other landscaping within settlement areas, and contributes to soil N_2O emissions. The area of settlements is considerably smaller than other land uses that are managed with fertilizer, particularly cropland soils, and therefore, settlements account for a smaller proportion of total synthetic fertilizer application in the United States. In addition to synthetic N fertilizers, a portion of surface applied biosolids (i.e., treated sewage sludge) is used as an organic fertilizer in settlement areas, and drained organic soils (i.e., soils with high organic matter content, known as *histosols*) also contribute to emissions of soil N_2O.

N additions to soils result in direct and indirect N_2O emissions. Direct emissions occur on-site due to the N additions in the form of synthetic fertilizers and biosolids as well as enhanced mineralization of N in drained organic soils. Indirect emissions result from fertilizer and biosolids N that is transformed and transported to another location in a form other than N_2O (i.e., volatilization of ammonia [NH_3] and nitrogen oxide [NO_x], and leaching/runoff of nitrate [NO_3^-]), and later converted into N_2O at the off-site location. The indirect emissions are assigned to settlements because the management activity leading to the emissions occurred in settlements.

Total N_2O emissions from soils in settlements remaining settlements[100] are 2.5 MMT CO_2 Eq. (10 kt of N_2O) in 2022. There is an overall increase of 23 percent from 1990 to 2022 due to an expanding settlement area leading to more synthetic N fertilizer applications that peaked in the mid-2000s. Inter-annual variability in these emissions is directly attributable to variability in total synthetic fertilizer consumption, area of drained organic soils, and biosolids applications in the United States. Emissions from this source are summarized in Table 6-129.

Table 6-129: N_2O Emissions from Soils in Settlements Remaining Settlements (MMT CO_2 Eq. and kt N_2O)

	1990	2005	2018	2019	2020	2021	2022
MMT CO_2 Eq.							
Direct N_2O Emissions from Soils	**1.7**	**2.6**	**2.1**	**2.1**	**2.2**	**2.2**	**2.2**
Synthetic Fertilizers	0.8	1.5	0.8	0.8	0.8	0.8	0.8

[100] Estimates of Soil N_2O for settlements remaining settlements include emissions from land converted to settlements because it was not possible to separate the activity data.

Biosolids	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Drained Organic Soils	0.8	1.0	1.2	1.2	1.2	1.2	1.2
Indirect N_2O Emissions from Soils	**0.3**	**0.5**	**0.3**	**0.3**	**0.3**	**0.3**	**0.3**
Total	**2.1**	**3.1**	**2.4**	**2.5**	**2.5**	**2.5**	**2.5**
kt N_2O							
Direct N_2O Emissions from Soils	**7**	**10**	**8**	**8**	**8**	**8**	**8**
Synthetic Fertilizers	3	5	3	3	3	3	3
Biosolids	1	1	1	1	1	1	1
Drained Organic Soils	3	4	4	4	4	4	4
Indirect N_2O Emissions from Soils	**1**	**2**	**1**	**1**	**1**	**1**	**1**
Total	**8**	**12**	**9**	**9**	**9**	**10**	**10**

Note: Totals may not sum due to independent rounding.

Methodology and Time-Series Consistency

For settlement soils, the IPCC Tier 1 approach is used to estimate soil N_2O emissions from synthetic N fertilizer, biosolids additions, and drained organic soils. Estimates of direct N_2O emissions from soils in settlements are based on the amount of N in synthetic commercial fertilizers applied to settlement soils, the amount of N in biosolids applied to non-agricultural land and surface disposal (see Section 7.2 for a detailed discussion of the methodology for estimating biosolids available for non-agricultural land application), and the area of drained organic soils within settlements.

Nitrogen applications to settlement soils are estimated using data compiled by the USGS (Brakebill and Gronberg 2017). The USGS estimated on-farm and non-farm fertilizer use is based on sales records at the county level from 1987 through 2012 (Brakebill and Gronberg 2017). Non-farm N fertilizer is assumed to be applied to settlements and forest lands; values for 2013 through 2017 are based on 2012 values adjusted for total annual total N fertilizer sales in the United States (AAPFCO 2016 through 2022) because there are no activity data on non-farm application after 2012. Settlement application is calculated by subtracting forest application from total non-farm fertilizer use. Since the total N fertilizer sales is only available through 2017 (AAPFCO 2022), the amount of synthetic fertilization from 2018 to 2022 is determined using a linear extrapolation method (see Box 6-4 in cropland remaining cropland). This method is based on a linear regression model with moving-average (ARMA) errors using the 1990 to 2017 fertilization data. To estimate direct N_2O for the time series, the total amount of fertilizer N applied to settlements is multiplied by the IPCC default emission factor (1 percent) (IPCC 2006) for 1990 to 2022.

Biosolids applications are derived from national data on biosolids generation, disposition, and N content (see Section 7.2 for further detail). The total amount of N resulting from these sources is multiplied by the IPCC default emission factor for applied N (one percent) to estimate direct N_2O emissions (IPCC 2006) for 1990 to 2022.

The IPCC (2006) Tier 1 method is also used to estimate direct N_2O emissions due to drainage of organic soils in settlements at the national scale. Estimates of the total area of drained organic soils are obtained from the 2017 National Resources Inventory (NRI) (USDA-NRCS 2020) using soils data from the Soil Survey Geographic Database (SSURGO) (Soil Survey Staff 2020). The NRI time series has been extended through 2020 using the National Land Cover Dataset (Yang et al. 2018). The areas have been modified through a process in which the Forest Inventory and Analysis (FIA) survey data are harmonized with the NRI data (Nelson et al. 2020). This process ensures that the land use areas are consistent across all land use categories (see Section 6.1 for more information). All settlements occurring on organic soil are assumed to be drained for the purposes of approximating greenhouse gas emissions. To estimate annual emissions from 1990 to 2020, the total area is multiplied by the IPCC default emission factor for temperate regions (IPCC 2006). The annual emissions for 2021 to 2022 are estimated using a linear extrapolation method (see Box 6-4 in Cropland Remaining Cropland). This *Inventory* does not include soil N_2O emissions from drainage of organic soils in Alaska and federal lands, although this is a planned improvement for a future *Inventory*.

For indirect emissions, the total N applied from fertilizer and biosolids is multiplied by the IPCC default factors of 10 percent for volatilization and 30 percent for leaching/runoff to calculate the amount of N volatilized and the

amount of N leached/runoff. The amount of N volatilized is multiplied by the IPCC default factor of one percent for the portion of volatilized N that is converted to N_2O off-site and the amount of N leached/runoff is multiplied by the IPCC default factor of 0.075 percent for the portion of leached/runoff N that is converted to N_2O off-site. The resulting estimates are summed to obtain total indirect emissions from 1990 to 2022 for biosolids and synthetic fertilization.

In order to ensure time-series consistency, the same methods are applied from 1990 to 2022 for biosolids. For synthetic fertilizer, a linear extrapolation method is used to approximate fertilizer application for the remainder of the 2018 to 2022 time series and then used to estimate emissions. For drainage of organic soils, the methods described above are applied for 1990 to 2020, and a linear extrapolation method is used to approximate emissions for the remainder of the 2021 to 2022 time series (see Box 6-4 in cropland remaining cropland). The extrapolation is based on a linear regression model with moving-average (ARMA) errors using the 1990 to 2020 emissions data, which is a standard data splicing method for imputing missing emissions data in a time series (IPCC 2006). The time series will be recalculated in a future *Inventory* with the methods described previously for drainage of organic soils.

Uncertainty

The amount of N_2O emitted from settlement soils depends not only on N inputs and area of drained organic soils, but also on a large number of variables that can influence rates of nitrification and denitrification, including organic C availability; rate, application method, and timing of N input; oxygen gas partial pressure; soil moisture content; pH; temperature; and irrigation/watering practices. The effect of the combined interaction of these variables on N_2O emissions is complex and highly uncertain. The IPCC default methodology does not explicitly incorporate these variables, except variation in the total amount of fertilizer N and biosolids application, which leads to uncertainty in the results.

Uncertainties exist in both the fertilizer N and biosolids application rates in addition to the emission factors. Uncertainty in fertilizer N application is assigned a default level of ±50 percent.[101] For emissions from drained organic soils, the total uncertainty was quantified with two variance components (Ogle et al. 2010) that are combined using simple error propagation methods provided by the IPCC (2006), i.e., by taking the square root of the sum of the squares of the standard deviations of the uncertain quantities. The first variance component is associated with uncertainty in the emission factor, and the second variance component is associated with scaling of the data from the NRI survey to the entire area of drained organic soils in settlements remaining settlements, and is computed using a standard variance estimator for a two-stage sample design (Särndal et al. 1992). There is also additional uncertainty associated with the fit of the linear regression model for the data splicing methods that was incorporated into the analysis for the latter part of the time series.

Uncertainty is propagated through the calculations of N_2O emissions from fertilizer N and drainage of organic soils based on a Monte Carlo analysis. The results are combined with the uncertainty in N_2O emissions from the biosolids application using simple error propagation methods (IPCC 2006). The results are summarized in Table 6-130. Direct N_2O emissions from soils in settlements remaining settlements in 2022 are estimated to be between 1.2 and 3.4 MMT CO_2 Eq. at a 95 percent confidence level. This indicates a range of 47 percent below to 54 percent above the 2022 emission estimate of 2.2 MMT CO_2 Eq. Indirect N_2O emissions in 2022 are between 0.1 and 1.1 MMT CO_2 Eq., ranging from 76 percent below to 218 percent above the estimate of 0.3 MMT CO_2 Eq.

[101] No uncertainty is provided with the USGS fertilizer consumption data (Brakebill and Gronberg 2017) so a conservative ±50 percent is used in the analysis. Biosolids data are also assumed to have an uncertainty of ±50 percent.

Table 6-130: Quantitative Uncertainty Estimates of N_2O Emissions from Soils in Settlements Remaining Settlements (MMT CO_2 Eq. and Percent)

Source	Gas	2022 Emissions (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Settlements Remaining Settlements						
Direct N_2O Emissions from Soils	N_2O	2.2	1.2	3.4	-47%	+54%
Indirect N_2O Emissions from Soils	N_2O	0.3	0.1	1.1	-76%	+218%

[a] Range of emission estimates is a 95 percent confidence interval.

Note: These estimates include direct and indirect N_2O emissions from settlements remaining settlements and land converted to settlements because it was not possible to separate the activity data.

QA/QC and Verification

The spreadsheet containing fertilizer, drainage of organic soils, and biosolids applied to settlements and calculations for N_2O and uncertainty ranges have been checked consistent with the U.S. *Inventory* QA/QC plan, which is in accordance with Volume 1, Chapter 6 of the *2006 IPCC Guidelines* (see Annex 8 for more details). An error was found in the initial calculations for emissions from drained organic soils, which was corrected.

Recalculations Discussion

Recalculations are associated with updated land areas for drainage of organic soils in settlements remaining settlements, by incorporating new USDA-NRCS NRI data through 2017 and extending the time series using CDL and NLCD for grassland converted to settlements, cropland converted to settlements, other land converted to settlements and wetlands converted to settlements. In addition, recalculations are associated with revised fertilizer application data from the AAPFCO report. As a result of these changes, CO_2-equivalent emissions changed annually with an average annual increase of 0.36 MMT CO_2 Eq., or 17 percent, over the time series from 1990 to 2021 compared to the previous *Inventory*.

Planned Improvements

This source will be extended to include soil N_2O emissions from drainage of organic soils in Alaska and federal lands in order to provide a complete inventory of emissions for this category. Data on fertilizer amounts from 2018 to 2022 will be updated after data are released for the latter part of the time series. These improvements will be incorporated into a future I*nventory*, pending prioritization of resources.

Changes in Yard Trimmings and Food Scrap Carbon Stocks in Landfills (CRT Category 4E1)

In the United States, yard trimmings (i.e., grass clippings, leaves, and branches) and food scraps account for a significant portion of the municipal waste stream, and a large fraction of the collected yard trimmings and food scraps are put in landfills. A portion of the carbon contained in landfilled yard trimmings and food scraps can be stored for very long periods.

Carbon storage estimates within the *Inventory* are associated with particular land uses. For example, harvested wood products are reported under forest land remaining forest land because these wood products originated from the forest ecosystem. Similarly, carbon stock changes in yard trimmings and food scraps are reported under settlements remaining settlements because the bulk of the carbon, which comes from yard trimmings, originates from settlement areas. While the majority of food scraps originate from cropland and grassland, in this *Inventory*

they are reported with the yard trimmings in the settlements remaining settlements section. Additionally, landfills are considered part of the managed land base under settlements (see Section 6.1), and reporting these carbon stock changes that occur entirely within landfills fits most appropriately within the settlements remaining settlements section. The CH_4 emissions resulting from anaerobic decomposition of yard trimmings and food scraps in landfills are reported in the Waste chapter, see Section 7.1.

The estimated amount of yard trimmings collected annually has stagnated since 1990 and the fraction that is landfilled has been declining since 1990. From 1970 to 1990, yard trimmings collected for disposal increased by about 51 percent. In 1990, over 53 million metric tons (wet weight) of yard trimmings and food scraps are estimated to have been generated (i.e., put at the curb for collection to be taken to disposal sites or to composting facilities) (EPA 2020). Since then, programs banning or discouraging yard trimmings disposal in landfills have led to an increase in backyard composting and the use of mulching mowers, and consequently a slowing of year-over-year increases in the tonnage of yard trimmings generated. From 1990 to 2022, yard trimmings collected for disposal are estimated to have increased 1.1. percent. At the same time, an increase in the number of municipal composting facilities has reduced the proportion of collected yard trimmings that are discarded in landfills per year—from 72 percent in 1990 to 30 percent in 2022. The net effect of the slight increase in generation and the increase in composting is a 58 percent decrease in the quantity of yard trimmings disposed of in landfills since 1990. Composting trends and emissions estimations are presented in the Waste chapter, Section 7.3 composting.

Food scrap generation has grown by an estimated 165 percent since 1990. Though the proportion of total food scraps generated that are eventually discarded in landfills has decreased from an estimated 82 percent in 1990 to 55 percent in 2020, the tonnage disposed of in landfills has increased considerably (by an estimated 78 percent) due to the increase in food scrap generation. Although the total tonnage of food scraps disposed of in landfills has increased from 1990 to 2022, the difference in the amount of food scraps added from one year to the next generally decreased, and consequently the annual *net changes* in carbon stock from food scraps have generally decreased as well (as shown in Table 6-131 and Table 6-132). Landfilled food scraps decompose over time, producing CH_4 and CO_2. Decomposition happens at a higher rate initially, then decreases. As decomposition decreases, the carbon stock becomes more stable. Because the cumulative carbon stock left in the landfill from previous years is (1) not decomposing as much as the carbon introduced from food scraps in a single more recent year; and (2) is much larger than the carbon introduced from food scraps in a single more recent year, the total carbon stock in the landfill is primarily driven by the more stable "older" carbon stock, thus resulting in decreasing annual changes in later years.

Overall, the decrease in the landfill disposal rate of yard trimmings has more than compensated for the increase in food scrap disposal in landfills, and the net result is a decrease in the annual net change in landfill carbon storage from 24.5 MMT CO_2 Eq. (6.7 MMT C) in 1990 to 11.8 MMT CO_2 Eq. (3.2 MMT C) in 2022 (Table 6-131 and Table 6-132), a decrease of 48 percent over the time series.

Table 6-131: Net Changes in Yard Trimmings and Food Scrap Carbon Stocks in Landfills (MMT CO_2 Eq.)

Carbon Pool	1990	2005	2018	2019	2020	2021	2022
Yard Trimmings	**(20.1)**	**(7.5)**	**(8.3)**	**(8.2)**	**(8.2)**	**(8.2)**	**(8.1)**
Grass	(1.7)	(0.6)	(0.8)	(0.8)	(0.8)	(0.8)	(0.7)
Leaves	(8.7)	(3.4)	(3.8)	(3.8)	(3.8)	(3.8)	(3.7)
Branches	(9.8)	(3.4)	(3.7)	(3.7)	(3.7)	(3.7)	(3.6)
Food Scraps	**(4.4)**	**(3.9)**	**(5.2)**	**(4.8)**	**(4.5)**	**(4.3)**	**(3.7)**
Total Net Flux	**(24.5)**	**(11.4)**	**(13.4)**	**(13.1)**	**(12.8)**	**(12.5)**	**(11.8)**

Notes: Totals may not sum due to independent rounding. Parentheses indicate net sequestration.

Table 6-132: Net Changes in Yard Trimmings and Food Scrap Carbon Stocks in Landfills (MMT C)

Carbon Pool	1990	2005	2018	2019	2020	2021	2022
Yard Trimmings	**(5.5)**	**(2.0)**	**(2.3)**	**(2.2)**	**(2.2)**	**(2.2)**	**(2.2)**
Grass	(0.5)	(0.2)	(0.2)	(0.2)	(0.2)	(0.2)	(0.2)
Leaves	(2.4)	(0.9)	(1.0)	(1.0)	(1.0)	(1.0)	(1.0)
Branches	(2.7)	(0.9)	(1.0)	(1.0)	(1.0)	(1.0)	(1.0)
Food Scraps	**(1.2)**	**(1.1)**	**(1.4)**	**(1.3)**	**(1.2)**	**(1.2)**	**(1.0)**
Total Net Flux	**(6.7)**	**(3.1)**	**(3.7)**	**(3.6)**	**(3.5)**	**(3.4)**	**(3.2)**

Notes: Totals may not sum due to independent rounding. Parentheses indicate net sequestration.

Methodology and Time-Series Consistency

When wastes of biogenic origin (such as yard trimmings and food scraps) are landfilled and do not completely decompose, the carbon that remains is effectively removed from the carbon cycle. Empirical evidence indicates that yard trimmings and food scraps do not completely decompose in landfills (Barlaz 1998, 2005, 2008; De la Cruz and Barlaz 2010), and thus the stock of carbon in landfills can increase, with the net effect being removal of carbon from the atmosphere. Estimates of the net carbon flux resulting from landfilled yard trimmings and food scraps were developed by estimating the change in landfilled carbon stocks between inventory years and uses a country-specific methodology based on the methodology for estimating the amount of harvested wood products stored in solid waste disposal systems that is provided in the Land Use, Land-Use Change, and Forestry sector in IPCC (2003) and the *2006 IPCC Guidelines for National Greenhouse Gas Inventories* (IPCC 2006). Carbon stock estimates were calculated by determining the mass of landfilled carbon resulting from yard trimmings and food scraps discarded in a given year; adding the accumulated landfilled carbon from previous years; and subtracting the mass of carbon that was landfilled in previous years and has since decomposed and been emitted as CO_2 and CH_4.

To determine the total landfilled carbon stocks for a given year, the following data and factors were assembled:

(1) The composition of the yard trimmings (i.e., the proportion of grass, leaves and branches);

(2) The mass of yard trimmings and food scraps discarded in landfills;

(3) The carbon storage factor of the landfilled yard trimmings and food scraps; and

(4) The rate of decomposition of the degradable carbon.

The composition of yard trimmings was assumed to be 30 percent grass clippings, 40 percent leaves, and 30 percent branches on a wet weight basis (Oshins and Block 2000). The yard trimmings were subdivided, because each component has its own unique adjusted carbon storage factor (i.e., based on differences in moisture content and carbon content) and rate of decomposition. The mass of yard trimmings and food scraps disposed of in landfills was estimated by multiplying the quantity of yard trimmings and food scraps discarded by the proportion of discards managed in landfills. Data on discards (i.e., the amount generated minus the amount diverted to centralized composting facilities) for both yard trimmings and food scraps were taken primarily from *Advancing Sustainable Materials Management: Facts and Figures 2018* (EPA 2020), which provides data for 1960, 1970, 1980, 1990, 2000, 2005, 2010, 2015, 2017 and 2018. To provide data for some of the missing years, detailed backup data were obtained from the 2012, 2013, and 2014, 2015, and 2017 versions of the *Advancing Sustainable Materials Management: Facts and Figures* reports (EPA 2019), as well as historical data tables that EPA developed for 1960 through 2012 (EPA 2016). Remaining years in the time series for which data were not provided were estimated using linear interpolation. Since the *Advancing Sustainable Materials Management: Facts and Figures* reports for 2019 through 2022 were unavailable, landfilled material generation, recovery, and disposal data for 2019 through 2022 were proxied equal to 2018 values.

The amount of carbon disposed of in landfills each year, starting in 1960, was estimated by converting the discarded landfilled yard trimmings and food scraps from a wet weight to a dry weight basis, and then multiplying

by the initial (i.e., pre-decomposition) carbon content (as a fraction of dry weight). The dry weight of landfilled material was calculated using dry weight to wet weight ratios (Tchobanoglous et al. 1993, cited by Barlaz 1998) and the initial carbon contents and the carbon storage factors were determined by Barlaz (1998, 2005, 2008).

The amount of carbon remaining in the landfill for each subsequent year was tracked based on a simple model of carbon fate based on a laboratory experiment simulating decomposition of landfilled biogenic materials by methanogenic microbes (Barlaz 1998, 2005, 2008). Carbon remaining in landfilled materials is expressed as a proportion of initial carbon content, shown in the row labeled "C Storage Factor, Proportion of Initial C Stored (%)" in Table 6-133.

The modeling approach applied to simulate U.S. landfill carbon flows builds on the findings of Barlaz (1998, 2005, 2008). The proportion of carbon stored is assumed to persist in landfills. The remaining portion is assumed to degrade over time, resulting in emissions of CH_4 and CO_2.[102] The degradable portion of the carbon is assumed to decay according to first-order kinetics. The decay rates for each of the materials are shown in Table 6-133.

The first-order decay rates, *k*, for each waste component are derived from De la Cruz and Barlaz (2010):

- De la Cruz and Barlaz (2010) calculate first-order decay rates using laboratory data published in Eleazer et al. (1997), and a correction factor, *f*, is calculated so that the weighted average decay rate for all components is equal to the EPA AP-42 default decay rate (0.04) for mixed municipal solid waste (MSW) for regions that receive more than 25 inches of rain annually (EPA 1995). Because AP-42 values were developed using landfill data from approximately 1990, De la Cruz and Barlaz used 1990 waste composition for the United States from EPA's *Characterization of Municipal Solid Waste in the United States: 1990 Update* (EPA 1991) to calculate *f*. De la Cruz and Barlaz multiplied this correction factor by the Eleazer et al. (1997) decay rates of each waste component to develop field-scale first-order decay rates.
- De la Cruz and Barlaz (2010) also use other assumed initial decay rates for mixed MSW in place of the AP-42 default value based on different types of environments in which landfills in the United States are located, including dry conditions (less than 25 inches of rain annually, *k*=0.02) and bioreactor landfill conditions (moisture is controlled for rapid decomposition, *k*=0.12).

Similar to the methodology in the Landfills section of the *Inventory* (Section 7.1), which estimates CH_4 emissions, the overall MSW decay rate is estimated by partitioning the U.S. landfill population into three categories based on annual precipitation ranges of: (1) Less than 20 inches of rain per year, (2) 20 to 40 inches of rain per year, and (3) greater than 40 inches of rain per year. These correspond to overall MSW decay rates of 0.020, 0.038, and 0.057 $year^{-1}$, respectively. De la Cruz and Barlaz (2010) calculate component-specific decay rates corresponding to the first value (0.020 $year^{-1}$), but not for the other two overall MSW decay rates.

To maintain consistency between landfill-related methodologies across the *Inventory*, EPA developed correction factors (*f*) for decay rates of 0.038 and 0.057 $year^{-1}$ through linear interpolation. A weighted national average component-specific decay rate is calculated by assuming that waste generation is proportional to population (the same assumption used in the landfill methane emission estimate), based on population data from the 2000 U.S. Census. The percent of census population is calculated for each of the three categories of annual precipitation (noted in the previous paragraph); the population data are used as a surrogate for the number of landfills in each annual precipitation category. Precipitation range percentages weighted by population are updated over time as new Census data are available, to remain consistent with percentages used in the Waste chapter, Section 7.1 landfills. The component-specific decay rates are shown in Table 6-133.

De la Cruz and Barlaz (2010) also use other assumed initial decay rates for mixed MSW in place of the AP-42 default value based on different types of environments in which landfills in the United States are located, including

[102] The CH_4 emissions resulting from anaerobic decomposition of yard trimmings and food scraps in landfills are reported in the Waste chapter, Section 7.1—Landfills.

dry conditions (less than 25 inches of rain annually, *k*=0.02) and bioreactor landfill conditions (moisture is controlled for rapid decomposition, *k*=0.12).

For each of the four materials (grass, leaves, branches, food scraps), the stock of carbon in landfills for any given year is calculated according to Equation 6-2:

Equation 6-2: Total Carbon Stock for Yard Trimmings and Food Scraps in Landfills

$$LFC_{i,t} = \sum_{n}^{t} W_{i,n} \times (1 - MC_i) \times ICC_i \times \left\{[CS_i \times ICC_i] + \left[\left(1 - (CS_i \times ICC_i)\right) \times e^{-k(t-n)}\right]\right\}$$

where,

t	=	Year for which carbon stocks are being estimated (year),
i	=	Waste type for which carbon stocks are being estimated (grass, leaves, branches, food scraps),
$LFC_{i,t}$	=	Stock of carbon in landfills in year *t*, for waste *i* (metric tons),
$W_{i,n}$	=	Mass of waste *i* disposed of in landfills in year *n* (metric tons, wet weight),
n	=	Year in which the waste was disposed of (year, where 1960 < *n* < *t*),
MC_i	=	Moisture content of waste *i* (percent of water),
CS_i	=	Proportion of initial carbon that is stored for waste *i* (percent),
ICC_i	=	Initial carbon content of waste *i* (percent),
e	=	Natural logarithm, and
k	=	First-order decay rate for waste *i*, (year^{-1}).

For a given year *t*, the total stock of carbon in landfills ($TLFC_t$) is the sum of stocks across all four materials (grass, leaves, branches, food scraps). The annual flux of carbon in landfills (F_t) for year *t* is calculated in as the change in carbon stock compared to the preceding year according to Equation 6-3:

Equation 6-3: Carbon Stock Annual Flux for Yard Trimmings and Food Scraps in Landfills

$$F_t = TLFC_t - TLFC_{(t-1)}$$

Thus, as seen in Equation 6-2, the carbon placed in a landfill in year *n* is tracked for each year *t* through the end of the inventory period. For example, disposal of food scraps in 1960 resulted in depositing about 1,135,000 metric tons of carbon in landfills. Of this amount, 16 percent (179,000 metric tons) is persistent; the remaining 84 percent (956,000 metric tons) is degradable. By 1965, more than half of the degradable portion (507,000 metric tons) decomposes, leaving a total of 628,000 metric tons (the persistent portion, plus the remainder of the degradable portion).

Continuing the example, by 2022, the total food scraps carbon originally disposed of in 1960 had declined to 179,000 metric tons (i.e., virtually all degradable carbon had decomposed). By summing the carbon remaining from 1960 with the carbon remaining from food scraps disposed of in subsequent years (1961 through 2021), the total landfill carbon from food scraps in 2022 was 53.0 million metric tons. This value is then added to the carbon stock from grass, leaves, and branches to calculate the total landfill carbon stock in 2022, yielding a value of 292.6 million metric tons (as shown in Table 6-134). In the same way total net flux is calculated for forest carbon and harvested wood products, the total net flux of landfill carbon for yard trimmings and food scraps for a given year (Table 6-132) is the difference in the landfill carbon stock for the following year and the stock in the current year. For example, the net change in 2022 shown in Table 6-132 (3.2 MMT C with rounding) is equal to the stock in 2023 (295.9 MMT C) minus the stock in 2022 (292.6 MMT C). The carbon stocks calculated through this procedure are shown in Table 6-134.

To develop the 2023 carbon stock estimate, estimates of yard trimming and food scrap carbon stocks were forecasted for 2023, based on data from 1990 through 2022. These forecasted values were used to calculate net changes in carbon stocks for 2022. Excel's FORECAST.ETS function was used to predict a 2023 value using historical data via an algorithm called "Exponential Triple Smoothing." This method determined the overall trend and provided appropriate carbon stock estimates for 2023.

Table 6-133: Moisture Contents, Carbon Storage Factors (Proportions of Initial Carbon Sequestered), Initial C Contents, and Decay Rates for Yard Trimmings and Food Scraps in Landfills

Variable	Yard Trimmings			Food Scraps
	Grass	Leaves	Branches	
Moisture Content (% H_2O)	70	30	10	70
C Storage Factor, Proportion of Initial C Stored (%)	53	85	77	16
Initial C Content (%)	45	46	49	51
Decay Rate ($year^{-1}$)	0.313	0.179	0.015	0.151

Note: The decay rates are presented as weighted averages based on annual precipitation categories and population residing in each precipitation category.

Table 6-134: Carbon Stocks in Yard Trimmings and Food Scraps in Landfills (MMT C)

Carbon Pool	1990	2005	2018	2019	2020	2021	2022	2023
Yard Trimmings	**156.0**	**203.1**	**231.6**	**233.9**	**236.1**	**238.4**	**240.6**	**242.8**
Branches	14.6	18.1	20.7	20.9	21.1	21.3	21.6	21.8
Leaves	66.7	87.4	100.4	101.5	102.5	103.6	104.6	105.6
Grass	74.7	97.7	110.5	111.5	112.5	113.5	114.5	115.4
Food Scraps	**17.9**	**33.2**	**46.9**	**48.3**	**49.6**	**50.9**	**52.0**	**53.0**
Total Carbon Stocks	**173.9**	**236.3**	**278.5**	**282.2**	**285.7**	**289.2**	**292.6**	**295.9**

[a] 2023 C stock estimate was forecasted using 1990 to 2022 data.

Note: Totals may not sum due to independent rounding.

Methodological recalculations were applied to the entire time series to ensure time-series consistency from 1990 through 2022. When available, the same data source was used across the entire time series for the analysis. When data were unavailable, missing values were estimated using linear interpolation or forecasting, as noted above.

Uncertainty

The uncertainty analysis for landfilled yard trimmings and food scraps includes an evaluation of the effects of uncertainty for the following data and factors: disposal in landfills per year (tons of carbon), initial carbon content, moisture content, decay rate, and proportion of carbon stored. The carbon storage landfill estimates are also a function of the composition of the yard trimmings (i.e., the proportions of grass, leaves and branches in the yard trimmings mixture). There are respective uncertainties associated with each of these factors.

A Monte Carlo (Approach 2) uncertainty analysis was applied to estimate the overall uncertainty of the sequestration estimate for 2022. The results of the Approach 2 quantitative uncertainty analysis are summarized in Table 6-135. Total yard trimmings and food scraps CO_2 flux in 2022 was estimated to be between -17.3 and -4.9 MMT CO_2 Eq. at a 95 percent confidence level. This indicates a range of 47 percent below to 58 percent above the 2022 flux estimate of -11.8 MMT CO_2 Eq.

Table 6-135: Approach 2 Quantitative Uncertainty Estimates for CO_2 Flux from Yard Trimmings and Food Scraps in Landfills (MMT CO_2 Eq. and Percent)

Source	Gas	2021 Flux Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Flux Estimate[a] (MMT CO_2 Eq.)		Uncertainty Range Relative to Flux Estimate[a] (%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Yard Trimmings and Food Scraps	CO_2	(11.8)	(17.3)	(4.9)	-47%	+58%

[a] Range of flux estimates predicted by Monte Carlo stochastic simulation for a 95 percent confidence interval.
Note: Parentheses indicate negative values or net carbon sequestration.

QA/QC and Verification

Tier 1 and Tier 2 QA/QC activities were conducted consistent with the U.S. Inventory QA/QC plan. Source-specific quality control measures for landfilled yard trimmings and food scraps included checking that input data were properly transposed within the spreadsheet, checking calculations were correct, and confirming that all activity data and calculations documentation was complete and updated to ensure data were properly handled through the inventory process.

Order of magnitude checks and checks of time-series consistency were performed to ensure data were updated correctly and any changes in emissions estimates were reasonable and reflected changes in activity data. An annual change trend analysis was also conducted to ensure the validity of the emissions estimates. Errors that were found during this process were corrected as necessary.

To ensure consistency across the LULUCF and Waste sectors, and the accuracy of emissions, EPA plans to perform a comparison of the activity data used and carbon inputs between the landfilled yard trimmings and food scraps, and the Waste chapter, Section 7.1—Landfills categories.

Recalculations Discussion

No recalculations were performed for the current *Inventory*.

Planned Improvements

EPA notes the following improvements may be implemented or investigated within the next two or three *Inventory* cycles pending time and resource constraints:

- MSW data more recent than 2018 have not been released through the *Advancing Sustainable Materials Management* reports. EPA will monitor the release schedule for these data and evaluate data for integration into the *Inventory* when released. Six new food waste management pathways were introduced in the 2018 *Advancing Sustainable Materials Management* report. Time series data for all of these pathways are not provided prior to 2018 but EPA plans to investigate potential data sources and/or methods to address time-series consistency and apply these data to the time series.
- EPA has been made aware of inconsistencies in landfilled food scraps data reported to the EPA Greenhouse Gas Reporting Program (GHGRP) and will evaluate changes to how landfilled and energy recovery values for yard trimmings and food scraps are calculated.

EPA notes the following improvements will continue to be investigated as time and resources allow, but there are no immediate plans to implement these improvements until data are available or identified:

- EPA also plans to continue to investigate updates to the decay rate estimates for food scraps, leaves, grass, and branches, as well as evaluate using decay rates that vary over time based on Census population

and climate data changes over time. Currently the inventory calculations use 2010 U.S. Census data, but 2020 U.S. Census data may be available.

- Other improvements include investigation into yard waste composition to determine if changes need to be made based on changes in residential practices. A review of available literature will be conducted to determine if there are changes in the allocation of yard trimmings. For example, leaving grass clippings in place is becoming a more common practice, thus reducing the percentage of grass clippings in yard trimmings disposed in landfills. In addition, agronomists may be consulted for determining the mass of grass per acre on residential lawns to provide an estimate of total grass generation for comparison with *Inventory* estimates.
- EPA will continue to evaluate data from recent peer-reviewed literature that may modify the default carbon storage factors, initial carbon contents, and decay rates for yard trimmings and food scraps in landfills – particularly updates to population precipitation ranges used to calculate k values. Based upon this evaluation, changes may be made to the default values.
- Finally, EPA plans to review available data to ensure all types of landfilled yard trimmings and food scraps are being included in the *Inventory* estimates, such as debris from road construction and commercial food waste not included in other *Inventory* estimates.

6.11 Land Converted to Settlements (CRT Category 4E2)

Land converted to settlements includes all settlements in an inventory year that had been in another land use(s) during the previous 20 years (USDA-NRCS 2015).[103] For example, cropland, grassland or forest land converted to settlements during the past 20 years would be reported in this category. Converted lands are retained in this category for 20 years as recommended by IPCC (2006).

Land use change can lead to large losses of carbon to the atmosphere, particularly conversions from forest land (Houghton et al. 1983). Moreover, conversion of forest to another land use (i.e., deforestation) is one of the largest anthropogenic sources of emissions to the atmosphere globally (Schimel 1995), although this source may be declining globally (Tubiello et al. 2015). IPCC (2006) recommends reporting changes in biomass, dead organic matter, and soil organic carbon stocks due to land-use change. All soil organic carbon stock changes are estimated and reported for land converted to settlements, but there is limited reporting of other pools in this *Inventory.* Loss of aboveground and belowground biomass, dead wood and litter carbon are reported for forest land converted to settlements and woodlands associated with grasslands converted to settlements, but not for other land-use conversions to settlements.

There are discrepancies between the current land representation (see Section 6.1) and the area data that have been used in the *Inventory* for land converted to settlements. Specifically, this *Inventory* includes all settlements in the conterminous United States and Hawaii, but does not include settlements in Alaska. Areas of drained organic soils in settlements on federal lands are also not included in this *Inventory.* These differences lead to discrepancies between the managed area in land converted to settlements and the settlement area included in the inventory analysis (Table 6-129). There is a planned improvement to include CO_2 emissions from drainage of organic soils in settlements of Alaska and federal lands as part of a future *Inventory* (see Planned Improvements section).

[103] NRI survey locations are classified according to land use histories starting in 1979, and consequently the classifications are based on less than 20 years from 1990 to 2001. This may have led to an underestimation of land converted to settlements in the early part of the time series to the extent that some areas are converted to settlements from 1971 to 1978.

Forest land converted to settlements is the largest source of emissions from 1990 to 2022, accounting for approximately 76 percent of the average total loss of carbon among all of the land-use conversions in Land Converted to Settlements. Total losses of aboveground and belowground biomass, dead wood and litter carbon losses in 2022 for all conversions are 35.6, 6.2, 6.7, and 9.2 MMT CO_2 Eq., respectively (9.7, 1.7, 1.8, and 2.5 MMT C). Mineral and organic soils also lost 9.2 and 1.3 MMT CO_2 Eq. in 2022 (2.5 and 0.3 MMT C). The total net flux is 68.2 MMT CO_2 Eq. in 2022 (18.6 MMT C), which is a 19 percent increase in CO_2 emissions compared to the emissions in the initial reporting year of 1990 (Table 6-136 and Table 6-137). The main driver of net emissions for this source category is the conversion of forest land to settlements, with large losses of biomass, deadwood and litter carbon.

Table 6-136: Net CO_2 Flux from Soil, Dead Organic Matter and Biomass Carbon Stock Changes for Land Converted to Settlements (MMT CO_2 Eq.)

	1990	2005	2018	2019	2020	2021	2022
Cropland Converted to Settlements	**2.6**	**8.2**	**3.9**	**3.5**	**3.1**	**2.9**	**2.9**
Mineral Soils	2.1	6.9	3.4	2.9	2.6	2.5	2.5
Organic Soils	0.5	1.2	0.6	0.5	0.4	0.4	0.4
Forest Land Converted to Settlements	**49.3**	**53.9**	**58.4**	**58.6**	**58.6**	**58.6**	**58.6**
Aboveground Live Biomass	30.0	32.4	35.0	35.2	35.2	35.2	35.2
Belowground Live Biomass	5.2	5.6	6.1	6.1	6.1	6.1	6.1
Dead Wood	5.5	6.0	6.5	6.6	6.6	6.6	6.6
Litter	7.6	8.2	9.0	9.0	9.0	9.0	9.0
Mineral Soils	1.0	1.5	1.5	1.5	1.5	1.5	1.5
Organic Soils	0.1	0.2	0.2	0.2	0.3	0.3	0.3
Grassland Converted to Settlements	**5.6**	**15.8**	**9.8**	**8.8**	**7.9**	**7.4**	**7.5**
Aboveground Live Biomass	0.4	0.4	0.5	0.5	0.5	0.5	0.5
Belowground Live Biomass	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Dead Wood	0.1	0.1	0.2	0.2	0.2	0.2	0.2
Litter	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Mineral Soils	4.3	13.7	8.2	7.3	6.5	6.0	6.0
Organic Soils	0.5	1.3	0.7	0.6	0.5	0.5	0.6
Other Lands Converted to Settlements	**(0.4)**	**(1.4)**	**(1.1)**	**(1.0)**	**(0.8)**	**(0.8)**	**(0.8)**
Mineral Soils	(0.4)	(1.5)	(1.1)	(1.0)	(0.9)	(0.8)	(0.8)
Organic Soils	+	0.1	+	+	+	+	+
Wetlands Converted to Settlements	**+**	**0.6**	**0.3**	**0.3**	**0.1**	+	**0.1**
Mineral Soils	+	0.1	+	+	+	+	+
Organic Soils	+	0.6	0.3	0.3	+	+	+
Total Aboveground Biomass Flux	**30.4**	**32.8**	**35.5**	**35.6**	**35.6**	**35.6**	**35.6**
Total Belowground Biomass Flux	**5.2**	**5.7**	**6.1**	**6.2**	**6.2**	**6.2**	**6.2**
Total Dead Wood Flux	**5.6**	**6.1**	**6.7**	**6.7**	**6.7**	**6.7**	**6.7**
Total Litter Flux	**7.7**	**8.4**	**9.2**	**9.2**	**9.2**	**9.2**	**9.2**
Total Mineral Soil Flux	**7.0**	**20.7**	**12.0**	**10.8**	**9.8**	**9.2**	**9.2**
Total Organic Soil Flux	**1.2**	**3.4**	**1.8**	**1.6**	**1.3**	**1.2**	**1.3**
Total Net Flux	**57.2**	**77.1**	**71.4**	**70.2**	**68.8**	**68.2**	**68.2**

+ Absolute value does not exceed 0.05 MMT CO_2 Eq.

Notes: Totals may not sum due to independent rounding. Parentheses indicate negative values or net sequestration.

Table 6-137: Net CO_2 Flux from Soil, Dead Organic Matter and Biomass Carbon Stock Changes for Land Converted to Settlements (MMT C)

	1990	2005	2018	2019	2020	2021	2022
Cropland Converted to Settlements	**0.7**	**2.2**	**1.1**	**1.0**	**0.8**	**0.8**	**0.8**
Mineral Soils	0.6	1.9	0.9	0.8	0.7	0.7	0.7
Organic Soils	0.1	0.3	0.2	0.1	0.1	0.1	0.1

Forest Land Converted to Settlements	**13.5**	**14.7**	**15.9**	**16.0**	**16.0**	**16.0**	**16.0**
Aboveground Live Biomass	8.2	8.8	9.6	9.6	9.6	9.6	9.6
Belowground Live Biomass	1.4	1.5	1.7	1.7	1.7	1.7	1.7
Dead Wood	1.5	1.6	1.8	1.8	1.8	1.8	1.8
Litter	2.1	2.2	2.5	2.5	2.5	2.5	2.5
Mineral Soils	0.3	0.4	0.4	0.4	0.4	0.4	0.4
Organic Soils	+	0.1	0.1	0.1	0.1	0.1	0.1
Grassland Converted to Settlements	**1.5**	**4.3**	**2.7**	**2.4**	**2.2**	**2.0**	**2.0**
Aboveground Live Biomass	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Belowground Live Biomass	+	+	+	+	+	+	+
Dead Wood	+	+	+	+	+	+	+
Litter	+	+	0.1	0.1	0.1	0.1	0.1
Mineral Soils	1.2	3.7	2.2	2.0	1.8	1.6	1.6
Organic Soils	0.1	0.3	0.2	0.2	0.1	0.1	0.2
Other Lands Converted to Settlements	**(0.1)**	**(0.4)**	**(0.3)**	**(0.3)**	**(0.2)**	**(0.2)**	**(0.2)**
Mineral Soils	(0.1)	(0.4)	(0.3)	(0.3)	(0.2)	(0.2)	(0.2)
Organic Soils	+	+	+	+	+	+	+
Wetlands Converted to Settlements	**+**	**0.2**	**0.1**	**0.1**	**+**	**+**	**+**
Mineral Soils	+	+	+	+	+	+	+
Organic Soils	+	0.2	0.1	0.1	+	+	+
Total Aboveground Biomass Flux	**8.3**	**8.9**	**9.7**	**9.7**	**9.7**	**9.7**	**9.7**
Total Belowground Biomass Flux	**1.4**	**1.5**	**1.7**	**1.7**	**1.7**	**1.7**	**1.7**
Total Dead Wood Flux	**1.5**	**1.7**	**1.8**	**1.8**	**1.8**	**1.8**	**1.8**
Total Litter Flux	**2.1**	**2.3**	**2.5**	**2.5**	**2.5**	**2.5**	**2.5**
Total Mineral Soil Flux	**1.9**	**5.6**	**3.3**	**2.9**	**2.7**	**2.5**	**2.5**
Total Organic Soil Flux	**0.3**	**0.9**	**0.5**	**0.4**	**0.4**	**0.3**	**0.3**
Total Net Flux	**15.6**	**21.0**	**19.5**	**19.1**	**18.8**	**18.6**	**18.6**

+ Absolute value does not exceed 0.05 MMT C.

Notes: Totals may not sum due to independent rounding. Parentheses indicate negative values or net sequestration

Methodology and Time-Series Consistency

The following section includes a description of the methodology used to estimate carbon stock changes for land converted to settlements, including (1) loss of aboveground and belowground biomass, dead wood and litter carbon with conversion to settlements from forest lands and woodlands designated in the grassland, as well as (2) the impact from all land-use conversions to settlements on soil organic carbon stocks in mineral and organic soils.

Biomass, Dead Wood, and Litter Carbon Stock Changes

A Tier 2 method is applied to estimate biomass, dead wood, and litter carbon stock changes for forest land converted to settlements. Estimates are calculated in the same way as those in the forest land remaining forest land category using data from the USDA Forest Service, Forest Inventory and Analysis (FIA) program (USDA Forest Service 2023) however there is no country-specific data for settlements so the biomass, litter, and dead wood carbon stocks were assumed to be zero. The difference between the stocks is reported as the stock change under the assumption that the change occurred in the year of the conversion. Details for each of the carbon attributes described below are available in Domke et al. (2022) and Westfall et al. (2023).

If FIA plots include data on individual trees, aboveground and belowground carbon density estimates are based on Woodall et al. (2011) and Westfall et al. (2023). Aboveground and belowground biomass estimates also include live understory which is a minor component of biomass defined as all biomass of undergrowth plants in a forest, including woody shrubs and trees less than 2.54 cm dbh. For this *Inventory*, it was assumed that 10 percent of total understory carbon mass is belowground (Smith et al. 2006). Estimates of carbon density are based on information in Birdsey (1996) and biomass estimates from Jenkins et al. (2003).

This *Inventory* also includes estimates of change in dead organic matter for standing dead, deadwood and litter. If FIA plots include data on standing dead trees, standing dead tree carbon density is estimated following the basic method applied to live trees (Woodall et al. 2011 and Westfall et al. 2023) with additional modifications for woodland species to account for decay and structural loss (Domke et al. 2011; Harmon et al. 2011). If FIA plots include data on downed dead wood, downed dead wood carbon density is estimated based on measurements of a subset of FIA plots for downed dead wood (Domke et al. 2013; Woodall and Monleon 2008). Downed dead wood is defined as pieces of dead wood greater than 7.5 cm diameter, at transect intersection, that are not attached to live or standing dead trees. This includes stumps and roots of harvested trees. To facilitate the downscaling of downed dead wood carbon estimates from the state-wide population estimates to individual plots, downed dead wood models specific to regions and forest types within each region are used. Litter carbon is the pool of organic carbon (also known as duff, humus, and fine woody debris) above the mineral soil and includes woody fragments with diameters of up to 7.5 cm. A subset of FIA plots is measured for litter carbon. If FIA plots include litter material, a modeling approach using litter carbon measurements from FIA plots is used to estimate litter carbon density (Domke et al. 2016).

In order to ensure time-series consistency, the same methods are applied from 1990 to 2020 so that changes reflect anthropogenic activity and not methodological adjustments. See Annex 3.13 for more information about reference carbon density estimates for forest land and the compilation system used to estimate carbon stock changes from forest land.

Soil Carbon Stock Changes

Soil organic carbon stock changes are estimated for land converted to settlements according to land use histories recorded in the 2017 USDA NRI survey for non-federal lands (USDA-NRCS 2020) and extended through 2020 using the USDA-NASS Crop Data Layer Product (USDA-NASS 2021; Johnson and Mueller 2010) and National Land Cover Dataset (NLCD) (Yang et al. 2018; Fry et al. 2011; Homer et al. 2007, 2015)). For federal lands, the land use history is derived from land cover changes in the NLCD. The areas have been modified through a process in which the Forest Inventory and Analysis (FIA) survey data are harmonized with the NRI data (Nelson et al. 2020). This process ensures that the land use areas are consistent across all land use categories (see Section 6.1 for more information). Land use and some management information were originally collected for each NRI survey location on a 5-year cycle beginning in 1982. In 1998, the NRI program began collecting annual data, and the annual data have been incorporated from the NRI into the inventory analysis through 2017 (USDA-NRCS 2020).

NRI survey locations are classified as land converted to settlements in a given year between 1990 and 2020 if the land use is settlements but had been classified as another use during the previous 20 years. NRI survey locations are classified according to land use histories starting in 1979, and consequently the classifications are based on less than 20 years from 1990 to 1998. This may have led to an underestimation of land converted to settlements in the early part of the time series to the extent that some areas are converted to settlement between 1971 and 1978.

Soil Carbon Stock Changes for Mineral Soils

An IPCC Tier 2 method (Ogle et al. 2003) is applied to estimate carbon stock changes for mineral soils on land converted to settlements from 1990 to 2020. Data on climate, soil types, land use, and land management activity are used to classify land area and apply appropriate stock change factors (Ogle et al. 2003, 2006). Reference carbon stocks are estimated using the National Soil Survey Characterization Database (USDA-NRCS 1997) with cultivated cropland as the reference condition, rather than native vegetation as used in IPCC (2006). Soil measurements under agricultural management are much more common and easily identified in the National Soil Survey Characterization Database (USDA-NRCS 1997) than are soils under a native condition, and therefore cultivated cropland provide a more robust sample for estimating the reference condition. Country-specific carbon stock change factors are derived from published literature to determine the impact of management practices on soil organic carbon storage (Ogle et al. 2003; Ogle et al. 2006). However, there are insufficient data to estimate a set of land use, management, and input factors for settlements. Moreover, the 2017 NRI survey data (USDA-NRCS 2020) do not provide the information needed to assign different land use subcategories to settlements, such as

turf grass and impervious surfaces, which is needed to apply the Tier 1 factors from the IPCC guidelines (2006). Therefore, the United States has adopted a land use factor of 0.7 to represent a net loss of soil organic carbon with conversion to settlements under the assumption that there are additional soil organic carbon losses with land clearing, excavation and other activities associated with development. More specific factor values can be derived in future Inventories as data become available. See Annex 3.12 for additional discussion of the Tier 2 methodology for mineral soils.

In order to ensure time-series consistency, the same methods are applied from 1990 to 2020 so that changes reflect anthropogenic activity and not methodological adjustments. Soil organic carbon stock changes from 2021 to 2022 are estimated using a linear extrapolation method described in Box 6-4 of the Methodology section in Cropland Remaining Cropland. The extrapolation is based on a linear regression model with moving-average (ARMA) errors using the 1990 to 2020 emissions data, which is a standard data splicing method for imputing missing emissions data in a time series (IPCC 2006). The Tier 2 method described previously will be applied to recalculate the 2021 to 2022 emissions in a future *Inventory*.

Soil Carbon Stock Changes for Organic Soils

Annual carbon emissions from drained organic soils in land converted to settlements are estimated using the Tier 2 method provided in IPCC (2006). The Tier 2 method assumes that organic soils are losing carbon at a rate similar to croplands, and therefore uses the country-specific values for cropland (Ogle et al. 2003). To estimate CO_2 emissions from 1990 to 2020, the area of organic soils in land converted to settlements is multiplied by the Tier 2 emission factor, which is 11.2 MT C per ha in cool temperate regions, 14.0 MT C per ha in warm temperate regions and 14.3 MT C per ha in subtropical regions (see Annex 3.12 for more information).

In order to ensure time-series consistency, the same methods are applied from 1990 to 2020, and a linear extrapolation method is used to approximate emissions for the remainder of the 2021 to 2022 time series (see Box 6-4 of the Methodology section in Cropland Remaining Cropland). The extrapolation is based on a linear regression model with moving-average (ARMA) errors using the 1990 to 2020 emissions data, and is a standard data splicing method for imputing missing emissions data in a time series (IPCC 2006). Estimates will be recalculated in future *Inventories* when new activity data are incorporated into the analysis.

Uncertainty

The uncertainty analysis for carbon losses with forest land converted to settlements is conducted in the same way as the uncertainty assessment for forest ecosystem carbon flux in the forest land remaining forest land category. Sample and model-based error are combined using simple error propagation methods provided by the IPCC (2006), i.e., by taking the square root of the sum of the squares of the standard deviations of the uncertain quantities. For additional details, see the Uncertainty Analysis in Annex 3.13.

Sources of uncertainty for mineral soil organic carbon stock changes and annual carbon emission estimates from drained organic soils include emission factors and variance associated with the NRI sample. The total uncertainty was quantified with two variance components (Ogle et al. 2010) that are combined using simple error propagation methods provided by the IPCC (2006), i.e., by taking the square root of the sum of the squares of the standard deviations of the uncertain quantities. For the first variance component, a Monte Carlo analysis was used to propagate uncertainties in the Tier 2 methods for the land use area and the country-specific factors or mineral and organic soils. The second variance component is associated with scaling of the data from the NRI survey to the entire area of land converted to settlements, and is computed using a standard variance estimator for a two-stage sample design (Särndal et al. 1992).

Uncertainty estimates are presented in Table 6-138 for each sub-source (i.e., biomass carbon, dead wood, litter, soil organic carbon in mineral soils and organic soils) and the method applied in the inventory analysis (i.e., Tier 2 and Tier 3). Uncertainty estimates are combined from the forest land converted to settlements and other land use conversions to settlements using the simple error propagation methods provided by the IPCC (2006). There are

also additional uncertainties propagated through the analysis associated with the data splicing methods applied to estimate soil organic carbon stock changes from 2021 to 2022. The combined uncertainty for total carbon stock changes in land converted to settlements ranges from 36 percent below to 36 percent above the 2022 stock change estimate of 68.2 MMT CO_2 Eq.

Table 6-138: Approach 2 Quantitative Uncertainty Estimates for Soil, Dead Organic Matter and Biomass Carbon Stock Changes occurring within Land Converted to Settlements (MMT CO_2 Eq. and Percent)

Source	2022 Flux Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Flux Estimate[a] (MMT CO_2 Eq.)		(%)	
		Lower Bound	Upper Bound	Lower Bound	Upper Bound
Cropland Converted to Settlements	**2.9**	**1.3**	**4.5**	**-56%**	**56%**
Mineral Soil C Stocks	2.5	0.9	4.1	-64%	63%
Federal Mineral Soil C Stocks	0.0	(0.0)	0.0	-146%	146%
Organic Soil C Stocks	0.4	0.1	0.7	-80%	80%
Forest Land Converted to Settlements	**58.6**	**35.3**	**81.9**	**-40%**	**40%**
Aboveground Biomass C Stocks	35.2	13.3	57.1	-62%	62%
Belowground Biomass C Stocks	6.1	2.3	9.9	-62%	62%
Dead Wood	6.6	2.5	10.6	-62%	62%
Litter	9.0	3.4	14.7	-62%	62%
Mineral Soil C Stocks	1.5	1.2	1.7	-19%	19%
Federal Mineral Soil C Stocks	0.0	0.0	0.0	0%	0%
Organic Soil C Stocks	0.3	0.1	0.4	-70%	70%
Grassland Converted to Settlements	**7.4**	**5.4**	**9.5**	**-27%**	**27%**
Aboveground Biomass C Stocks	0.5	0.2	0.8	-62%	60%
Belowground Biomass C Stocks	0.1	0.0	0.1	-45%	66%
Dead Wood	0.2	0.1	0.3	-51%	70%
Litter	0.2	0.1	0.3	-61%	57%
Mineral Soil C Stocks	6.0	4.1	7.9	-32%	32%
Federal Mineral Soil C Stocks	0.0	(0.0)	0.0	-194%	194%
Organic Soil C Stocks	0.5	(0.0)	1.1	-108%	108%
Other Lands Converted to Settlements	**-0.8**	**(1.1)**	**(0.4)**	**-44%**	**44%**
Mineral Soil C Stocks	-0.8	(1.1)	(0.5)	-38%	38%
Federal Mineral Soil C Stocks	0.0	(0.2)	0.1	-738%	738%
Organic Soil C Stocks	0.0	(0.1)	0.1	-511%	511%
Wetlands Converted to Settlements	**0.1**	**(0.3)**	**0.3**	**-557%**	**533%**
Mineral Soil C Stocks	0.0	0.0	0.1	-69%	69%
Federal Mineral Soil C Stocks	0.0	0.0	0.0	0%	0%
Organic Soil C Stocks	0.0	(0.3)	0.3	-1,269%	1,214%
Total: Land Converted to Settlements	**68.2**	**43.5**	**92.9**	**-36%**	**36%**
Aboveground Biomass C Stocks	**35.6**	**13.3**	**57.1**	**-62%**	**62%**
Belowground Biomass C Stocks	**6.2**	**2.3**	**9.9**	**-62%**	**62%**
Dead Wood	**6.7**	**2.5**	**10.6**	**-62%**	**62%**
Litter	**9.2**	**3.4**	**14.7**	**-62%**	**62%**
Mineral Soil C Stocks	**9.2**	**6.6**	**11.7**	**-28%**	**28%**
Organic Soil C Stocks	**1.2**	**(6.6)**	**9.1**	**-625%**	**625%**

+ Does not exceed 0.05 MMT CO_2 Eq.

[a] Range of C stock change estimates is a 95 percent confidence interval.

Note: Totals may not sum due to independent rounding. Parentheses indicate negative values or net sequestration.

QA/QC and Verification

Quality control measures included checking input data, model scripts, and results to ensure data are properly handled throughout the inventory process. Inventory reporting forms and text are reviewed and revised as needed to correct transcription errors. No errors were found in this *Inventory*.

Recalculations Discussion

Recalculations are associated with new FIA data from 1990 to 2022 on biomass, dead wood and litter carbon stocks in forest land converted to settlements and woodland conversion associated with grassland converted to settlements. Additional recalculations are associated with incorporating new USDA-NRCS NRI data through 2017 and extending the time series using CDL and NLCD for grassland converted to settlements, cropland converted to settlements, other land converted to settlements and wetlands converted to settlements. As a result, land converted to settlements has an estimated smaller carbon loss of 7.7 MMT CO_2 Eq. on average over the time series. This represents a 19 percent decrease in carbon stock changes for land converted to settlements compared to the previous *Inventory.*

Planned Improvements

A key improvement is to develop an inventory of mineral soil organic carbon stock changes in Alaska and losses of carbon from drained organic soils in federal lands. These improvements will resolve most of the differences between the managed land base for land converted to settlements and amount of area currently included in the *Inventory* for land converted to settlements (see Table 6-139).

There are plans to improve classification of trees in settlements and to include transfer of biomass from forest land to those areas in this category. There are also plans to extend the inventory to included carbon losses associated with drained organic soils in settlements occurring on federal lands.

These improvements will be made pending prioritization of resources to expand the inventory for this source category.

Table 6-139: Area of Managed Land in Land Converted to Settlements that is not included in the current *Inventory* (Thousand Hectares)

	Area (Thousand Hectares)		
Year	LCS Managed Land Area (Section 6.1)	LCS Area Included in *Inventory*	LCS Area Not Included in *Inventory*
1990	2,865	2,865	1
1991	3,213	3,213	1
1992	3,573	3,573	1
1993	4,138	4,138	1
1994	4,703	4,702	1
1995	5,262	5,261	1
1996	5,833	5,832	1
1997	6,409	6,408	1
1998	6,929	6,928	1
1999	7,446	7,446	1
2000	7,952	7,952	1
2001	8,362	8,361	1
2002	8,696	8,695	1
2003	8,705	8,704	1
2004	8,710	8,708	2
2005	8,727	8,724	2

2006	8,691	8,688	3
2007	8,672	8,668	3
2008	8,501	8,497	4
2009	8,309	8,305	5
2010	8,130	8,124	5
2011	7,930	7,925	6
2012	7,717	7,711	6
2013	7,325	7,318	6
2014	6,942	6,935	7
2015	6,530	6,523	7
2016	6,112	6,105	7
2017	5,715	5,708	7
2018	5,201	5,194	7
2019	4,696	4,689	7
2020	4,175	4,168	7
2021	3,771	*	*
2022	3,437	*	*

NRI data have not been incorporated into the *Inventory* after 2020, designated with asterisks (*).

6.12 Other Land Remaining Other Land (CRT Category 4F1)

Land use is constantly occurring, and areas under a number of differing land-use types remain in their respective land-use type each year, just as other land can remain as other land. While the magnitude of other land remaining other land is known (see Table 6-4), research is ongoing to track carbon pools in this land use. Until such time that reliable and comprehensive estimates of carbon for other land remaining other land can be produced, it is not possible to estimate CO_2, CH_4 or N_2O fluxes on other land remaining other land at this time.

6.13 Land Converted to Other Land (CRT Category 4F2)

Land-use change is constantly occurring, and areas under a number of differing land-use types are converted to other land each year, just as other land is converted to other uses. While the magnitude of these area changes is known (see Table 6-4), research is ongoing to track carbon across other land remaining other land and land converted to other land. Until such time that reliable and comprehensive estimates of carbon across these land-use and land-use change categories can be produced, it is not possible to separate CO_2, CH_4 or N_2O fluxes on land converted to other land from fluxes on other land remaining other land at this time.

7. Waste

Waste management and treatment activities are sources of greenhouse gas emissions (see Figure 7-1 and Figure 7-2). Landfills were the third largest source of anthropogenic methane (CH_4) in the United States in 2022, accounting for approximately 17.1 percent of total U.S. CH_4 emissions. Additionally, wastewater treatment and discharge, composting of organic waste, and anaerobic digestion at biogas facilities accounted for approximately 3.0 percent, 0.4 percent, and less than 0.1 percent of U.S. CH_4 emissions, respectively. Nitrous oxide (N_2O) emissions resulting from the discharge of wastewater treatment effluents into aquatic environments were estimated, along with the wastewater treatment process itself and composting. Together, these waste activities account for 6.1 percent of total U.S. N_2O emissions. Nitrogen oxides (NO_x), carbon monoxide (CO), and non-CH_4 volatile organic compounds (NMVOCs) are emitted by waste activities and are addressed separately at the end of this chapter. A summary of greenhouse gas emissions from the Waste sector is presented in Table 7-1 and Table 7-2. Overall, in 2022, waste activities generated emissions of 166.9 MMT CO_2 Eq., or 2.6 percent of total U.S. greenhouse gas emissions.

Emissions from landfills contributed 71.8 percent of Waste sector emissions in 2022 (see Figure 7-1) and are primarily composed of CH_4 emissions from municipal solid waste landfills. Landfill emissions decreased by 2.3 MMT CO_2 Eq. (1.9 percent) since 2021. Emissions from wastewater treatment were the second largest source of waste-related emissions in 2022, accounting for 25.6 percent of sector emissions. The remaining two sources of emissions, composting and anaerobic digestion at biogas facilities, account for 2.6 percent and less than 0.1 percent of Waste sector emissions in 2022, respectively.

Figure 7-1: 2022 Waste Sector Greenhouse Gas Sources

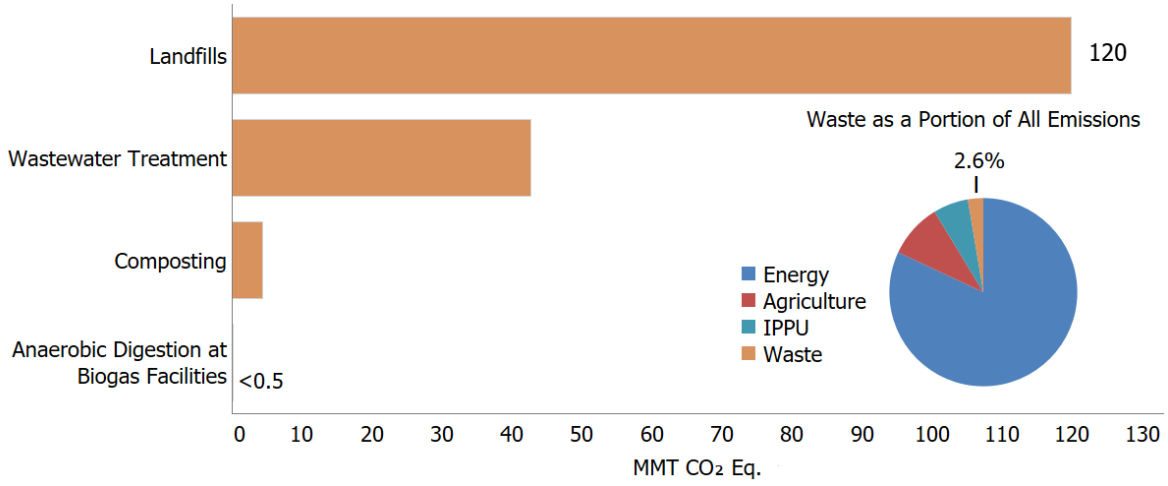


Figure 7-2: Trends in Waste Sector Greenhouse Gas Sources

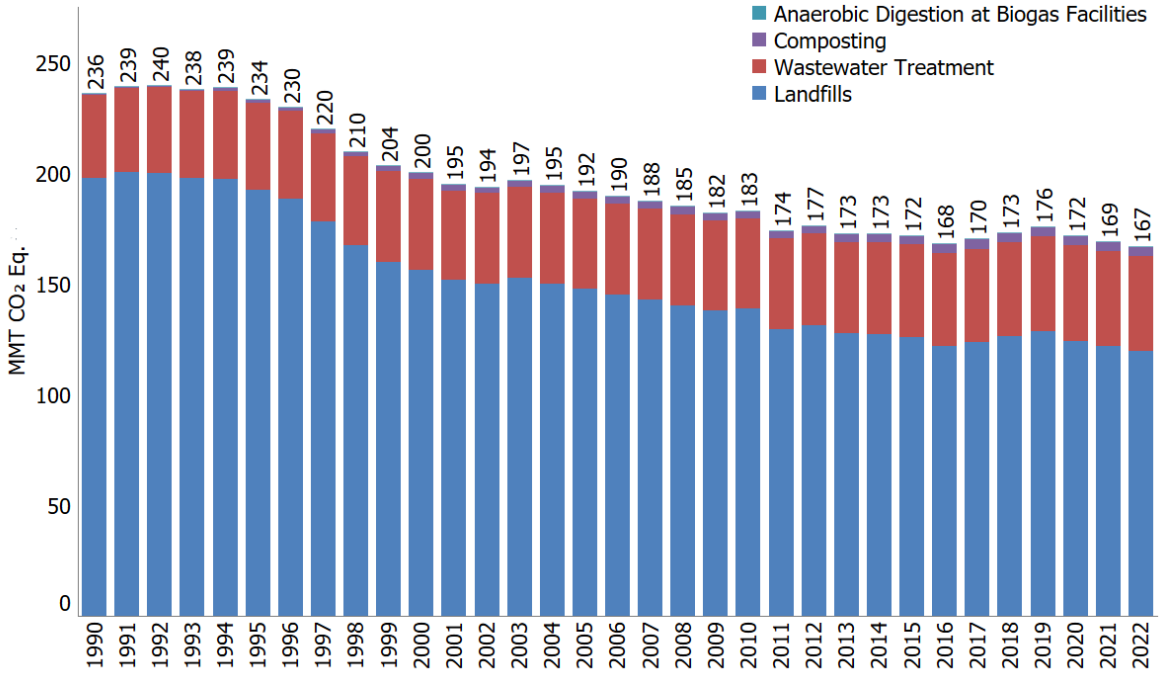


Table 7-1: Emissions from Waste (MMT CO_2 Eq.)

Gas/Source	1990	2005	2018	2019	2020	2021	2022
CH_4	**220.9**	**172.4**	**150.2**	**152.4**	**147.6**	**145.3**	**143.2**
Landfills	197.8	147.7	126.3	128.7	124.1	122.0	119.8
Wastewater Treatment	22.7	22.7	21.4	21.1	21.0	20.7	20.8
Composting	0.4	2.1	2.5	2.5	2.6	2.6	2.6
Anaerobic Digestion at Biogas Facilities	+	+	+	+	+	+	+
N_2O	**15.1**	**19.5**	**23.0**	**23.4**	**24.1**	**23.9**	**23.7**
Wastewater Treatment	14.8	18.1	21.2	21.6	22.3	22.1	21.9
Composting	0.3	1.5	1.8	1.8	1.8	1.8	1.8
Total	**235.9**	**192.0**	**173.2**	**175.8**	**171.7**	**169.2**	**166.9**

+ Does not exceed 0.05 MMT CO_2 Eq.

Note: Totals may not sum due to independent rounding.

Table 7-2: Emissions from Waste (kt)

Gas/Source	1990	2005	2018	2019	2020	2021	2022
CH_4	**7,889**	**6,159**	**5,365**	**5,441**	**5,271**	**5,189**	**5,113**
Landfills	7,063	5,275	4,512	4,595	4,431	4,359	4,277
Wastewater Treatment	811	809	763	755	748	738	743
Composting	15	75	90	91	92	92	92
Anaerobic Digestion at Biogas Facilities	+	+	+	1	+	+	+
N_2O	**57**	**74**	**87**	**88**	**91**	**90**	**89**
Wastewater Treatment	56	68	80	81	84	83	83
Composting	1	6	7	7	7	7	7

+ Does not exceed 0.5 kt.

Note: Totals by gas may not sum due to independent rounding.

Carbon dioxide (CO_2), CH_4, and N_2O emissions from the incineration of waste are accounted for in the Energy sector rather than in the Waste sector because almost all incineration of municipal solid waste (MSW) in the United States occurs at waste-to-energy facilities where useful energy is recovered. Similarly, the Energy sector also includes an estimate of emissions from burning waste tires and hazardous industrial waste, because virtually all of the combustion occurs in industrial and utility boilers that recover energy. The incineration of waste in the United States in 2022 resulted in 12.7 MMT CO_2 Eq. emissions, more than half of which is attributable to the combustion of plastics. For more details on emissions from the incineration of waste, see Section 7.5. Greenhouse Gas Precursor Emissions from the Waste sector are presented in Section 7.6.

Each year, some emission and sink estimates in the *Inventory* are recalculated and revised with improved methods and/or data. In general, recalculations are made to the U.S. greenhouse gas emission estimates either to incorporate new methodologies or, most commonly, to update recent historical data. These improvements are implemented consistently across the previous *Inventory*'s time series (i.e., 1990 to 2021) to ensure that the trend is accurate. For the current *Inventory*, minor improvements were implemented beyond routine activity data updates, including changes to MSW and industrial waste landfill activity data, updates to production activity affecting wastewater influent, and methodological changes for CH_4 emissions from anaerobic digesters processing food waste. In total, the methodological and historic data improvements made to the Waste sector in this *Inventory* resulted in an average decrease in greenhouse gas emissions across the time series by 0.06 MMT CO_2 Eq. (0.03 percent). For more information on specific methodological updates, please see the Recalculations Discussion section for each category in this chapter.

Due to lack of data availability, EPA is not able to estimate emissions associated with sludge generated from the treatment of industrial wastewater. Emissions reported in the Waste chapter for landfills, wastewater treatment, and anaerobic digestion at biogas facilities include those from all 50 states, including Hawaii and Alaska, the District of Columbia, and U.S. Territories. Emissions from landfills include modern, managed sites in most U.S. Territories except for outlying Pacific Islands. Emissions from domestic wastewater treatment include most U.S. Territories except for outlying Pacific Islands. Those emissions are likely insignificant as those outlying Pacific Islands (e.g., Baker Island) have no permanent population. No industrial wastewater treatment emissions are estimated for U.S. Territories, due to lack of data availability. However, industrial wastewater treatment emissions are not expected for outlying Pacific Islands and assumed to be small for other U.S. Territories. Emissions for composting include Puerto Rico and all states except Alaska. Some composting operations in Alaska are known, but these consist of aerated composting facilities. Composting emissions are not included from the remaining U.S. Territories, and these are assumed to be small. Similarly, EPA is not aware of any anaerobic digestion at biogas facilities in U.S. Territories but will review this on an ongoing basis to include these emissions if they are occurring. See Annex 5 for more information on EPA's assessment of the sources not included in this *Inventory*.

Box 7-1: Methodological Approach for Estimating and Reporting U.S. Emissions and Removals, including Relationship to Greenhouse Gas Reporting Data

Consistent with Article 13.7(a) of the Paris Agreement and Article 4.1(a) of the UNFCCC as well as relevant decisions under those agreements, the emissions and removals presented in this report and this chapter are organized by source and sink categories and calculated using internationally-accepted methods provided by the Intergovernmental Panel on Climate Change (IPCC) in the *2006 IPCC Guidelines for National Greenhouse Gas Inventories* (*2006 IPCC Guidelines)* and its supplements and refinements. Additionally, the calculated emissions and removals in a given year for the United States are presented in a common format in line with the reporting guidelines for the reporting of inventories under the Paris Agreement and the UNFCCC. The Parties' use of consistent methods to calculate emissions and removals for their inventories helps to ensure that these reports are comparable. The presentation of emissions and sinks provided in the Waste chapter do not preclude alternative examinations, but rather, this chapter presents emissions and removals in a common format consistent with how Parties are to report inventories under the Paris Agreement and the UNFCCC. The report itself, and this chapter, follows this common format, and provides an explanation of the application of methods used to calculate emissions and removals from waste management and treatment activities.

EPA also collects greenhouse gas emissions data from individual facilities and suppliers of certain fossil fuels and industrial gases through its Greenhouse Gas Reporting Program (GHGRP). The GHGRP applies to direct greenhouse gas emitters, fossil fuel suppliers, industrial greenhouse gas suppliers, and facilities that inject CO_2 underground for sequestration or other reasons and requires reporting by sources or suppliers in 41 industrial categories. Annual reporting is at the facility level, except for certain suppliers of fossil fuels and industrial greenhouse gases. In general, the threshold for reporting is 25,000 metric tons or more of CO_2 Eq. per year. See Annex 9 "Use of EPA Greenhouse Gas Reporting Program in Inventory" for more information.

Waste Data from EPA's Greenhouse Gas Reporting Program

EPA uses annual GHGRP facility-level data in the Landfills category to compile the national estimate of emissions from Municipal Solid Waste (MSW) landfills (see Section 7.1 of this chapter for more information). EPA uses directly reported GHGRP data for net CH_4 emissions from MSW landfills for the years 2010 to 2022 of the *Inventory*. MSW landfills subject to the GHGRP began collecting data in 2010. These data are also used to recalculate emissions from MSW landfills for the years 2005 to 2009 to ensure time-series consistency.

7.1 Landfills (CRT Source Category 5A1)

In In the United States, solid waste is managed by landfilling, recovery through recycling or composting, and combustion through waste-to-energy facilities. Disposing of solid waste in modern, managed landfills is the most used waste management technique in the United States. More information on how solid waste data are collected and managed in the United States is provided in Box 7-3. The municipal solid waste (MSW) and industrial waste landfills referred to in this section are all modern landfills that must comply with a variety of regulations as discussed in Box 7-2. Disposing of waste in illegal dumping sites is not considered to have occurred in years later than 1980 and these sites are not considered to contribute to net emissions in this section for the timeframe of 1990 to the current *Inventory* year. MSW landfills, or sanitary landfills, are sites where MSW is managed to prevent or minimize health, safety, and environmental impacts. Waste is deposited in different cells and covered daily with soil; many have environmental monitoring systems to track performance, collect leachate, and collect landfill gas. Industrial waste landfills are constructed in a similar way as MSW landfills, but are used to dispose of industrial solid waste, such as RCRA Subtitle D wastes (e.g., non-hazardous industrial solid waste defined in Title 40 of the Code of Federal Regulations [CFR] in section 257.2), commercial solid wastes, or conditionally exempt small-quantity generator wastes (EPA 2016a).

After being placed in a landfill, organic waste (such as paper, food scraps, and yard trimmings) is initially decomposed by aerobic bacteria. After the oxygen has been depleted, the remaining waste is available for consumption by anaerobic bacteria, which break down organic matter into substances such as cellulose, amino acids, and sugars. These substances are further broken down through fermentation into gases and short-chain organic compounds that form the substrates for the growth of methanogenic bacteria. These CH_4 producing anaerobic bacteria convert the fermentation products into stabilized organic materials and biogas consisting of approximately 50 percent biogenic carbon dioxide (CO_2) and 50 percent CH_4, by volume. Landfill biogas also contains trace amounts of non-methane organic compounds (NMOC) and volatile organic compounds (VOC) that either result from decomposition byproducts or volatilization of biodegradable wastes (EPA 2008).

Box 7-2: Description of a Modern, Managed Landfill in the United States

Modern, managed landfills are well-engineered facilities that are located, designed, operated, and monitored to ensure compliance with federal, state, and tribal regulations. A modern, managed landfill is EPA's interpretation of the IPCC's terminology of a managed solid waste disposal site. Municipal solid waste (MSW) landfills must be designed to protect the environment from contaminants which may be present in the solid waste stream.

Additionally, many new landfills collect and destroy landfill gas through flares or landfill gas-to-energy projects. Requirements for affected MSW landfills may include:

- Siting requirements to protect sensitive areas (e.g., airports, floodplains, wetlands, fault areas, seismic impact zones, and unstable areas);
- Design requirements for new landfills to ensure that Maximum Contaminant Levels (MCLs) will not be exceeded in the uppermost aquifer (e.g., composite liners and leachate collection systems);
- Leachate collection and removal systems;
- Operating practices (e.g., daily and intermediate cover, receipt of regulated hazardous wastes, use of landfill cover material, access options to prevent illegal dumping, use of a collection system to prevent stormwater run-on/run-off, record-keeping);
- Air monitoring requirements (explosive gases);
- Groundwater monitoring requirements;
- Closure and post-closure care requirements (e.g., final cover construction); and
- Corrective action provisions.

Specific federal regulations that affected MSW landfills must comply with include the 40 CFR Part 258 (Subtitle D of RCRA), or equivalent state regulations and the NSPS 40 CFR Part 60 Subparts WWW and XXX.[1] Additionally, state and tribal requirements may exist.

Methane and CO_2 are the primary constituents of landfill gas generation and emissions. Net carbon dioxide flux from carbon stock changes of materials of biogenic origin in landfills are estimated and reported under the Land Use, Land-Use Change, and Forestry (LULUCF) sector (see Chapter 6 of this *Inventory*). Nitrous oxide (N_2O) emissions from the disposal and application of sewage sludge on landfills are also not explicitly modeled as part of greenhouse gas emissions from landfills. Nitrous oxide emissions from sewage sludge applied to landfills as a daily cover or for disposal are expected to be relatively small because the microbial environment in an anaerobic landfill is not very conducive to the nitrification and denitrification processes that result in N_2O emissions. Furthermore, the *2006 IPCC Guidelines* did not include a methodology for estimating N_2O emissions from solid waste disposal sites "because they are not significant." Therefore, only CH_4 generation and emissions are estimated for landfills under the Waste sector.

Methane generation and emissions from landfills are a function of several factors, including: (1) the total amount and composition of waste-in-place, which is the total waste landfilled annually over the operational lifetime of a landfill; (2) the characteristics of the landfill receiving waste (e.g., size, climate, cover material); (3) the amount of CH_4 that is recovered and either flared or used for energy purposes; and (4) the amount of CH_4 oxidized as the landfill gas–that is not collected by a gas collection system – passes through the cover material into the atmosphere. Each landfill has unique characteristics, but all managed landfills employ similar operating practices, including the application of a daily and intermediate cover material over the waste being disposed of in the landfill to prevent odor and reduce risks to public health. Based on recent literature, the specific type of cover material used can affect the rate of oxidation of landfill gas (RTI 2011). The most used cover materials are soil, clay, and sand. Some states also permit the use of green waste, tarps, waste derived materials, sewage sludge or biosolids, and contaminated soil as a daily cover. Methane production typically begins within the first year after the waste is

[1] For more information regarding federal MSW landfill regulations, see http://www.epa.gov/osw/nonhaz/municipal/landfill/msw_regs.htm.

disposed of in a landfill and will continue for 10 to 50 or more years as the degradable waste decomposes over time.

In 2022, landfill CH_4 emissions were approximately 119.8 MMT CO_2 Eq. (4,277 kt), representing the third largest source of CH_4 emissions in the United States, behind enteric fermentation and natural gas systems. Emissions from MSW landfills accounted for approximately 84 percent of total landfill emissions (100.9 MMT CO_2 Eq.), while industrial waste landfills accounted for the remainder (18.9 MMT CO_2 Eq.). Nationally, there are significantly less industrial waste landfills compared to MSW landfills, which contributes to the lower national estimate of CH_4 emissions for industrial waste landfills. Additionally, the average organic content of waste streams disposed in industrial waste landfills is lower than MSW landfills. Estimates of operational MSW landfills in the United States have ranged from 1,700 to 2,000 facilities (EPA 2023a; EPA 2023b; EPA 2020c; Waste Business Journal [WBJ] 2016; WBJ 2010). The Environment Research & Education Foundation (EREF) conducted a nationwide analysis of MSW management and counted 1,540 operational MSW landfills in 2013 (EREF 2016). Conversely, there are approximately 3,200 MSW landfills in the United States that have been closed since 1980 (for which a closure data is known, (EPA 2023b; WBJ 2010). While the number of active MSW landfills has decreased significantly over the past 20 years, from approximately 6,326 in 1990 to as few as 1,540 in 2013, the average landfill size has increased (EPA 2023a; EREF 2016; BioCycle 2010). Larger landfills may have deeper cells where a greater amount of area will be anaerobic (more CH_4 is generated in anaerobic versus aerobic areas) and larger landfills tend to generate more CH_4 compared to a smaller landfill (assuming the same waste composition and age of waste). Regarding industrial waste landfills, the WBJ database includes approximately 1,100 landfills accepting industrial and/or construction and demolition debris for 2021 (WBJ 2021). Only 169 facilities with industrial waste landfills met the reporting threshold under Subpart TT (Industrial Waste Landfills) in the first year (2011) of EPA's Greenhouse Gas Reporting Program for this subpart (GHGRP codified in 40 CFR Part 98), indicating that there may be several hundred industrial waste landfills that are not required to report under EPA's GHGRP. Less industrial waste landfills meet the GHGRP eligibility threshold because they typically accept waste streams with low to no organic content, which will not decompose and generate CH_4 when disposed.

The annual amount of MSW generated and subsequently disposed in MSW landfills varies annually and depends on several factors (e.g., the economy, consumer patterns, recycling and composting programs, inclusion in a garbage collection service). The estimated annual quantity of waste placed in MSW landfills increased 10 percent from approximately 205 MMT in 1990 to 226 MMT in 2000, then decreased by 11 percent to 202 MMT in 2010, and then increased by 7 percent to approximately 217 MMT in 2022 (see Annex 3.14, Table A-233). Emissions decreased between 1990 to 2022 largely because of increased use of landfill gas collection and control systems, closure of older landfills, better management practices, and increased diversion of organics through state and local policy and regulations. The total amount of MSW generated is expected to increase as the U.S. population continues to grow. The impacts of the coronavirus (COVID-19) pandemic with respect to landfilled waste cannot be quantified as data sources such as the EPA's *Advancing Sustainable Materials Management: Facts and Figures* report have not been published for 2019 through 2022. The quantities of waste landfilled for 2019 to 2022 (presented in Annex 3.14) are extrapolated based on population growth and the last national assessment of MSW landfilled from 2013 (EREF 2016). Net CH_4 emissions from MSW landfills have decreased since 1990 (see Table 7-3 and Table 7-4).

The estimated quantity of waste placed in industrial waste landfills (from the pulp and paper, and food processing sectors) has remained relatively steady since 1990, ranging from 9.7 MMT in 1990 to 11.0 MMT in 2022 (see Annex 3.14, Table A-219). CH_4 emissions from industrial waste landfills have also remained at similar levels recently, ranging from 16.1 MMT CO_2 Eq. in 2005 to 18.9 MMT CO_2 Eq. in 2022 when accounting for both CH_4 generation and oxidation. The EPA has focused the industrial waste landfills source category on industrial sectors known to generate and dispose of by-products that are organic and contribute to CH_4 generation, which are the pulp and paper and food processing sectors. Construction and demolition (C&D) landfills, another type of industrial waste landfill, may accept waste that could degrade (e.g., treated wood), but these waste streams are unlikely to generate significant amounts of CH_4 and are therefore not as relevant to the purpose of national greenhouse gas emissions estimate. There is also a general lack of data on annual quantities of waste disposed in industrial waste

landfills, and the GHGRP Subpart TT (Industrial Waste Landfills) dataset has confirmed C&D landfills, for example, are insignificant CH_4 generators.

EPA's Landfill Methane Outreach Program (LMOP) collects information on landfill gas energy projects currently operational or under construction throughout the United States. LMOP's Landfill and Landfill Gas Energy Database contains certain information on the gas collection and control systems in place at landfills provided by organizations that are a part of the program, which can include the amount of landfill gas collected and flared. In 2022, LMOP identified 9 new landfill gas-to-energy (LFGE) projects (EPA 2023b) that began operation.

Landfill gas collection and control is not accounted for at industrial waste landfills in this chapter (see the Methodology discussion for more information).

Table 7-3: CH_4 Emissions from Landfills (MMT CO_2 Eq.)

Activity	1990	2005	2018	2019	2020	2021	2022
MSW CH_4 Generation[a]	230.0	303.7	332.0	340.9	340.9	335.9	331.4
Industrial CH_4 Generation	13.6	17.9	20.8	20.9	21.0	21.0	21.0
MSW CH_4 Recovered[a]	(23.8)	(148.4)	(195.2)	(201.4)	(206.3)	(203.3)	(199.8)
MSW CH_4 Oxidized[a]	(20.6)	(23.6)	(29.2)	(29.6)	(29.4)	(29.5)	(30.7)
Industrial CH_4 Oxidized	(1.4)	(1.8)	(2.1)	(2.1)	(2.1)	(2.1)	(2.1)
MSW net CH_4 Emissions	185.5	131.6	107.7	109.9	105.2	103.1	100.9
Industrial CH_4 Emissions[b]	12.2	16.1	18.7	18.8	18.9	18.9	18.9
Total	**197.8**	**147.7**	**126.3**	**128.7**	**124.1**	**122.0**	**119.8**

[a] For years 1990 to 2004, the *Inventory* methodology for MSW landfills uses the first order decay methodology. A methodological change occurs in year 2005. For years 2005 to 2022, directly reported net CH_4 emissions from the GHGRP data plus a scale-up factor are used to account for emissions from landfill facilities that are not subject to the GHGRP. More details on the scale-up factor and how it was developed can be found in Annex 3.14. These data incorporate CH_4 recovered and oxidized for MSW landfills. As such, CH_4 generation, CH_4 oxidation, and CH_4 recovery are not calculated separately and totaled to net CH_4 emissions. See the Methodology and Time-Series Consistency section of this chapter for more information.

[b] Methane recovery is not calculated for industrial landfills because this is not a common practice in the United States. Only 1 landfill of 167 that report to Subpart TT (Industrial Waste Landfills) of the GHGRP had an active gas collection and control system during the year 2021 (EPA 2023a).

Notes: Parentheses indicate negative values. Totals may not sum due to independent rounding.

Table 7-4: CH_4 Emissions from Landfills (kt CH_4)

Activity	1990	2005	2018	2019	2020	2021	2022
MSW CH_4 Generation[a]	8,214	10,845	11,857	12,175	12,174	11,997	11,834
Industrial CH_4 Generation	484	638	741	745	748	750	750
MSW CH_4 Recovered[a]	(851)	(5,301)	(6,970)	(7,193)	(7,367)	(7,262)	(7,135)
MSW CH_4 Oxidized[a]	(736)	(843)	(1,041)	(1,058)	(1,050)	(1,052)	(1,097)
Industrial CH_4 Oxidized	(48)	(64)	(74)	(75)	(75)	(75)	(75)
MSW net CH_4 Emissions	6,627	4,701	3,845	3,924	3,757	3,683	3,602
Industrial net CH_4 Emissions[b]	436	574	667	671	674	675	675
Total	**7,063**	**5,275**	**4,512**	**4,595**	**4,431**	**4,359**	**4,277**

[a] For years 1990 to 2004, the *Inventory* methodology for MSW landfills uses the first order decay methodology. A methodological change occurs in year 2005. For years 2005 to 2022, directly reported net CH_4 emissions from the GHGRP data plus a scale-up factor are used to account for emissions from landfill facilities that are not subject to the GHGRP. More details on the scale-up factor and how it was developed can be found in Annex 3.14. These data incorporate CH_4 recovered and oxidized for MSW landfills. As such, CH_4 generation, CH_4 oxidation, and CH_4 recovery are not calculated separately and totaled to net CH_4 emissions. See the Methodology and Time-Series Consistency section of this chapter for more information.

[b] Methane recovery is not calculated for industrial landfills because this is not a common practice in the United States. Only 1 landfill of 167 that report to Subpart TT (Industrial Waste Landfills) of the GHGRP had an active gas collection and control system during the year 2021 (EPA 2023a).

Notes: Parentheses indicate negative values. Totals may not sum due to independent rounding.

Methodology and Time-Series Consistency

Methodology Applied for MSW Landfills

A combination of IPCC Tier 2 and 3 approaches (IPCC 2006) are used over the reported time series to calculate emissions from MSW Landfills, using two primary methods in accordance with IPCC methodological decision trees based on available data. The first method uses the first order decay (FOD) model as described by the *2006 IPCC Guidelines* to estimate CH_4 generation. The amount of CH_4 recovered and combusted from MSW landfills is subtracted from the CH_4 generation and is then adjusted with an oxidation factor. The oxidation factor represents the amount of CH_4 in a landfill that is oxidized to CO_2 as it passes through the landfill cover (e.g., soil, clay, geomembrane). This method is presented below.

Equation 7-1: Landfill Methane Generation

$$\mathrm{CH}_{4,\mathrm{MSW}} = (G_{CH4} - \sum_{n-1}^{N} R_n) * (1 - OX)$$

where,

$CH_{4,MSW}$	=	Net CH_4 emissions from solid waste
$G_{CH4,MSW}$	=	CH_4 generation from MSW landfills, using emission factors for DOC, k, MCF, F from IPCC (2006) and other peer-reviewed sources
R	=	CH_4 recovered and combusted
Ox	=	CH_4 oxidized from MSW landfills before release to the atmosphere, using Ox values from IPCC (2006) and other peer-reviewed or scientifically validated literature (40 CFR Part 98)

The second method used to calculate CH_4 emissions from landfills, also called the back-calculation method, is based on directly measured amounts of recovered CH_4 from the landfill gas and is expressed below and by Equation HH-8 in 40 CFR Part 98.343. The two parts of the equation consider the portion of CH_4 in the landfill gas that is not collected by the landfill gas collection system, and the portion that is collected. First, the recovered CH_4 is adjusted with the collection efficiency of the gas collection and control system and the fraction of hours the recovery system operated in the calendar year. This quantity represents the amount of CH_4 in the landfill gas that is not captured by the collection system; this amount is then adjusted for oxidation. The second portion of the equation adjusts the portion of CH_4 in the collected landfill gas with the efficiency of the destruction device(s), and the fraction of hours the destruction device(s) operated during the year.

The current *Inventory* uses both methods to estimate CH_4 emissions across the time series within EPA's Waste Model, as summarized in Figure 7-3 below. This chapter provides a summary of the methods, activity data, and parameters used. Additional stepwise explanations to generate the net emissions are provided in Annex 3.14.

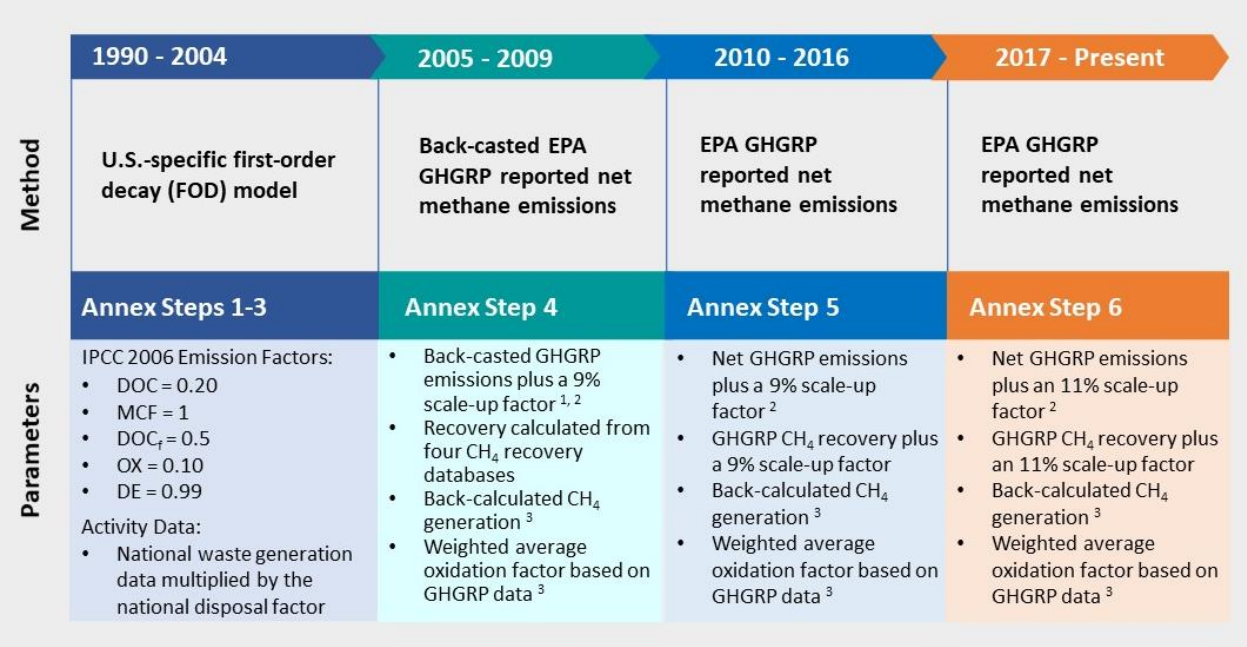
Equation 7-2: Net Methane Emissions from MSW Landfills

$$\mathrm{CH}_{4,\mathrm{Solid\ Waste}} = [\left(\frac{R}{CE\ x\ f_{REC}} - R\right) x(1 - OX) + R\ x\ \left(1 - (DE\ x\ f_{Dest})\right)]$$

where,

$CH_{4,Solid\ Waste}$	=	Net CH_4 emissions from solid waste
R	=	Quantity of recovered CH_4 from Equation HH-4 of EPA's GHGRP
CE	=	Collection efficiency estimated at the landfill, considering system coverage, operation, and cover system materials from Table HH-3 of EPA's GHGRP. If area by soil cover type information is not available, the default value of 0.75 should be used (percent)
f_{REC}	=	fraction of hours the recovery system was operating (percent)
OX	=	oxidation factor (percent)
DE	=	destruction efficiency (percent)
f_{Dest}	=	fraction of hours the destruction device was operating (fraction)

Figure 7-3: Methodologies Used Across the Time Series to Compile the U.S. Inventory of Emission Estimates for MSW Landfills



[1] The intent of the scale-up factor is to estimate emissions from landfills that do not report to the GHGRP. More details on the scale-up factor and how it was developed can be found in Annex 3.14. The back-casted emissions are calculated using directly reported net methane emissions for GHGRP reporting years 2010 to 2016. The back-casted emissions are subject to change in each *Inventory* based on new reporting year reports and resubmitted greenhouse gas reports for previous years. This method is compatible with the *2006 IPCC Guidelines* because facilities reporting to the GHGRP either use the FOD method, or directly measured methane recovery data with default emission factors either directly included in the *2006 IPCC Guidelines* or scientifically validated through peer review.

[2] Emission factors used by facilities reporting to GHGRP Subpart HH are facility-specific defaults derived from peer-reviewed literature and the *2006 IPCC Guidelines*.

[3] Methane generation is back-calculated from the net MSW emissions, estimated methane recovery data, and the weighted average oxidation factor based on GHGRP Subpart HH reported data of 0.18 between 2010 to 2016, and 0.21 between 2017 to 2020, and 0.23 in 2021 and 2022.

The Waste Model is a spreadsheet developed by the IPCC for purposes of estimating methane emissions from solid waste disposal sites, adapted to the United States by the inclusion and usage of U.S.-specific parameters. The Waste Model contains activity and waste generation information from both the MSW and Industrial landfill sectors and estimates the amount of CH_4 emissions from each sector for each year of the time series, using both methods. Prior to the 1990 through 2015 *Inventory*, only the FOD method was used. Methodological changes were made to the 1990 through 2015 *Inventory* to incorporate higher tier data (i.e., CH_4 emissions as directly reported to EPA's GHGRP), which cannot be directly applied to earlier years in the time series without significant bias. The technique used to merge the directly reported GHGRP data with the previous methodology is described as the overlap technique in the Time-Series Consistency chapter of the *2006 IPCC Guidelines*. Additional details on the technique used is included in Annex 3.14, and a technical memorandum (RTI 2017).

Supporting information, including details on the techniques used to ensure time-series consistency by incorporating the directly reported GHGRP emissions is presented in Annex 3.14.

Methodology Applied for Industrial Waste Landfills

Emissions from industrial waste landfills are estimated using a Tier 2 approach (IPCC 2006) and a tailored (country-specific) IPCC waste model in accordance with IPCC methodological decision trees based on available data. Activity

data used are industrial production data (ERG 2023) for two sectors (pulp and paper manufacturing, and food and beverage manufacturing) to which country-specific default waste disposal factors are applied (a separate disposal factor for each sector). The disposal factors, as described below, are based on scientifically reviewed data, and are the same across the entire time series. The emission factors are based on those recommended by the *2006 IPCC Guidelines* and are the same across the entire time series.

The FOD equation from IPCC (2006) is used via the waste model to estimate methane emissions:

Equation 7-3: Net Methane Emissions from Industrial Waste Landfills

$$\mathrm{CH}_{4,\mathrm{IND}} = (G_{CH4} - \sum_{n-1}^{N} R_n) * (1 - OX)$$

where,

$CH_{4,Solid\ Waste}$	=	Net CH_4 emissions from solid waste
$G_{CH4,Ind}$	=	CH_4 generation from industrial waste landfills, using production data multiplied by a disposal factor and emission factors for DOC, k, MCF, F (IPCC 2006)
R	=	CH_4 recovered and combusted (no recovery is assumed for industrial waste landfills)
OX	=	CH_4 oxidized from industrial waste landfills before release to the atmosphere (using the *2006 IPCC Guidelines* value for OX of 0.10)

The activity data used in the emission calculations are production data (e.g., the amount of meat, poultry, vegetables processed; the amount of paper produced) versus disposal data. There are currently no facility-specific data sources that track and report the amount and type of waste disposed of in the universe of industrial waste landfills in the United States. Based on this limited information, the *Inventory* methodology assumes most of the organic waste placed in industrial waste landfills originates from the food processing (meat, vegetables, fruits) and pulp and paper sectors, thus estimates of industrial landfill emissions focused on these two sectors.

A waste disposal factor is applied to the annual quantities of key food products generated. A waste disposal factor of 4.86 percent is used for 1990 to 2009 and a factor of 6 percent is used for 2010 to the current year. The 4.86 percent disposal factor is based on available data from a 1993 Report to Congress (EPA 1993). The 6 percent waste disposal factor is derived from recent surveys of the food and beverage industry where approximately 94 percent of food waste generated is repurposed (FWRA 2016). The composition of waste disposed of in industrial waste landfills is expected to be more consistent in terms of composition and quantity than that disposed of in MSW landfills. The amount of waste landfilled is assumed to be a fraction of production that is held constant over the time series as explained in Annex 3.14.

Landfill CH_4 recovery is not accounted for in industrial waste landfills and is believed to be minimal based on available data collected under EPA's GHGRP for industrial waste landfills (Subpart TT), which shows that only one of the 167 facilities, or 1 percent of facilities, have active gas collection systems (EPA 2023a). The amount of CH_4 oxidized by the landfill cover at industrial waste landfills is assumed to be 10 percent of the CH_4 generated (IPCC 2006; Mancinelli and McKay 1985; Czepiel et al. 1996) for all years.

Additionally, the *2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories* (IPCC 2019) were reviewed to determine if any revisions were required to emission factors, methodologies, and assumptions underlying emission estimates for all source categories. None of the 2019 Refinements are applicable to the country-specific methodology applied for the landfills source category.

Box 7-3: Nationwide Municipal Solid Waste Data Sources

Municipal solid waste (MSW) generated in the United States can be managed through a variety of methods. MSW that is not recycled, composted, combusted with energy recovery, or digested is assumed to be landfilled. In addition to these management pathways, waste or excess food from the food manufacturing and processing sector may be disposed through the sewerage network, used for animal feed, land application, donated for human consumption, and rendered or recycled into biofuels in the case of animal by-products, fats, oils and greases.

There have been three main sources for nationwide solid waste management data in the United States that the *Inventory* has used (see Annex 3.14, Box A-3 for comparison of estimates from these data sources):

- The *BioCycle* and Earth Engineering Center of Columbia University's SOG in America surveys [no longer published];
- The EPA's *Advancing Sustainable Materials Management: Facts and Figures* reports; and
- The EREF's *MSW Generation in the United States* reports.

The SOG surveys and, most recently EREF, collected state-reported data on the amount of waste generated and the amount of waste managed via different management options: landfilling, recycling, composting, and combustion. These data sources used a 'bottom-up' method. The survey asked for actual tonnages instead of percentages in each waste category (e.g., residential, commercial, industrial, construction and demolition, organics, tires) for each waste management option. If such a breakdown was not available, the survey asked for total tons landfilled. The data were adjusted for imports and exports across state lines so that the principles of mass balance were adhered to for completeness, whereby the amount of waste managed did not exceed the amount of waste generated. The SOG and EREF reports present survey data aggregated to the state level.

The EPA *Advancing Sustainable Materials Management: Facts and Figures* report characterizes national post-consumer municipal solid waste (MSW) generation and management using a top-down materials flow (mass balance) methodology. It captures an annual snapshot of MSW generation and management in the United States for specific products. Data are gathered from U.S. Government (e.g., U.S. Census Bureau and U.S. Department of Commerce), state environmental agencies, industry and trade groups, and sampling studies. The materials flow methodology develops MSW waste generation estimates of quantities of MSW products in the marketplace (using product sales and replacement data) and assessing waste generation by component material based on product lifespans. The data are used to estimate tons of materials and products generated, recycled, combusted with energy recovery, managed via other food waste management pathways, or landfilled nationwide. MSW that is not recycled or composted is assumed to be combusted or landfilled, except for wasted food, which uses a different methodology and includes nine different management pathways. The 2018 Facts and Figures Report (EPA 2020) uses a methodology that expanded the number of management pathways to include: animal feed; bio-based materials and/or biochemical processing (i.e., rendering); co-digestion and/or anaerobic digestion; composting/aerobic processes; combustion; donation; land application; landfill; and sewer or wastewater treatment.

In this *Inventory*, emissions from solid waste management are presented separately by waste disposal option, except for recycling of waste materials.

- **Recycling**: Emissions from recycling are attributed to the stationary combustion of fossil fuels that may be used to power on-site recycling machinery and are presented in the stationary combustion chapter in the Energy sector. The emissions estimates for recycling are not called out separately.
- **Landfill Disposal**: Emissions from solid waste disposal in landfills and the composting of solid waste materials are presented in the Landfills and Composting sections in the Waste sector of this report.
- **Anaerobic Digestion**: Emissions from anaerobic digesters are presented in three different sections depending on the digester category:
    - Emissions from on-farm digesters are included in the Agriculture sector.
    - Emissions from digesters at wastewater treatment plants are included in the Waste sector, and
    - Emissions from stand-alone digesters are also included in the Waste sector.
- **Waste Incineration**: Emissions from waste incineration are accounted for in the Incineration chapter of the Energy sector of this report because, in the United States, almost all incineration of MSW occurs at waste-to-energy (WTE) facilities or industrial facilities where useful energy is recovered.

Uncertainty

Several types of uncertainty are associated with the estimates of CH_4 emissions from MSW and industrial waste landfills when the FOD method is applied directly for 1990 to 2004 in the Waste Model and, to some extent, in the GHGRP methodology. The approach used in the MSW emission estimates assumes that the CH_4 generation potential (L_o) and the rate of decay that produces CH_4 from MSW, as determined from several studies of CH_4 recovery at MSW landfills, are representative of conditions at U.S. MSW landfills. When this top-down approach is applied at the nationwide level, the uncertainties are assumed to be less than when applying this approach to individual landfills and then aggregating the results to the national level. In other words, the FOD method as applied in this *Inventory* is not facility-specific modeling and while this approach may over- or underestimate CH_4 generation at some landfills if used at the facility-level, the result is expected to balance out because it is being applied nationwide.

There is a high degree of uncertainty associated with the FOD model, particularly when a homogeneous waste composition and hypothetical decomposition rates are applied to heterogeneous landfills (IPCC 2006). There is less uncertainty in EPA's GHGRP data because this methodology is facility-specific, uses directly measured CH_4 recovery data (when applicable), and allows for a variety of landfill gas collection efficiencies, destruction efficiencies, and/or oxidation factors to be used.

Uncertainty also exists in the scale-up factors (both 9 percent and 11 percent) applied for years 2005 to 2016 and 2017 to 2022, respectively, and in the back-casted emissions estimates for 2005 to 2009. As detailed in RTI (2018), limited information is available for landfills that do not report to the GHGRP. RTI developed an initial list of landfills that do not report to the GHGRP with the intent of quantifying the total waste-in-place for these landfills that would add up to the scale-up factor. Input was provided by industry, LMOP, and additional EPA support. However, many gaps existed in the initial development of this Non-Reporting Landfills Database. Assumptions were made for hundreds of landfills to estimate their waste-in-place and the subsequent scale-up factors. The waste-in-place estimated for each landfill is likely not 100 percent accurate and should be considered a reasonable estimate. Additionally, a simple methodology was used to back-cast emissions for 2005 to 2009 using the GHGRP-reported emissions from 2010 to 2022. This methodology does not factor in annual landfill to landfill changes in landfill CH_4 generation and recovery. Because of this, an uncertainty factor of 25 percent is applied to the scale-up factor and years (emission estimates) the scale-up factor is applied to.

Aside from the uncertainty in estimating landfill CH_4 generation, uncertainty also exists in the estimates of the landfill gas oxidized at MSW landfills. Facilities directly reporting to EPA's GHGRP can use oxidation factors ranging from 0 to 35 percent, depending on their facility-specific CH_4 flux. As recommended by the *2006 IPCC Guidelines* for managed landfills, a 10 percent default oxidation factor is applied in the *Inventory* for both MSW landfills (those not reporting to the GHGRP and for the years 1990 to 2004 when GHGRP data are not available) and industrial waste landfills regardless of climate, the type of cover material, and/or presence of a gas collection system.

Another significant source of uncertainty lies with the estimates of CH_4 recovered by flaring and gas-to-energy projects at MSW landfills that are sourced from the *Inventory*'s CH_4 recovery databases (used for years 1990 to 2004). Four CH_4 recovery databases are used to estimate nationwide CH_4 recovery for MSW landfills for 1990 to 2009. The GHGRP MSW landfills database was added as a fourth recovery database starting with the 1990 to 2013 *Inventory* report (two years before the full GHGRP data set started being used for net CH_4 emissions for the *Inventory*). Relying on multiple databases for a complete picture introduces uncertainty because the coverage and characteristics of each database differs, which increases the chance of double counting avoided emissions. The methodology and assumptions that go into each database differ. For example, the flare database assumes the midpoint of each flare capacity at the time it is sold and installed at a landfill; the flare may be achieving a higher capacity, in which case the flare database would underestimate the amount of CH_4 recovered. Additionally, two databases, the EIA database and flare vendor database, could no longer be updated for the entire time series due to external factors. For example, the EIA database has not been updated since 2006 because the EIA stopped collecting landfill recovery data. The EIA database has, for the most part, been replaced by the GHGRP MSW

landfills database. The flare database was populated annually until 2015, but decreasing, voluntary participation from flare vendors sharing their flare sales data for several years prior to 2015.

To avoid double counting and to use the most relevant estimate of CH_4 recovery for a given landfill, a hierarchical approach is used among the four databases. GHGRP data and the EIA data are given precedence because facility data were directly reported; the LFGE data are given second priority because CH_4 recovery is estimated from facility-reported LFGE system characteristics; and the flare data are given the lowest priority because this database contains minimal information about the flare, no site-specific operating characteristics, and includes smaller landfills not included in the other three databases (Bronstein et al. 2012). The coverage provided across the databases most likely represents the complete universe of landfill CH_4 gas recovery; however, the number of unique landfills between the four databases does differ.

The *2006 IPCC Guidelines* default value of 10 percent for uncertainty in recovery estimates was used for two of the four recovery databases in the uncertainty analysis where metering of landfill gas was in place (for about 64 percent of the CH_4 estimated to be recovered). This 10 percent uncertainty factor applies to the LFGE database; 12 percent to the EIA database; and 1 percent for the GHGRP MSW landfills dataset because of the supporting information provided and rigorous verification process. For flaring without metered recovery data (the flare database), a much higher uncertainty value of 50 percent is used. The compounding uncertainties associated with the four databases in addition to the uncertainties associated with the FOD method and annual waste disposal quantities leads to the large upper and lower bounds for MSW landfills presented in Table 7-5.

The lack of landfill-specific information regarding the number and type of industrial waste landfills in the United States is a primary source of uncertainty with respect to the industrial waste generation and emission estimates. The approach used here assumes that most of the organic waste disposed of in industrial waste landfills that would result in CH_4 emissions consists of waste from the pulp and paper and food processing sectors. However, because waste generation and disposal data are not available in an existing data source for all U.S. industrial waste landfills, a straight disposal factor is applied over the entire time series to the amount produced to determine the amounts disposed. Industrial waste facilities reporting under EPA's GHGRP do report detailed waste stream information, and these data have been used to improve, for example, the DOC value used in the *Inventory* methodology for the pulp and paper sector. A 10 percent oxidation factor is also applied to CH_4 generation estimates for industrial waste landfills and carries the same amount of uncertainty as with the factor applied to CH_4 generation for MSW landfills. The specified probability density functions (PDFs) are assumed to be normal for most activity data and emission factors, and due to lack of data, are based on expert judgement (RTI 2004).

The results of the *2006 IPCC Guidelines* Approach 2 quantitative uncertainty analysis are summarized in Table 7-5. There is considerable uncertainty for the MSW landfills estimates due to the many data sources used, each with its own uncertainty factor.

Table 7-5: Approach 2 Quantitative Uncertainty Estimates for CH_4 Emissions from Landfills (MMT CO_2 Eq. and Percent)

Source	Gas	2022 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Total Landfills	**CH_4**	**119.8**	**109.9**	**137.2**	**-8%**	**+15%**
MSW	CH_4	100.9	98.8	121.2	-2%	+20%
Industrial	CH_4	18.9	13.1	23.7	-31%	+25%

[a] Range of emission estimates predicted by Monte Carlo stochastic simulation for a 95 percent confidence interval. Individual uncertainty factors are applied to activity data and emission factors in the Monte Carlo analysis.

QA/QC and Verification

General quality assurance/quality control (QA/QC) procedures were applied consistent with the *U.S. Inventory QA/QC Plan*, which is in accordance with Vol. 1, Chapter 6 of the *2006 IPCC Guidelines* (see Annex 8 for more details). QA/QC checks are performed for the transcription of the published data set (e.g., EPA's GHGRP dataset) used to populate the *Inventory* data set in terms of completeness and accuracy against the reference source. Additionally, all datasets used for this category have been checked to ensure they are of appropriate quality and are representative of U.S. conditions. The primary calculation spreadsheet is tailored from the *2006 IPCC Guidelines* waste model and has been verified previously using the original, peer-reviewed IPCC waste model. All model input values and calculations were verified by secondary QA/QC review. Stakeholder engagements sessions in 2016 and 2017 were used to gather input on methodological improvements and facilitate an external expert review on the methodology, activity data, and emission factors.

Category-specific checks include the following:

- Evaluation of the secondary data sources used as inputs to the *Inventory* dataset to ensure they are appropriately collected and are reliable;
- Cross-checking the data (activity data and emissions estimates) with previous years to ensure the data are reasonable, and that any significant variation can be explained through the activity data;
- Conducting literature reviews to evaluate the appropriateness of country-specific emission factors (e.g., DOC values, precipitation zones with respect to the application of the k values) given findings from recent peer-reviewed studies; and
- Reviewing secondary datasets to ensure they are nationally complete and supplementing where necessary (e.g., using a scale-up factor to account for emissions from landfills that do not report to EPA's GHGRP).

A primary focus of the QA/QC checks in past Inventories was to ensure that CH_4 recovery estimates were not double-counted and that all LFGE projects and flares were included in the respective project databases. QA/QC checks performed in the past for the recovery databases were not performed in this *Inventory*, because new data were not added to the recovery databases in this *Inventory* year.

For the GHGRP data, EPA verifies annual facility-level reports through a multi-step process (e.g., combination of electronic checks and manual reviews by staff) to identify potential errors and ensure that data submitted to EPA are accurate, complete, and consistent.[2] Based on the results of the verification process, EPA follows up with facilities to resolve mistakes that may have occurred. The post-submittals checks are consistent with several general and category-specific QC procedures, including range checks, statistical checks, algorithm checks, and year-to-year checks of reported data and emissions. For the MSW Landfills sector, under Subpart HH of the GHGRP, MSW Landfills with gas collection are required to report emissions from their site using both a forward- (using a first order decay model as a basis) and back-calculating (using parameters specific to the landfill itself, such as measured recovery and collection efficiency of the landfill gas) methodology. Details on the forward- and back-calculation approach can be found in Annex 3.14 and 40 CFR Subpart HH of Part 98. Reporters can choose which of these two methodologies they believe best represents the emissions at their landfill and are required to submit that value as their total Subpart HH emissions. Facilities are generally not expected to switch between the two equations each year, as the emissions calculated using each method can vary greatly and can have a significant effect on emission trends for that landfill, and potentially the entire MSW Landfill sector under the GHGRP. Key checks are in place to assure that emissions are trending in a sensible way year over year for each reporting landfill.

[2] See https://www.epa.gov/sites/production/files/2015-07/documents/ghgrp_verification_factsheet.pdf.

Recalculations Discussion

Revisions to the individual facility reports submitted to EPA's GHGRP can be made at any time and a portion of facilities have revised their reports since 2010 for various reasons, resulting in changes to the total net CH_4 emissions for MSW landfills. Each *Inventory* year, the back-casted emissions for 2005 to 2009 will be recalculated using the most recently verified data from the GHGRP. Changes in these data result in changes to the back-casted emissions. The impact of the revisions to the GHGRP Subpart HH annual greenhouse gas reports resubmitted for 2017 to 2021 slightly decreased total Subpart HH reported net emissions, which decreased net MSW emissions by an average of 0.5 percent. A change in net Subpart HH reported emissions results in the same percentage change in the *Inventory* emissions for that year.

Slight revisions were also made to the food and beverage sector production data for nearly every year of the time series. The production data increased by 1 to 2 MMT per year between 1990 to 2017 and decreased by a few MMT per year between 2019 to 2021. These revisions decreased net emissions from industrial waste landfills by less than 0.1 percent between 1990 to 2010. Emissions increased slightly between 2011 to 2017 (ranging from 0.3 percent in 2011 to a high of 1.3 percent in 2017). The revisions to the production data also slightly increased emissions by an average of 0.6 percent between 2018 to 2021.

The combined changes to the MSW and industrial waste landfills activity data resulted in annual increases ranging from 0.005 percent to 0.01 percent to net emissions between 2005 to 2010. A slight decrease in net emissions is observed between 2011 to 2016 (-0.04 percent to -0.2 percent), and an increase, averaging 0.36 percent of emissions, is observed between 2017 to 2021. A 0.6 percent increase is observed for 2020, and a 0.5 percent increase is observed for 2021. Between 2005 to 2020, on average, the impact or change was very small (less than 0.1 percent).

Planned Improvements

EPA received recommendations from industry stakeholders regarding the DOC values and decay rates (k values) required to be used in the GHGRP calculations. Stakeholders have suggested that newer, more up-to-date default values considering recent trends in the composition of waste disposed in MSW landfills for both k and DOC in the GHGRP should be developed and reflected in the 2005 and later years of the *Inventory*. In response, EPA developed a multivariate analysis using publicly available Subpart HH GHGRP data, solving for optimized DOC and k values across the more than 1,100 landfills reporting to the program. The results of this analysis could help inform a current GHGRP rulemaking (87 FR 36920) where changes could be made to the default DOC and k values contained within Subpart HH, which could then be carried over to the *Inventory* emissions estimates for MSW landfills upon promulgation of any revisions to 40 CFR Part 98. This potential improvement may be long-term.

With respect to the scale-up factor, EPA received comments on revisions made to the scale-up for the 1990 to 2020 *Inventory* from a total waste-in-place approach to a time-based threshold of 50 years. Commenters noted that this time-based threshold approach does not adjust for the non-linearity of methane production of landfill gas. In response, EPA will further investigate how best to account for emissions from MSW landfills that do not report to the GHGRP, including using the FOD model for these landfills based on estimated annual waste disposed for this subset of landfills between 2005 to 2022, reverting to the total waste-in-place approach, or modifying the time-based threshold approach. Any methodological revisions to accounting for emissions from this subset of landfills will be made in the next (1990 to 2023) *Inventory*.

Relatedly, EPA will periodically assess the impact to the waste-in-place and emissions data from GHGRP facilities that have resubmitted annual reports during any reporting years, are new reporting facilities, and from facilities that have stopped reporting to the GHGRP to ensure national estimates are as complete as possible. Facilities may stop reporting to the GHGRP when they meet the "off-ramp" provisions (reported less than 15,000 metric tons of CO_2 equivalent emissions for 3 consecutive years or less than 25,000 metric tons of CO_2 equivalent emissions for 5 consecutive years). If warranted, EPA will revise the scale-up factor to reflect newly acquired information to ensure completeness of the *Inventory*. EPA considered public comments received on the 1990 through 2019 *Inventory*

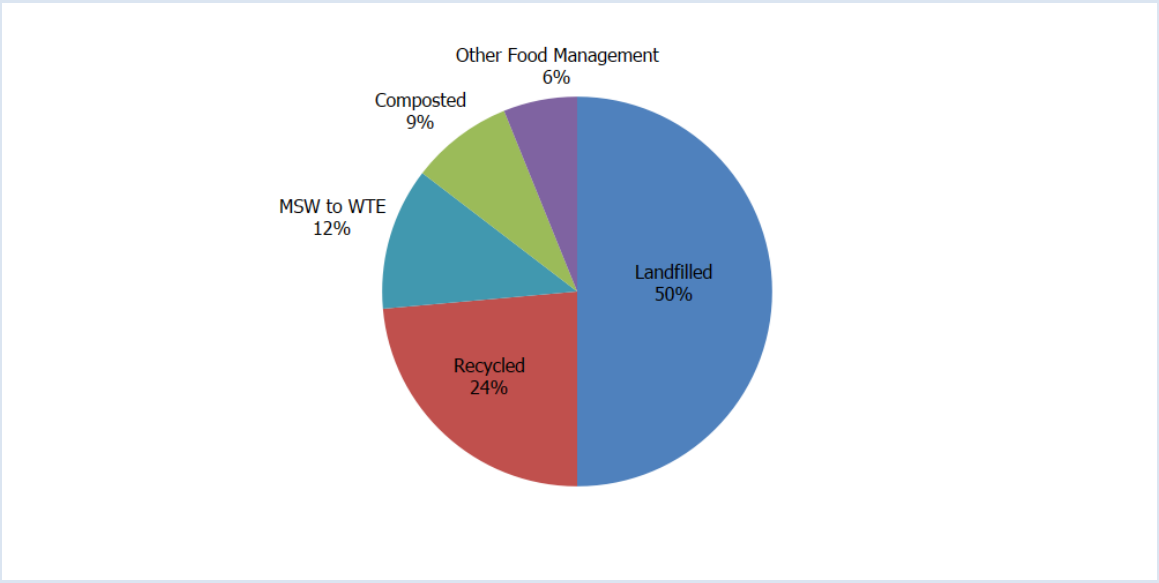
specific to using a time-based threshold to calculate the scale-up factor instead of a total waste-in-place approach. The rationale supporting the comments was that older, closed landfills with large quantities of waste-in-place are driving up the scale-up factor but have little impact on total methane generation. EPA assessed two time-based scenarios for developing the scale-up factor – one scenario looking at the past 30 years of waste disposed, and the second looking at the past 50 years of waste disposed. The 50-year time-based threshold was applied and resulted in the 11 percent scale-up factor used between 2017 and 2022.

EPA is planning to account for unmanaged landfills in Puerto Rico and other U.S. Territories to the landfill emissions estimates. Data limitations for historical waste received at these sites make this challenging. Presently, emissions from managed sites in Puerto Rico and Guam are accounted for in 2005 to present as part of the GHGRP Subpart HH dataset.

Box 7-4: Overview of U.S. Solid Waste Management Trends

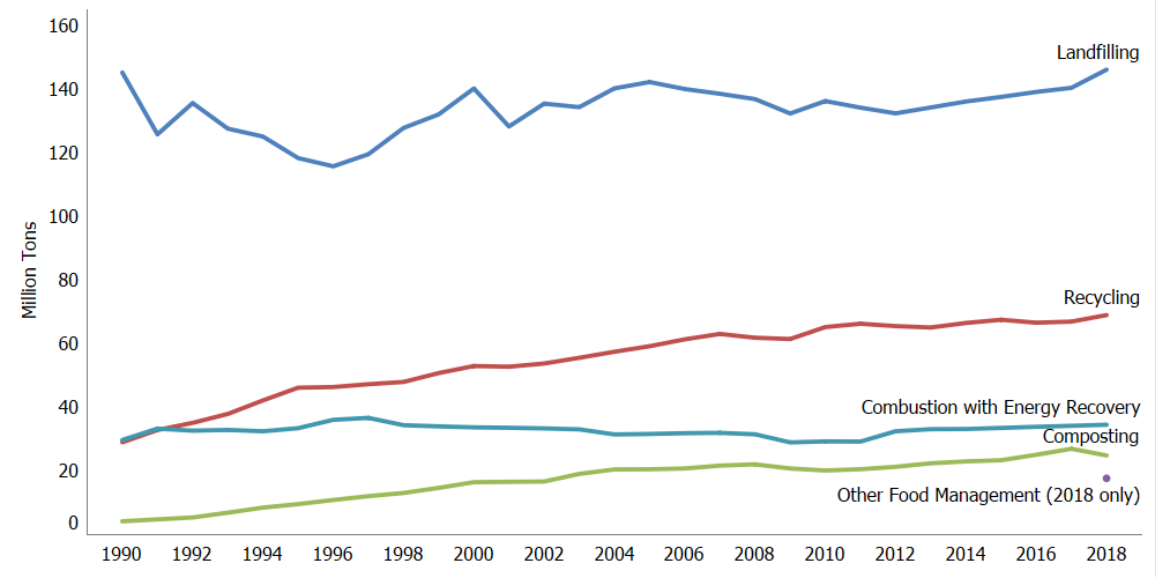
As shown in Figure 7-4 and Figure 7-5 landfilling of MSW is currently and has been the most common waste management practice. A large portion of materials in the waste stream are recovered for recycling and composting, which is becoming an increasingly prevalent trend throughout the country. Materials that are composted and recycled would have previously been disposed in a landfill.

Figure 7-4: Management of Municipal Solid Waste in the United States, 2018



Note: 2018 is the latest year of available data. Data taken from Table 35 of EPA (2020a). MSW to WTE is combustion with energy recovery (WTE = waste-to-energy).
Source: EPA (2020b)

Figure 7-5: MSW Management Trends from 1990 to 2018



Note: 2018 is the latest year of available data. Only one year of data (2018) is available for the "Other Food Management" category.

Source: EPA (2020b). The EPA Advancing Sustainable Materials Management reports only present data for select years, thus several reports were used in the compilation of this figure. All data were taken from Table 35 in EPA 2020b for 1990, 2000, 2015, 2017 and 2018. Data were taken from Table 35 in EPA (2019) for 2010 and 2016. Data were taken from EPA (2018) for 2014. Data were taken from Table 35 of EPA (2016b) for 2012 and 2013. Data were taken from Table 30 of EPA (2014) for 2008 and 2011. The reports with data available for years prior to EPA (2012) can be provided upon request but are no longer on the EPA's Advancing Sustainable Materials Management web site.[3]

Table 7-6 presents the national-level material composition of waste disposed across typical MSW landfills in the United States over time. It is important to note that the actual composition of waste entering each landfill will vary from that presented in Table 7-6.

Understanding how the waste composition changes over time, specifically for the degradable waste types (i.e., those types known to generate CH_4 as they break down in a modern MSW landfill), is important for estimating greenhouse gas emissions. Increased diversion of degradable materials so that they are not disposed of in landfills reduces the CH_4 generation potential and CH_4 emissions from landfills. For certain degradable waste types (i.e., paper and paperboard), the amounts discarded have decreased over time due to an increase in waste diversion through recycling and composting (see Table 7-6 and Figure 7-6). As shown in Figure 7-6, the diversion of food scraps has been consistently low since 1990 because most cities and counties do not practice curbside collection of these materials, although the quantity has been slowly increasing in recent years. Neither Table 7-6 nor Figure 7-6 reflect the frequency of backyard composting of yard trimmings and food waste because this information is largely not collected nationwide and is hard to estimate.

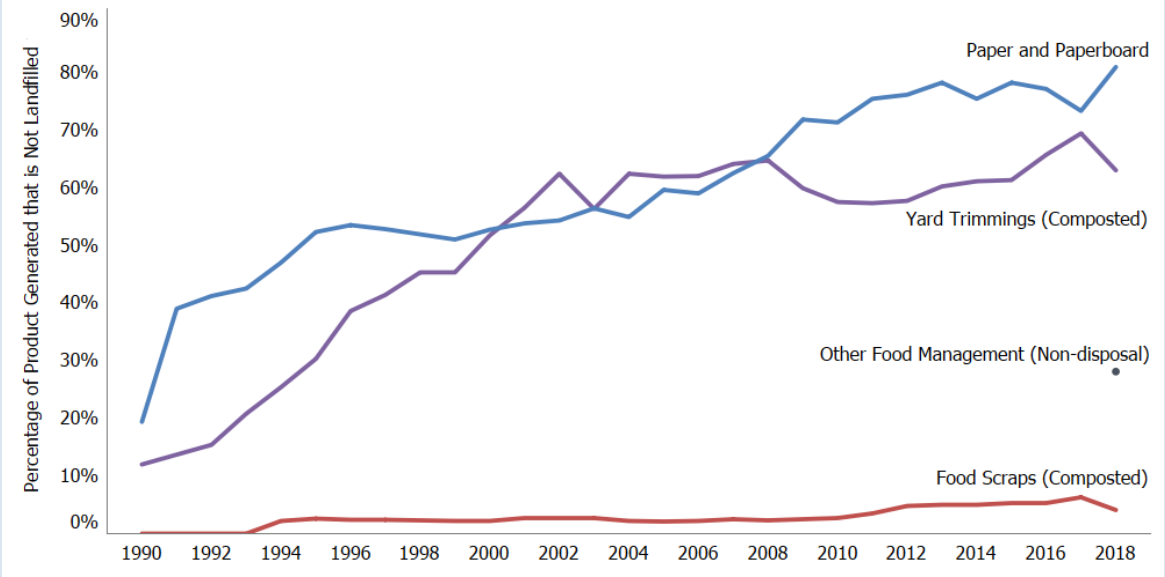
Table 7-6: Materials Discarded in the Municipal Waste Stream by Waste Type from 1990 to 2018 (Percent)

Waste Type	1990	2005	2015	2016	2017	2018
Paper and Paperboard	30.0%	24.7%	13.3%	12.7%	13.1%	11.8%
Glass	6.0%	5.8%	5.0%	4.9%	4.9%	5.2%
Metals	7.2%	7.9%	9.5%	9.8%	9.9%	9.5%
Plastics	9.5%	16.4%	18.9%	18.9%	19.2%	18.5%
Rubber and Leather	3.2%	2.9%	3.3%	3.4%	3.5%	3.4%

Textiles	2.9%	5.3%	7.7%	8.0%	8.0%	7.7%
Wood	6.9%	7.5%	8.0%	8.8%	8.7%	8.3%
Other	1.4%	1.8%	2.2%	2.2%	2.2%	2.0%
Food Scraps	13.6%	18.5%	22.0%	22.1%	22.0%	24.1%
Yard Trimmings	17.6%	7.0%	7.8%	6.9%	6.2%	7.2%
Miscellaneous Inorganic Wastes	1.7%	2.2%	2.3%	2.3%	2.3%	2.3%

Source: EPA (2020b)

Figure 7-6: Percent of Degradable Materials Diverted from Landfills from 1990 to 2018 (Percent)



Note: The data shown in this chart are for recycling of paper and paperboard, composting of food scraps and yard trimmings, and alternative management pathways for the Other Food Management (non-disposal) category. The Other Food Management (non-disposal) category is a new addition and only one year of data are available for 2018 (28 percent of the food waste generated was beneficially reused or managed using a method that was not landfilling, recycling, or composting). The Other Food Management pathways include animal feed, bio-based materials/biochemical processing, co-digestion/anaerobic digestion, donation, land application, and sewer/wastewater treatment.

Source: EPA (2020b). The EPA Advancing Sustainable Materials reports only present data for select years, thus several reports were used in the compilation of this figure. All data were taken from Table 35 in EPA (2020b) for 1990, 2000, 2015, 2017 and 2018. Data were taken from Table 35 in EPA (2019) for 2010 and 2016. Data were taken from EPA (2018) for 2014. Data were taken from Table 35 of EPA (2016b) for 2012 and 2013. Data were taken from Table 30 of EPA (2014) for 2008 and 2011. The reports with data available for years prior to EPA (2012) can be provided upon request, but are not longer on the EPA's Advancing Sustainable Materials Management website.[4]

[3] See https://www.epa.gov/facts-and-figures-about-materials-waste-and-recycling/advancing-sustainable-materials-management.

[4] See https://www.epa.gov/facts-and-figures-about-materials-waste-and-recycling/advancing-sustainable-materials-management.

7.2 Wastewater Treatment and Discharge (CRT Source Category 5D)

Wastewater treatment and discharge processes are sources of anthropogenic methane (CH_4) and nitrous oxide (N_2O) emissions. Wastewater from domestic and industrial sources is treated to remove soluble organic matter, suspended solids, nutrients, pathogenic organisms, and chemical contaminants.[5] Treatment of domestic wastewater may either occur on site, most commonly through septic systems, or off site at centralized treatment systems, most commonly at publicly owned treatment works (POTWs). In the United States, approximately 16 percent of domestic wastewater is treated in septic systems or other on-site systems, while the rest is collected and treated centrally (U.S. Census Bureau 2021a). Treatment of industrial wastewater may occur at the industrial plant using package or specially designed treatment plants or be collected and transferred off site for co-treatment with domestic wastewater in centralized treatment systems.

Centralized Treatment. Centralized wastewater treatment systems use sewer systems to collect and transport wastewater to the treatment plant. Sewer collection systems provide an environment conducive to the formation of CH_4, which can be substantial depending on the configuration and operation of the collection system (Guisasola et al. 2008). Recent research has shown that at least a portion of CH_4 formed within the collection system enters the centralized system where it contributes to CH_4 emissions from the treatment system (Foley et al. 2015).

The treatment plant may include a variety of processes, ranging from physical separation of material that readily settles out (typically referred to as primary treatment), to treatment operations that use biological processes to convert and remove contaminants (typically referred to as secondary treatment), to advanced treatment for removal of targeted pollutants, such as nutrients (typically referred to as tertiary treatment). Not all wastewater treatment plants conduct primary treatment prior to secondary treatment, and not all plants conduct advanced or tertiary treatment (EPA 2010).

Soluble organic matter is generally removed using biological processes in which microorganisms consume the organic matter for maintenance and growth. Microorganisms can biodegrade soluble organic material in wastewater under aerobic or anaerobic conditions, where the latter condition produces CH_4. The resulting biomass (sludge) is removed from the wastewater (effluent) prior to discharge to the receiving stream and may be further biodegraded under aerobic or anaerobic conditions, such as anaerobic sludge digestion. Sludge can be produced from both primary and secondary treatment operations. Some wastewater may also be treated using constructed (or semi-natural) wetland systems, though this is much less common in the United States and represents a relatively small portion of wastewater treated centrally (<0.1 percent) (ERG 2016). Constructed wetlands are a coupled anaerobic-aerobic system and may be used as the primary method of wastewater treatment, or are more commonly used as a final treatment step following settling and biological treatment. Constructed wetlands develop natural processes that involve vegetation, soil, and associated microbial assemblages to trap and treat incoming contaminants (IPCC 2014). Constructed wetlands do not produce secondary sludge (sewage sludge). Emissions from flooded lands or constructed waterbodies (not used for wastewater treatment) and lands converted to flooded lands (not used for wastewater treatment) are estimated and reported in Chapter 6, under Sections 6.8 Wetlands Remaining Wetlands and 6.9 Lands Converted to Wetlands.

The generation of N_2O may also result from the treatment of wastewater during both nitrification and denitrification of the nitrogen (N) present, usually in the form of urea, proteins, and ammonia in wastewater. Ammonia N is converted to nitrate (NO_3) through the aerobic process of nitrification. Denitrification occurs under anoxic/anaerobic conditions, whereby anaerobic or facultative organisms reduce oxidized forms of nitrogen (e.g.,

[5] Throughout the *Inventory*, emissions from domestic wastewater also include any commercial and industrial wastewater collected and co-treated with domestic wastewater.

nitrite, nitrate) in the absence of free oxygen to produce nitrogen gas (N_2). Nitrous oxide is generated as a by-product of nitrification, or as an intermediate product of denitrification. No matter where N_2O is formed it is typically stripped (i.e., transferred from the liquid stream to the air and ultimately emitted to the atmosphere) in aerated parts of the treatment process. Stripping also occurs in non-aerated zones at rates lower than in aerated zones.

On-site Treatment. The vast majority of on-site systems in the United States are septic systems composed of a septic tank, generally buried in the ground, and a soil dispersion system. Solids and dense materials contained in the incoming wastewater (influent) settle in the septic tank as sludge. Floatable material (scum) is also retained in the tank. The sludge that settles on the bottom of the tank undergoes anaerobic digestion. Partially treated water is discharged in the soil dispersal system. The solid fraction accumulates and remains in the tank for several years, during which time it degrades anaerobically. The gas produced from anaerobic sludge digestion (mainly CH_4 and biogenic CO_2) rises to the liquid surface and is typically released through vents. The gas produced in the effluent dispersal system (mainly N_2O and biogenic CO_2) is released through the soil.

Discharge. Dissolved CH_4 and N_2O that is present in wastewater discharges to aquatic environments has the potential to be released into the atmosphere (Short et al. 2014; Short et al. 2017). In addition, the presence of organic matter or nitrogen in wastewater discharges is generally expected to increase CH_4 and N_2O emissions from these aquatic environments. Where organic matter is released to slow-moving aquatic systems, such as lakes, estuaries, and reservoirs, CH_4 emissions are expected to be higher. Similarly, in the case of discharge to nutrient-impacted or hypoxic waters, N_2O emissions can be significantly higher.

In summary, the principal factor in determining the CH_4 generation potential of wastewater is the amount of degradable organic material in the wastewater. Common parameters used to measure the organic component of the wastewater are the biochemical oxygen demand (BOD) and chemical oxygen demand (COD). Under the same conditions, wastewater with higher COD (or BOD) concentrations will generally yield more CH_4 than wastewater with lower COD (or BOD) concentrations. BOD represents the amount of oxygen that would be required to completely consume the organic matter contained in the wastewater through aerobic decomposition processes, while COD measures the total material available for chemical oxidation (both biodegradable and non-biodegradable). The BOD value is most commonly expressed in milligrams of oxygen consumed per liter of sample during 5 days of incubation at 20°C, or BOD_5. Throughout the rest of this chapter, the term "BOD" refers to BOD_5. Because BOD is an aerobic parameter, it is preferable to use COD to estimate CH_4 production, since CH_4 is produced only in anaerobic conditions. Where present, biogas recovery and flaring operations reduce the amount of CH_4 generated that is actually emitted. Per IPCC guidelines (IPCC 2019), emissions from anaerobic sludge digestion, including biogas recovery and flaring operations, where the digester's primary use is for treatment of wastewater treatment solids, are estimated and reported under wastewater treatment. The principal factor in determining the N_2O generation potential of wastewater is the amount of N in the wastewater. The variability of N in the influent to the treatment system, as well as the operating conditions of the treatment system itself, also impact the N_2O generation potential. The methods and underlying data sources to estimate emissions from are described in further detail in the "Methodology and Time Series Consistency" section below for treatment of domestic and industrial wastewater.

Overall, treatment of wastewater emitted 42.7 MMT CO_2 Eq. in 2022. Total methane (CH_4) emissions from wastewater treatment and discharge were estimated to be 20.8 MMT CO_2 Eq. (743 kt CH_4). Methane (CH_4) emissions from domestic wastewater treatment and discharge were estimated to be 11.6 MMT CO_2 Eq. (413 kt CH_4) and 2.0 MMT CO_2 Eq. (72 kt CH_4), respectively, totaling 13.6 MMT CO_2 Eq. (485 kt CH_4) in 2022. Emissions remained fairly steady from 1990 through 2002 but have decreased since that time due to decreasing percentages of wastewater being treated in anaerobic systems, generally including reduced use of on-site septic systems and central anaerobic treatment systems (EPA 1992, 1996, 2000, and 2004; U.S. Census Bureau 2021a). In 2022, CH_4 emissions from industrial wastewater treatment and discharge were estimated to be 6.7 MMT CO_2 Eq. (239 kt CH_4) and 0.5 MMT CO_2 Eq. (19 kt CH_4), respectively, totaling 7.2 MMT CO_2 Eq. (258 kt CH_4). Industrial emissions from wastewater treatment have generally increased across the time series through 1999 and then fluctuated up and correspond with production changes from the pulp and paper manufacturing, meat and poultry processing, fruit

and vegetable processing, starch-based ethanol production, petroleum refining, and brewery industries. Industrial wastewater emissions have generally seen an uptick since 2016. Table 7-7 and Table 7-8 provide CH_4 emission estimates from domestic and industrial wastewater treatment.

Nitrous oxide (N_2O) emissions from wastewater treatment and discharge in 2022 totaled 21.9 MMT CO_2 Eq. (83 kt N_2O). In 2022, domestic treatment and discharge were estimated to be 17.0 MMT CO_2 Eq. (64 kt N_2O) and 4.4 MMT CO_2 Eq. (16 kt N_2O), respectively, totaling 21.4 MMT CO_2 Eq. (81 kt N_2O). Domestic emission sources have gradually increased across the time series because of an increasing U.S. population and protein consumption. In 2022, N_2O emissions from industrial wastewater treatment and discharge were estimated to be 0.4 MMT CO_2 Eq. (1.5 kt N_2O) and 0.1 MMT CO_2 Eq. (0.3 kt N_2O), respectively, totaling 0.5 MMT CO_2 Eq. (1.8 kt N_2O). Industrial emission sources have gradually increased across the time series with production changes associated with the treatment of wastewater namely from meat and poultry processing and petroleum refining, but also with contributions from pulp and paper manufacturing and brewery industries. Table 7-7 and Table 7-8 provide N_2O emission estimates from domestic wastewater treatment.

Table 7-7: CH_4 and N_2O Emissions from Domestic and Industrial Wastewater Treatment (MMT CO_2 Eq.)

Activity	1990	2005	2018	2019	2020	2021	2022
CH_4	**22.7**	**22.7**	**21.4**	**21.1**	**21.0**	**20.7**	**20.8**
Domestic Treatment	15.1	14.6	12.3	11.9	11.7	11.4	11.6
Domestic Effluent	1.4	1.4	2.0	2.0	2.1	2.1	2.0
Industrial Treatment[a]	5.5	6.1	6.5	6.6	6.6	6.7	6.7
Industrial Effluent[a]	0.7	0.6	0.6	0.5	0.5	0.5	0.5
N_2O	**14.8**	**18.1**	**21.2**	**21.6**	**22.3**	**22.1**	**21.9**
Domestic Treatment	10.5	13.7	16.2	16.6	17.2	17.1	17.0
Domestic Effluent	3.9	3.9	4.5	4.5	4.6	4.5	4.4
Industrial Treatment[b]	0.3	0.4	0.4	0.4	0.4	0.4	0.4
Industrial Effluent[b]	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Total	**37.5**	**40.7**	**42.5**	**42.7**	**43.2**	**42.7**	**42.7**

[a] Industrial activity for CH_4 includes the pulp and paper manufacturing, meat and poultry processing, fruit and vegetable processing, starch-based ethanol production, petroleum refining, and breweries industries.
[b] Industrial activity for N_2O includes the pulp and paper manufacturing, meat and poultry processing, starch-based ethanol production, and petroleum refining.
Note: Totals may not sum due to independent rounding.

Table 7-8: CH_4 and N_2O Emissions from Domestic and Industrial Wastewater Treatment (kt)

Activity	1990	2005	2018	2019	2020	2021	2022
CH_4	**811**	**809**	**763**	**755**	**748**	**738**	**743**
Domestic Treatment	539	521	438	426	419	407	413
Domestic Effluent	49	49	73	73	74	74	72
Industrial Treatment[a]	196	216	232	236	236	238	239
Industrial Effluent[a]	27	22	20	19	19	19	19
N_2O	**56**	**68**	**80**	**81**	**84**	**83**	**83**
Domestic Treatment	40	52	61	63	65	65	64
Domestic Effluent	15	15	17	17	17	17	16
Industrial Treatment[b]	1	1	2	2	1	1	1
Industrial Effluent[b]	+	+	+	+	+	+	+

[+] Does not exceed 0.5 kt.
[a] Industrial activity for CH_4 includes the pulp and paper manufacturing, meat and poultry processing, fruit and vegetable processing, starch-based ethanol production, petroleum refining, and breweries industries.
[b] Industrial activity for N_2O includes the pulp and paper manufacturing, meat and poultry processing, starch-based ethanol production, and petroleum refining.
Note: Totals by gas may not sum due to independent rounding

Methodology and Time-Series Consistency

The methodologies presented in IPCC (2019) form the basis of the CH_4 and N_2O emission estimates for both domestic and industrial wastewater treatment and discharge.[6] Domestic wastewater treatment follows the IPCC Tier 2 methodology for key pathways, while domestic wastewater discharge follows IPCC Tier 2 discharge methodology and emission factors in accordance with IPCC methodological decision trees based on available data for treatment and discharge. Default factors from IPCC (2019) or IPCC (2006) are used when there are insufficient U.S.-specific data to develop a U.S.-specific factor, though IPCC default factors are often based in part on data from or representative of U.S. wastewater treatment systems. Industrial wastewater treatment follows IPCC Tier 1 and wastewater treatment discharge follows Tier 1 or Tier 2 methodologies, again in accordance with methodological decision trees and available data, depending on the industry. EPA will continue to implement the Tier 2 discharge methodology for more industries as data are investigated and time and resource constraints allow (see the Planned Improvements section below). Similar to domestic wastewater, IPCC default factors are used when there are insufficient U.S.-specific data to develop a U.S.-specific factor.

Methodological approaches were applied to the entire time series to ensure consistency in emissions from 1990 through 2022. In the following cases, the source used to capture activity data changed over the time series. EPA transitioned to these newer data sources to continue estimating emissions in a way that ensured both accuracy and continuity. For example:

- Starch-based ethanol production data: the source used for 1990 to 2017 production was no longer available after 2017. A new, publicly available source was identified and is used for production in 2015-2022. However, this source does not have sufficient data for the earlier timeseries. EPA confirmed with experts familiar with the sources that combining these two sources to populate the time series was accurate (ERG 2019; Lewis 2019) and does not present any significant discontinuities in the time series.
- Brewery production data: the source used for production changed in 2007 to publish craft brewery production broken out by size but does not include data prior to 2007. Therefore, rather than estimating total production data prior to 2007 with this source, another data source was used to ensure accuracy of production data through the time series (ERG 2018b).

Refer to the Recalculations Discussion section below for details on updates implemented to improve accuracy, consistency and/or completeness of the time series.

Domestic Wastewater CH_4 Emission Estimates

Domestic wastewater CH_4 emissions originate from both septic systems and from centralized treatment systems. Within these centralized systems, CH_4 emissions can arise from aerobic systems that liberate dissolved CH_4 that formed within the collection system or that are designed to have periods of anaerobic activity (e.g., constructed wetlands and facultative lagoons), anaerobic systems (anaerobic lagoons and anaerobic reactors), and from anaerobic sludge digesters when the captured biogas is not completely combusted. Emissions will also result from the discharge of treated effluent from centralized wastewater plants to waterbodies where carbon accumulates in sediments (typically slow-moving systems, such as lakes, reservoirs, and estuaries). The systems with emissions estimates are:

[6] IPCC (2019) updates, supplements, and elaborates the *2006 IPCC Guidelines* where gaps or out-of-date science have been identified. EPA used these methodologies to improve completeness and include sources of greenhouse gas emissions that have not been estimated prior to the 1990 to 2019 *Inventory*, such as N_2O emissions from industrial wastewater treatment, and to improve emission estimates for other sources, such as emissions from wastewater discharge and centralized wastewater treatment.

- Septic systems (A);
- Centralized treatment aerobic systems (B), including aerobic systems (other than constructed wetlands) (B1), constructed wetlands only (B2), and constructed wetlands used as tertiary treatment (B3);
- Centralized anaerobic systems (C);
- Anaerobic sludge digesters (D); and
- Centralized wastewater treatment effluent (E).

Methodological equations for each of these systems are presented in the subsequent subsections; total domestic CH_4 emissions are estimated as follows:

Equation 7-4: Total Domestic CH_4 Emissions from Wastewater Treatment and Discharge

$$\text{Total Domestic } CH_4 \text{ Emissions from Wastewater Treatment and Discharge (kt)} = A + B + C + D + E$$

Table 7-9 presents domestic wastewater CH_4 emissions for both septic and centralized systems, including anaerobic sludge digesters and emissions from centralized wastewater treatment effluent, in 2022.

Table 7-9: Domestic Wastewater CH_4 Emissions from Septic and Centralized Systems (2022, kt, MMT CO_2 Eq. and Percent)

	CH_4 Emissions (kt)	CH_4 Emissions (MMT CO_2 Eq.)	% of Domestic Wastewater CH_4
Septic Systems (A)	215	6.0	44.4%
Centrally-Treated Aerobic Systems (B)	77	2.2	15.9%
Centrally-Treated Anaerobic Systems (C)	113	3.2	23.2%
Anaerobic Sludge Digesters (D)	8	0.2	1.7%
Centrally-Treated Wastewater Effluent (E)	72	2.0	14.9%
Total	**485**	**13.6**	**100%**

Notes: Totals may not sum due to independent rounding.

Emissions from Septic Systems:

Methane emissions from septic systems were estimated by multiplying the U.S. population by the percent of wastewater treated in septic systems (about 16 percent in 2022; U.S. Census Bureau 2021a) and an emission factor and then converting the result to kt/year. The method was selected in accordance with IPCC methodological decision trees in based on available data for septic systems.

U.S. population data were taken from historic U.S. Census Bureau national population totals data and include the populations of the United States and Puerto Rico (U.S. Census Bureau 2002; U.S. Census Bureau 2011; U.S. Census Bureau 2022 and 2023; Instituto de Estadísticas de Puerto Rico 2021). Population data for American Samoa, Guam, Northern Mariana Islands, and the U.S. Virgin Islands were taken from the U.S. Census Bureau International Database (U.S. Census Bureau 2023). Table 7-10 presents the total U.S. population for 1990 through 2022. The fraction of the U.S. population using septic systems or centralized treatment systems is based on data from the *American Housing Surveys* (U.S. Census Bureau 2021a).

Methane emissions for septic systems are estimated as follows:

Equation 7-5: CH_4 Emissions from Septic Systems

$$Emissions\ from\ Septic\ Systems\ (\mathrm{U.S.\ Specific}) = \mathrm{A}$$
$$= \mathrm{US}_{POP} \times (\mathrm{T}_{SEPTIC}) \times (\mathrm{EF}_{SEPTIC}) \times 1/10^9 \times 365.25$$

Table 7-10: Variables and Data Sources for CH_4 Emissions from Septic Systems

Variable	Variable Description	Units	Inventory Years: Source of Value
US_{POP}	U.S. population[a]	Persons	United States and Puerto Rico: 1990-1999: U.S. Census Bureau (2002); Instituto de Estadísticas de Puerto Rico (2021) 2000-2009: U.S. Census Bureau (2011) 2010-2019: U.S. Census Bureau (2021b) 2020-2022: U.S. Census Bureau (2022) U.S. Territories other than Puerto Rico: 1990-2022: U.S. Census Bureau (2023)
T_{SEPTIC}	Percent treated in septic systems[a]	%	Odd years from 1989 through 2021: U.S. Census Bureau (2021a) Data for intervening years obtained by linear interpolation 2022: Forecasted from the rest of the time series
EF_{SEPTIC}	Methane emission factor – septic systems (10.7)	g CH_4/capita/day	1990-2022: Leverenz et al. (2010)
$1/10^9$	Conversion factor	g to kt	Standard conversion
365.25	Conversion factor	Days in a year	Standard conversion

[a] Value of activity data varies over the *Inventory* time series.

Emissions from Centrally Treated Aerobic and Anaerobic Systems:

Methane emissions from POTWs depend on the total organics in wastewater. Table 7-12 presents the total organically degradable material in wastewater, or TOW, for 1990 through 2022. The TOW was determined using BOD generation rates per capita weighted average both with and without kitchen scraps as well as an estimated percent of housing units that utilize kitchen garbage disposals. Households with garbage disposals (with kitchen scraps or ground up food scraps) typically have wastewater with higher BOD than households without garbage disposals due to increased organic matter contributions (ERG 2018a). The equations are as follows:

Equation 7-6: Total Wastewater BOD5 Produced per Capita (U.S.-Specific [ERG 2018a])

$$\mathrm{BOD}_{\mathrm{gen\ rate}}\ (\mathrm{kg/capita/day}) = \mathrm{BOD}_{\mathrm{without\ scraps}} \times (1 - \%\mathrm{kitchen\ disposal}) + \mathrm{BOD}_{\mathrm{with\ scraps}} \times (\%\mathrm{kitchen\ disposal})$$

Equation 7-7: Total Organically Degradable Material in Domestic Wastewater (IPCC 2019 [Eq. 6.3])

$$\text{TOW}\left(\frac{\text{Gg BOD}}{\text{year}}\right) = \text{US}_{POP} \times \text{BOD}_{gen\ rate} \times 365.25 \times \frac{1}{10^6}$$

Table 7-11: Variables and Data Sources for Organics in Domestic Wastewater

Variable	Variable Description	Units	Inventory Years: Source of Value
$BOD_{gen\ rate}$	Total wastewater BOD produced per capita	kg/capita/day	1990-2022: Calculated
$BOD_{without\ scrap}$	Wastewater BOD produced per capita without kitchen scraps[a]	kg/capita/day	1990-2003: Metcalf & Eddy (2003) 2004-2013: Linear interpolation 2014-2022: Metcalf & Eddy (2014)
$BOD_{with\ scraps}$	Wastewater BOD produced per capita with kitchen scraps[a]	kg/capita/day	
% kitchen disposal	Percent of housing units with kitchen disposal[a]	%	1990-2013: U.S. Census Bureau (2013) 2014-2022: Forecasted from the rest of the time series
TOW	Total wastewater BOD Produced per Capita[a]	Gg BOD/year	1990-2022: Calculated, ERG (2018a)
US_{POP}	U.S. population[a]	Persons	United States and Puerto Rico: 1990-1999: U.S. Census Bureau (2002); Instituto de Estadísticas de Puerto Rico (2021) 2000-2009: U.S. Census Bureau (2011) 2010-2019: U.S. Census Bureau (2021b) 2020-2022: U.S. Census Bureau (2022) U.S. Territories other than Puerto Rico: 1990-2022: U.S. Census Bureau (2023)
365.25	Conversion factor	Days in a year	Standard conversion
$1/10^6$	Conversion factor	kg to Gg	Standard conversion

[a] Value of activity data varies over the *Inventory* time series.

Table 7-12: U.S. Population (Millions) and Domestic Wastewater TOW (kt)

Activity	1990	2005	2018	2019	2020	2021	2022
Population	253	300	330	332	335	336	337
TOW	8,131	9,624	9,958	10,019	10,132	10,163	10,216

Sources: U.S. Census Bureau (2002); U.S. Census Bureau (2011); U.S. Census Bureau (2021b and 2022); Instituto de Estadísticas de Puerto Rico (2021); U.S. Census Bureau (2023); ERG (2018a).

Methane emissions from POTWs were estimated by multiplying the total organics in centrally treated wastewater (total BOD_5) produced per capita in the United States by the percent of wastewater treated centrally, or percent collected (about 84 percent in 2022), the correction factor for additional industrial BOD discharged to the sewer system, the relative percentage of wastewater treated by aerobic systems (other than constructed wetlands),

constructed wetlands only, and anaerobic systems, and the emission factor[7] for aerobic systems, constructed wetlands only, and anaerobic systems. Methane emissions from constructed wetlands used as tertiary treatment were estimated by multiplying the flow from treatment to constructed wetlands, wastewater BOD concentration entering tertiary treatment, constructed wetlands emission factor, and then converting to kt/year.

In the United States, the removal of sludge[8] from wastewater reduces the biochemical oxygen demand of the wastewater that undergoes aerobic treatment. The amount of this reduction (S) is estimated using the default IPCC (2019) methodology and multiplying the amount of sludge removed from wastewater treatment in the United States by the default factors in IPCC (2019) to estimate the amount of BOD removed based on whether the treatment system has primary treatment with no anaerobic sludge digestion (assumed to be zero by expert judgment), primary treatment with anaerobic sludge digestion, or secondary treatment without primary treatment. The organic component removed from anaerobic wastewater treatment and the amount of CH_4 recovered or flared from both aerobic and anaerobic wastewater treatment were set equal to the IPCC default of zero.

The methodological equations for CH_4 emissions from aerobic and anaerobic systems are:

Equation 7-8: Total Domestic CH_4 Emissions from Centrally Treated Aerobic Systems

$$Emissions\ from\ Centrally\ Treated\ Aerobic\ Systems\ (other\ than\ Constructed\ Wetlands)(B1) + Emissions\ from\ Centrally\ Treated\ Aerobic\ Systems\ (Constructed\ Wetlands\ Only)(B2) + Emissions\ from\ Centrally\ Treated\ Aerobic\ Systems\ (Constructed\ Wetlands\ used\ as\ Tertiary\ Treatment)(B3) = B$$

where,

Equation 7-9: Total Organics in Centralized Wastewater Treatment [IPCC 2019 (Eq. 6.3A)]

$$TOW_{CENTRALIZED}\left(\frac{\text{Gg BOD}}{\text{year}}\right) = \text{TOW} \times \text{T}_{\text{CENTRALIZED}} \times \text{I}_{\text{COLLECTED}}$$

Table 7-13: Variables and Data Sources for Organics in Centralized Domestic Wastewater

Variable	Variable Description	Units	Inventory Years: Source of Value
Centrally Treated Organics (Gg BOD/year)			
$TOW_{CENTRALIZED}$	Total organics in centralized wastewater treatment[a]	Gg BOD/year	1990-2022: Calculated
TOW	Total wastewater BOD Produced per Capita[a]	Gg BOD/capita/year	1990-2022: Calculated, ERG (2018a)
$T_{CENTRALIZED}$	Percent collected[a]	%	1990-2019: U.S. Census Bureau (2021a) Data for intervening years obtained by linear interpolation 2020-2022: Forecasted from the rest of the time series
$I_{COLLECTED}$	Correction factor for additional industrial BOD discharged (1.25)	No units	1990-2022: IPCC (2019) Eq. 6.3a

[7] Emission factors are calculated by multiplying the maximum CH_4-producing capacity of domestic wastewater (B_0, 0.6 kg CH_4/kg BOD) and the appropriate methane correction factors (MCF) for aerobic (0.03) and anaerobic (0.8) systems (IPCC 2019, Table 6.3) and constructed wetlands (0.4) (IPCC 2014, Table 6.4).

[8] Throughout this document, the term "sludge" refers to the solids separated during the treatment of municipal wastewater. The definition includes domestic septage. "Biosolids" refers to treated sewage sludge that meets the EPA pollutant and pathogen requirements for land application and surface disposal.

[a] Value of this activity data varies over the time series.

Equation 7-10: Organic Component Removed from Aerobic Wastewater Treatment (IPCC 2019 [Eq. 6.3B])

$$S_{aerobic}\left(\frac{Gg}{year}\right) = S_{mass} \times \left[\left(\%\ \text{aerobic}\frac{w}{primary} \times K_{rem,aer_{prim}}\right) + \left(\%\ \text{aerobic}\frac{w}{out}\text{primary} \times K_{rem,aer_{noprim}}\right) + \left(\%\text{aerobic} + \text{digestion} \times K_{rem,aer_{digest}}\right)\right] \times 1000$$

Equation 7-11: CH_4 Emissions from Centrally Treated Aerobic Systems (other than Constructed Wetlands) (IPCC 2019 [Eq. 6.1])

$$B1(\text{kt } CH_4/\text{year}) = [(TOW_{CENTRALIZED}) \times (\%\ \text{aerobic}_{OTCW}) - S_{aerobic}] \times EF_{aerobic} - R_{aerobic}$$

Table 7-14: Variables and Data Sources for CH_4 Emissions from Centrally Treated Aerobic Systems (Other than Constructed Wetlands)

Variable	Variable Description	Units	Inventory Years: Source of Value
Emissions from Centrally Treated Aerobic Systems (Other than Constructed Wetlands) (kt CH_4/year)			
$S_{aerobic}$	Organic component removed from aerobic wastewater treatment[a]	Gg BOD/year	1990-2022: Calculated
S_{mass}	Raw sludge removed from wastewater treatment as dry mass[a]	Tg dry weight/year	1988: EPA (1993c); EPA (1999) 1990-1995: Calculated based on sewage sludge production change per year EPA (1993c); EPA (1999); Beecher et al. (2007) 1996: EPA (1999) 2004: Beecher et al. (2007) Data for intervening years obtained by linear interpolation 2005-2017: Interpolated 2018: NEBRA (2022), as described in ERG (2023) 2019-2022: Forecasted from the rest of the time series. Methodology for estimating sludge generated from the U.S. territories provided in ERG (2023).
% $aerobic_{OTCW}$	Percent of flow to aerobic systems, other than wetlands[a]	%	1990, 1991: Set equal to 1992 1992, 1996, 2000, 2004: EPA (1992, 1996, 2000, 2004), respectively Data for intervening years obtained by linear interpolation. 2005-2022: Forecasted from the rest of the time series
% aerobic w/primary	Percent of aerobic systems with primary treatment and no anaerobic sludge digestion (0)	%	
% aerobic w/out primary	Percent of aerobic systems without primary treatment[a]	%	
%aerobic+digestion	Percent of aerobic systems with primary and anaerobic sludge digestion[a]	%	
K_{rem,aer_prim}	Sludge removal factor for aerobic treatment plants with primary treatment (mixed primary and secondary sludge, untreated or treated aerobically) (0.8)	kg BOD/kg sludge	1990-2022: IPCC (2019) Table 6.6a
K_{rem,aer_noprim}	Sludge removal factor for aerobic wastewater treatment plants without separate primary treatment (1.16)	kg BOD/kg sludge	

Variable	Variable Description	Units	Inventory Years: Source of Value
K_{rem,aer_digest}	Sludge removal factor for aerobic treatment plants with primary treatment and anaerobic sludge digestion (mixed primary and secondary sludge, treated anaerobically) (1)	kg BOD/kg sludge	
$EF_{aerobic}$	Emission factor – aerobic systems (0.018)	kg CH_4/kg BOD	1990-2022: IPCC (2019) Table 6.3
$R_{aerobic}$	Amount CH_4 recovered or flared from aerobic wastewater treatment (0)	kg CH_4/year	1990-2022: IPCC (2019) Eq. 6.1
1000	Conversion factor	metric tons to kilograms	Standard conversion

[a] Value of this activity data varies over the time series.

Constructed wetlands provide aerobic treatment but also exhibit partially anaerobic conditions; however, they are referred to in this chapter as aerobic systems. Constructed wetlands may be used as the sole treatment unit at a centralized wastewater treatment plant or may serve as tertiary treatment after simple settling and biological treatment. Emissions from all constructed wetland systems were included in the estimates of emissions from centralized wastewater treatment plant processes and effluent from these plants. Methane emissions equations from constructed wetlands used as sole treatment were previously described. Methane emissions from constructed wetlands used as tertiary treatment were estimated by multiplying the flow from treatment to constructed wetlands, wastewater BOD concentration entering tertiary treatment, constructed wetlands emission factor, and then converting to kt/year.

For constructed wetlands, an IPCC default emission factor for surface flow wetlands was used. This is the most conservative factor for constructed wetlands and was recommended by IPCC (2014) when the type of constructed wetland is not known. A median BOD_5 concentration of 9.1 mg/L was used for wastewater entering constructed wetlands used as tertiary treatment based on U.S. secondary treatment standards for POTWs. This median value is based on plants generally utilizing simple settling and biological treatment (EPA 2013). Constructed wetlands do not have secondary sludge removal.

Equation 7-12: CH_4 Emissions from Centrally Treated Aerobic Systems (Constructed Wetlands Only) [IPCC 2014 (Eq. 6.1)]

$$\text{B2}\left(\frac{\text{kt CH}_4}{\text{year}}\right) = [(\text{TOW}_{\text{CENTRALIZED}}) \times (\%\ \text{aerobic}_{\text{CW}})] \times (EF_{\text{CW}})$$

Equation 7-13: CH_4 Emissions from Centrally Treated Aerobic Systems (Constructed Wetlands used as Tertiary Treatment) (U.S. Specific)

$$\text{B3}\left(\frac{\text{kt CH}_4}{\text{year}}\right) = \left[\left(\text{POTW}_{\text{flow}_{\text{CW}}}\right) \times \left(\text{BOD}_{\text{CW,INF}}\right) \times 3.785 \times (\text{EF}_{\text{CW}})\right] \times \frac{1}{10^6} \times 365.25$$

Table 7-15: Variables and Data Sources for CH_4 Emissions from Centrally Treated Aerobic Systems (Constructed Wetlands)

Variable	Variable Description	Units	Inventory Years: Source of Value
Emissions from Constructed Wetlands Only (kt CH_4/year)			
$TOW_{CENTRALIZED}$	Total organics in centralized wastewater treatment[a]	Gg BOD/year	1990-2022: Calculated
% $aerobic_{CW}$	Flow to aerobic systems, constructed wetlands used as sole treatment / total flow to POTWs.[a]	%	1990, 1991: Set equal to 1992 1992, 1996, 2000, 2004, 2008, 2012: EPA (1992, 1996, 2000, 2004, 2008, and 2012)

Variable	Variable Description	Units	Inventory Years: Source of Value
			Data for intervening years obtained by linear interpolation. 2013-2022: Forecasted from the rest of the time series
EF_{CW}	Emission factor for constructed wetlands (0.24)	kg CH_4/kg BOD	1990-2022: IPCC (2014)
Emissions from Constructed Wetlands used as Tertiary Treatment (kt CH_4/year)			
POTW_flow_CW	Wastewater flow to POTWs that use constructed wetlands as tertiary treatment[a]	MGD	1990, 1991: Set equal to 1992 1992, 1996, 2000, 2004, 2008, 2012: EPA (1992, 1996, 2000, 2004, 2008, and 2012) Data for intervening years obtained by linear interpolation. 2013-2022: Forecasted from the rest of the time series
$BOD_{CW,INF}$	BOD concentration in wastewater entering the constructed wetland (9.1)	mg/L	1990-2022: EPA (2013)
3.785	Conversion factor	liters to gallons	Standard conversion
EF_{CW}	Emission factor for constructed wetlands (0.24)	kg CH_4/kg BOD	1990-2022: IPCC (2014)
$1/10^6$	Conversion factor	kg to kt	Standard conversion
365.25	Conversion factor	Days in a year	Standard conversion

[a] Value of this activity data varies over the time series.

Data sources and methodologies for centrally treated anaerobic systems are similar to those described for aerobic systems, other than constructed wetlands. See discussion above.

Equation 7-14: CH_4 Emissions from Centrally Treated Anaerobic Systems (IPCC 2019 (Eq. 6.1])

$$C\left(\frac{\text{kt CH}_4}{\text{year}}\right) = [(\text{TOW}_{\text{CENTRALIZED}}) \times (\%\ \text{anaerobic}) - S_{\text{anaerobic}}] \times EF_{\text{anaerobic}} - R_{\text{anaerobic}}$$

Table 7-16: Variables and Data Sources for CH_4 Emissions from Centrally Treated Anaerobic Systems

Variable	Variable Description	Units	Inventory Years: Source of Value
Emissions from Centrally Treated Anaerobic Systems (kt CH_4/year)			
$TOW_{CENTRALIZED}$	Total organics in centralized wastewater treatment[a]	Gg BOD/year	1990-2022: Calculated
% anaerobic	Percent centralized wastewater that is anaerobically treated[a]	%	1990, 1991: Set equal to 1992 1992, 1996, 2000, 2004: EPA (1992, 1996, 2000, 2004), respectively Data for intervening years obtained by linear interpolation. 2005-2022: Forecasted from the rest of the time series
$S_{anaerobic}$	Organic component removed from anaerobic wastewater treatment (0)	Gg/year	1990-2022: IPCC (2019) Table 6.3
$EF_{anaerobic}$	Emission factor for anaerobic reactors/deep lagoons (0.48)	kg CH_4/kg BOD	

Variable	Variable Description	Units	Inventory Years: Source of Value
$R_{anaerobic}$	Amount CH_4 recovered or flared from anaerobic wastewater treatment (0)	kg CH_4/year	

[a] Value of this activity data varies over the time series.

Emissions from Anaerobic Sludge Digesters:

Total CH_4 emissions from anaerobic sludge digesters were estimated by multiplying the wastewater influent flow to POTWs with anaerobic sludge digesters, the cubic feet of digester gas generated per person per day divided by the flow to POTWs, the fraction of CH_4 in biogas, the density of CH_4, one minus the destruction efficiency from burning the biogas in an energy/thermal device and then converting the results to kt/year.

Equation 7-15: CH_4 Emissions from Anaerobic Sludge Digesters (U.S. Specific)

$$\mathrm{D}\left(\frac{\mathrm{kt\ CH_4}}{\mathrm{year}}\right) = \left[\left(\mathrm{POTW_{flow_{AD}}}\right) \times \frac{\mathrm{biogas\ gen}}{100}\right] \times\ 0.0283\ \times\ \left(\mathrm{FRAC_{CH_4}}\right) \times\ 365.25\ \times\ (662) \times\ (1 - \mathrm{DE}) \times \frac{1}{10^9}$$

Table 7-17: Variables and Data Sources for Emissions from Anaerobic Sludge Digesters

Variable	Variable Description	Units	Inventory years: Source of Value
Emissions from Anaerobic Sludge Digesters (kt CH_4/year)			
POTW_flow_AD	POTW Flow to Facilities with Anaerobic Sludge Digesters[a]	MGD	1990, 1991: Set equal to 1992 1992, 1996, 2000, 2004: EPA (1992, 1996, 2000, and 2004), respectively Data for intervening years obtained by linear interpolation. 2005-2022: Forecasted from the rest of the time series
biogas gen	Gas Generation Rate (1.0)	ft^3/capita/day	1990-2022: Metcalf & Eddy (2014)
100	Per Capita POTW Flow (100)	gal/capita/day	1990-2022: Ten-State Standards (2004)
0.0283	Conversion factor	ft^3 to m^3	Standard Conversion
$FRAC_{CH_4}$	Proportion of Methane in Biogas (0.65)	No units	1990-2022: Metcalf & Eddy (2014)
365.25	Conversion factor	Days in a year	Standard conversion
662	Density of Methane (662)	g CH_4/m^3 CH_4	1990-2022: EPA (1993a)
DE	Destruction Efficiency (99% converted to fraction)	No units	1990-2022: EPA (1998); CAR (2011); Sullivan (2007); Sullivan (2010); and UNFCCC (2012)
$1/10^9$	Conversion factor	g to kt	Standard conversion

[a] Value of this activity data varies over the time series.

Emissions from Discharge of Centralized Treatment Effluent:

Methane emissions from the discharge of wastewater treatment effluent were estimated by multiplying the total BOD of the discharged wastewater effluent by an emission factor associated with the location of the discharge. The BOD in treated effluent was determined by multiplying the total organics in centrally treated wastewater by the percent of wastewater treated in primary, secondary, and tertiary treatment, and the fraction of organics remaining after primary treatment (one minus the fraction of organics removed from primary treatment, secondary treatment, and tertiary treatment).

Equation 7-16: CH_4 Emissions from Centrally Treated Systems Discharge (U.S.-Specific)

$$\mathrm{E}\left(\frac{\mathrm{kt\ CH_4}}{\mathrm{year}}\right) = \left(\mathrm{TOW_{RLE}} \times \mathrm{EF_{RLE}}\right) + \left(\mathrm{TOW_{Other}} \times \mathrm{EF_{Other}}\right)$$

where,

Equation 7-17: Total Organics in Centralized Treatment Effluent (IPCC 2019 [Eq. 6.3D])

$$\mathrm{TOW_{EFFtreat,CENTRALIZED}}\left(\frac{\mathrm{Gg\ BOD}}{\mathrm{year}}\right) = \left[\mathrm{TOW_{CENTRALIZED}} \times \%\ \mathrm{primary} \times \left(1 - \mathrm{TOW_{rem,PRIMARY}}\right)\right] + \left[\mathrm{TOW_{CENTRALIZED}} \times \%\ \mathrm{secondary} \times \left(1 - \mathrm{TOW_{rem,SECONDARY}}\right)\right] + \left[\mathrm{TOW_{CENTRALIZED}} \times \%\ \mathrm{tertiary} \times \left(1 - \mathrm{TOW_{rem,TERTIARY}}\right)\right]$$

Equation 7-18: Total Organics in Effluent Discharged to Reservoirs, Lakes, or Estuaries (U.S.-Specific)

$$\mathrm{TOW_{RLE}}\left(\frac{\mathrm{Gg\ BOD}}{\mathrm{year}}\right) = \mathrm{TOW_{EFFtreat,CENTRALIZED}} \times \mathrm{Percent_{RLE}}$$

Equation 7-19: Total Organics in Effluent Discharged to Other Waterbodies (U.S.-Specific)

$$\mathrm{TOW_{Other}}\left(\frac{\mathrm{Gg\ BOD}}{\mathrm{year}}\right) = \mathrm{TOW_{EFFtreat,CENTRALIZED}} \times \mathrm{Percent_{Other}}$$

Table 7-18: Variables and Data Sources for CH_4 Emissions from Centrally Treated Systems Discharge

Variable	Variable Description	Units	Source of Value
$\mathrm{TOW_{EFFtreat,CENTRALIZED}}$	Total organics in centralized treatment effluent[a]	Gg BOD/year	1990-2022: Calculated
$\mathrm{TOW_{CENTRALIZED}}$	Total organics in centralized wastewater treatment[a]	Gg BOD/year	1990-2022: Calculated
% primary	Percent of primary domestic centralized treatment[a]	%	1990, 1991: Set equal to 1992. 1992, 1996, 2000, 2004, 2008, 2012: EPA (1992, 1996, 2000, 2004, 2008, and 2012), respectively Data for intervening years obtained by linear interpolation. 2013-2022: Forecasted from the rest of the time series
% secondary	Percent of secondary domestic centralized treatment[a]	%	
% tertiary	Percent of tertiary domestic centralized treatment[a]	%	
$\mathrm{TOW_{rem,PRIMARY}}$	Fraction of organics removed from primary domestic centralized treatment (0.4)	No units	1990-2022: IPCC (2019) Table 6.6B
$\mathrm{TOW_{rem,SECONDARY}}$	Fraction of organics removed from secondary domestic centralized treatment (0.85)	No units	
$\mathrm{TOW_{rem,TERTIARY}}$	Fraction of organics removed from tertiary domestic centralized treatment (0.90)	No units	
$\mathrm{TOW_{RLE}}$	Total organics in effluent discharged to reservoirs, lakes, and estuaries[a]	Gg BOD/year	1990-2022: Calculated

Variable	Variable Description	Units	Source of Value
TOW_{Other}	Total organics in effluent discharge to other waterbodies[a]	Gg BOD/year	
EF_{RLE}	Emission factor (discharge to reservoirs/lakes/estuaries) (0.114)	kg CH_4/kg BOD	1990-2022: IPCC (2019) Table 6.8
EF_{Other}	Emission factor (discharge to other waterbodies) (0.021)	kg CH_4/kg BOD	
$Percent_{RLE}$	% discharged to reservoirs, lakes, and estuaries[a]	%	1990-2010: Set equal to 2010 2010: ERG (2021a) 2011: Obtained by linear interpolation 2012: ERG (2021a) 2013-2022: Set equal to 2012
$Percent_{Other}$	% discharged to other waterbodies[a]	%	

[a] Value of this activity data varies over the time series.

Industrial Wastewater CH_4 Emission Estimates

Industrial wastewater CH_4 emissions originate from on-site treatment systems, typically comprised of biological treatment operations. The collection systems at an industrial plant are not as extensive as domestic wastewater sewer systems; therefore, it is not expected that dissolved CH_4 will form during collection. However, some treatment systems are designed to have anaerobic activity (e.g., anaerobic reactors or lagoons), or may periodically have anaerobic conditions form (facultative lagoons or large stabilization basins). Emissions will also result from discharge of treated effluent to waterbodies where carbon accumulates in sediments (typically slow-moving systems, such as lakes, reservoirs, and estuaries).

Industry categories that are likely to produce significant CH_4 emissions from wastewater treatment were identified and included in the *Inventory*. The main criteria used to identify U.S. industries likely to generate CH_4 from wastewater treatment are whether an industry generates high volumes of wastewater, whether there is a high organic wastewater load, and whether the wastewater is treated using methods that result in CH_4 emissions. The top six industries that meet these criteria are pulp and paper manufacturing; meat and poultry processing; vegetables, fruits, and juices processing; starch-based ethanol production; petroleum refining; and breweries. Wastewater treatment and discharge emissions for these sectors for 2022 are displayed in Table 7-19 below. Further discussion of wastewater treatment for each industry is included below.

Table 7-19: Total Industrial Wastewater CH_4 Emissions by Sector (2022, MMT CO_2 Eq. and Percent)

Industry	CH_4 Emissions (MMT CO_2 Eq.)	% of Industrial Wastewater CH_4
Meat & Poultry	5.7	79.0%
Pulp & Paper	0.8	11.6%
Fruit & Vegetables	0.2	3.3%
Ethanol Refineries	0.2	2.3%
Breweries	0.1	2.0%
Petroleum Refineries	0.1	1.7%
Total	**7.2**	**100%**

Note: Totals may not sum due to independent rounding.

Emissions from Industrial Wastewater Treatment Systems:

Equation 7-20 presents the general IPCC equation (Equation 6.4, IPCC 2019) to estimate CH_4 emissions from each type of treatment system used for each industrial category.

Equation 7-20: Total CH_4 Emissions from Industrial Wastewater

$$\mathrm{CH_4\ (industrial\ sector)} = [(\mathrm{TOW}_i - \mathrm{S}_i) \times \mathrm{EF} - \mathrm{R}_i]$$

where,

CH_4 (industrial sector)	=	Total CH_4 emissions from industrial sector wastewater treatment (kg/year)
I	=	Industrial sector
TOW_i	=	Total organics in wastewater for industrial sector *i* (kg COD/year)
S_i	=	Organic component removed from aerobic wastewater treatment for industrial sector *i* (kg COD/year)
EF	=	System-specific emission factor (kg CH_4/kg COD)
R_i	=	Methane recovered for industrial sector *i* (kg CH_4/year)

Equation 7-21 presents the general IPCC equation to estimate the total organics in wastewater (TOW) for each industrial category.

Equation 7-21: TOW in Industry Wastewater Treatment Systems

$$\mathrm{TOW}_i = \mathrm{P}_i \times \mathrm{W}_i \times \mathrm{COD}_i$$

where,

TOW_i	=	Total organically degradable material in wastewater for industry *i* (kg COD/yr)
i	=	Industrial sector
P_i	=	Total industrial product for industrial sector *i* (t/yr)
W_i	=	Wastewater outflow (m^3/t product)
COD_i	=	Chemical oxygen demand (industrial degradable organic component in wastewater) (kg COD/m^3)

The annual industry production is shown in Table 7-20, and the average wastewater outflow and the organics loading in the outflow is shown in Table 7-21.

For some industries, U.S.-specific data on organics loading is reported as BOD rather than COD. In those cases, an industry-specific COD:BOD ratio is used to convert the organics loading to COD.

The amount of organics treated in each type of wastewater treatment system was determined using the percent of wastewater in the industry that is treated on site and whether the treatment system is anaerobic, aerobic or partially anaerobic. Table 7-22 presents the industrial wastewater treatment activity data used in the calculations and described in detail in ERG (2008a), ERG (2013a), ERG (2013b), and ERG (2021a). For CH_4 emissions, wastewater treated in anaerobic lagoons or reactors was categorized as "anaerobic", wastewater treated in aerated stabilization basins or facultative lagoons were classified as "ASB" (meaning there may be pockets of anaerobic activity), and wastewater treated in aerobic systems such as activated sludge systems were classified as "aerobic/other."

The amount of organic component removed from aerobic wastewater treatment as a result of sludge removal ($S_{aerobic}$) was either estimated as an industry-specific percent removal, if available, or as an estimate of sludge produced by the treatment system and IPCC default factors for the amount of organic component removed (K_{rem}), using one of the following equations. Table 7-23 presents the sludge variables used for industries with aerobic wastewater treatment operations (i.e., pulp and paper, fruit/vegetable processing, and petroleum refining).

Equation 7-22: Organic Component Removed from Aerobic Wastewater Treatment – Pulp, Paper, and Paperboard

$$S_{pulp,asb} = TOW_{pulp} \times \%\ \text{removal w/primary}$$

where,

$S_{pulp,asb}$ = Organic component removed from pulp and paper wastewater during primary treatment before treatment in aerated stabilization basins (Gg COD/yr)
TOW_{pulp} = Total organically degradable material in pulp and paper wastewater (Gg COD/yr)
% removal w/primary = Percent reduction of organics in pulp and paper wastewater associated with sludge removal from primary treatment (%)

Equation 7-23: Organic Component Removed from Aerobic Treatment Plants

$$S_{aerobic} = S_{mass} \times K_{rem} \times 10^{-6}$$

where,

$S_{aerobic}$ = Organic component removed from fruit and vegetable or petroleum refining wastewater during primary treatment before treatment in aerated stabilization basins (Gg COD/yr)
S_{mass} = Raw sludge removed from wastewater treatment as dry mass (kg sludge/yr)
K_{rem} = Sludge factor (kg BOD/kg sludge)
10^{-6} = Conversion factor, kilograms to Gigagrams

Equation 7-24: Raw Sludge Removed from Wastewater Treatment as Dry Mass

$$S_{mass} = (S_{prim} + S_{aer}) \times P \times W$$

where,

S_{mass} = Raw sludge removed from wastewater treatment as dry mass (kg sludge/yr)
S_{prim} = Sludge production from primary sedimentation (kg sludge/m^3)
S_{aer} = Sludge production from secondary aerobic treatment (kg sludge/m^3)
P = Production (t/yr)
W = Wastewater outflow (m^3/t)

Default emission factors[9] from IPCC (2019) were used. Information on methane recovery operations varied by industry. See industry descriptions below.

[9] Emission factors are calculated by multiplying the maximum CH_4-producing capacity of wastewater (B_0, 0.25 kg CH_4/kg COD) and the appropriate methane correction factors (MCF) for aerobic (0), partially anaerobic (0.2), and anaerobic (0.8) systems (IPCC 2019), Table 6.3.

Table 7-20: U.S. Pulp and Paper, Meat, Poultry, Vegetables, Fruits and Juices, Ethanol, Breweries, and Petroleum Refining Production (MMT)

Activity	1990	2005	2018	2019	2020	2021	2022
Pulp and Paper[a]	83.6	92.4	78.7	76.3	74.7	75.5	73.9
Meat (Live Weight Killed)	27.3	31.4	36.4	37.4	37.8	38.1	37.9
Poultry (Live Weight Killed)	14.6	25.1	29.4	30.1	30.5	30.5	31.1
Vegetables, Fruits and Juices	40.8	45.3	42.3	41.8	40.6	39.2	38.4
Ethanol Production	2.5	11.7	48.1	47.1	41.6	44.8	48.3
Breweries	23.9	23.1	21.5	21.1	21.1	21.2	21.6
Petroleum Refining	702.4	818.6	951.7	940	806.5	858.3	892.1

[a] Pulp and paper production is the sum of market pulp production plus paper and paperboard production.

Sources: Pulp and Paper – FAO (2023a) and FAO (2023b); Meat, Poultry, and Fruits and Vegetables – USDA (2023a,2023b, 2023c, 2023d, 2022a, and 2022b), ERG (2023); Ethanol – Cooper (2018) and RFA (2023a and 2023b); Breweries – Beer Institute (2011) and TTB (2022); Petroleum Refining – EIA (2023).

Table 7-21: U.S. Industrial Wastewater Characteristics Data (2022)

Industry	Wastewater Outflow (m^3/ton)	Wastewater BOD (g/L)	Wastewater COD (kg/m^3)	COD:BOD Ratio
Pulp and Paper	See Table 7-25	0.3	--	2.5
Meat Processing	5.3	2.8	--	3
Poultry Processing	12.5	1.5	--	3
Fruit/Vegetable Processing	See Table 7-26		--	1.5
Ethanol Production – Wet Mill	10[a]	1.5	--	2
Ethanol Production – Dry Mill	1.25[a]	3[b]	--	2
Petroleum Refining	0.8	--	0.45	2.5
Breweries – Craft	3.21	--	17.6	1.67
Breweries – NonCraft	1.69	--	17.6	1.67

[a] Units are gallons per gallons ethanol produced.

[b] Units are COD (g/L).

Sources: Pulp and Paper (BOD, COD:BOD) – Malmberg (2018); Meat and Poultry (Outflow, BOD) – ERG (2006a); Meat and Poultry (COD:BOD) – EPA (1997a); Fruit/Vegetables (Outflow, BOD) – CAST (1995), EPA (1974), EPA (1975); Fruit/Vegetables (COD:BOD) – EPA (1997a); Ethanol Production – Wet Mill (Outflow) – Donovan (1996), NRBP (2001), Ruocco (2006b); Ethanol Production – Wet Mill (BOD) – White and Johnson (2003); Ethanol Production – Dry Mill (Outflow and COD) – Merrick (1998), Ruocco (2006a); Ethanol Production (Dry and Wet, COD:BOD) – EPA (1997a); Petroleum Refining (Outflow) – ERG (2013b); Petroleum Refining (COD) – Benyahia et al. (2006); Petroleum Refining (COD:BOD) – EPA (1982); Breweries – Craft BIER (2021); ERG (2018b); Breweries – NonCraft ERG (2018b); Brewers Association (2016a); Breweries (Craft and NonCraft; COD and COD:BOD) – Brewers Association (2016b).

Table 7-22: U.S. Industrial Wastewater Treatment Activity Data

Industry	% Wastewater Treated On-Site	% Treated Anaerobically	% Treated Aerobically	% Treated Aerobically	
				% Treated in ASBs	% Treated in Other Aerobic
Pulp and Paper[b]	60	5.2	75.9	38.5	37.4
Meat Processing	33	33[a]	33	0	33
Poultry Processing	25	25[a]	25	0	25
Fruit/Vegetable Processing	11	0	11	5.5	5.5
Ethanol Production – Wet Mill	33.3	33.3	66.7	0	0
Ethanol Production – Dry Mill	75	75	25	0	0
Petroleum Refining	62.1	0	62.1	23.6	38.5
Breweries – Craft	0.5	0.5	0	0	0
Breweries – NonCraft	100	99	1	0	1

[a] Wastewater is pretreated in anaerobic lagoons prior to aerobic treatment.

[b] Remaining onsite treated in other treatment assumed to be non-emissive and not shown here.

Note: Due to differences in data availability and methodology, zero values in the table are for calculation purposes only and may indicate unavailable data.

Sources: ERG (2008a, 2008b); ERG (2013a); ERG (2013b); ERG (2021a).

Table 7-23: Sludge Variables for Aerobic Treatment Systems

Variable	Industry		
	Pulp and Paper	Fruit/Vegetable Processing	Petroleum Refining
Organic reduction associated with sludge removal (%)	58		
Sludge Production (kg/m^3)			
Primary Sedimentation		0.15	
Aerobic Treatment		0.096	0.096
Sludge Factor (kg BOD/kg dry mass sludge)			
Aerobic Treatment w/Primary Sedimentation and No Anaerobic Sludge Digestion		0.8	
Aerobic Treatment w/out Primary Sedimentation			1.16

Sources: Organic reduction (pulp) – ERG (2008a); Sludge production – Metcalf & Eddy (2003); Sludge factors – IPCC (2019), Table 6.6a.

Emissions from Discharge of Industrial Wastewater Treatment Effluent:

Methane emissions from discharge of industrial wastewater treatment effluent are estimated via a Tier 1 method for all industries except for pulp, paper, and paperboard in accordance with IPCC methodological decision trees in based on available data for treatment and discharge. Emissions from discharge of pulp, paper, and paperboard treatment effluent is estimated via a Tier 2 method and is described in the industry-specific data section. Tier 1 emissions from effluent are estimated by multiplying the total organic content of the discharged wastewater effluent by an emission factor associated with the discharge:

Equation 7-25: CH_4 Emissions from Industrial Wastewater Treatment Discharge

$$\mathrm{CH_4\ Effluent_{IND}} = \mathrm{TOW_{EFFLUENT,IND}} \times \mathrm{EF_{EFFLUENT}}$$

where,

$CH_4\ Effluent_{IND}$ = CH_4 emissions from industrial wastewater discharge for inventory year (kg CH_4/year)

$TOW_{EFFLUENT,IND}$ = Total organically degradable material in wastewater effluent from industry for inventory year (kg COD/year or kg BOD/year)

$EF_{EFFLUENT}$ = Tier 1 emission factor for wastewater discharged to aquatic environments (0.028 kg CH_4/kg COD or 0.068 kg CH_4/kg BOD) (IPCC 2019)

The COD or BOD in industrial treated effluent ($TOW_{EFFLUENT,IND}$) was determined by multiplying the total organics in the industry's untreated wastewater that is treated on site by an industry-specific percent removal where available or a more general percent removal based on biological treatment for other industries. Table 7-22 presents the percent of wastewater treated onsite, while Table 7-24 presents the fraction of TOW removed during treatment.

Equation 7-26: TOW in Industrial Wastewater Effluent

$$\mathrm{TOW_{EFFLUENT,IND}} = \mathrm{TOW_{IND}} \times \%\,\mathrm{onsite} \times (1 - \mathrm{TOW_{REM}})$$

where,

$TOW_{EFFLUENT,IND}$ = Total organically degradable material in wastewater effluent from industry for inventory year (kg COD/year or kg BOD/year)

TOW_{IND} = Total organics in untreated wastewater for industry for inventory year (kg COD/year)

%onsite = Percent of industry wastewater treated on site (%)

TOW_{REM} = Fraction of organics removed during treatment

Table 7-24: Fraction of TOW Removed During Treatment by Industry

Industry	TOW_{REM}	Source
Pulp, Paper, and Paperboard	0.91	Malmberg (2018)
Red Meat and Poultry	0.85	IPCC (2019), Table 6.6b
Fruits and Vegetables	0.85	IPCC (2019), Table 6.6b
Ethanol Production		
Biomethanator Treatment	0.90	ERG (2008a), ERG (2006b)
Other Treatment	0.85	IPCC (2019), Table 6.6b
Petroleum Refining	0.93	Kenari, Sarrafzadeh, and Tavakoli (2010)
Breweries	0.85	IPCC (2019), Table 6.6b

Discussion of Industry-Specific Data:

Pulp, Paper, and Paperboard Manufacturing Wastewater Treatment. Wastewater treatment for the pulp, paper, and paperboard manufacturing (hereinafter referred to as "pulp and paper") industry typically includes neutralization, screening, sedimentation, and flotation/hydrocycloning to remove solids (World Bank 1999; Nemerow and Dasgupta 1991). Secondary treatment (storage, settling, and biological treatment) mainly consists of lagooning. About 60 percent of pulp and paper mills have on-site treatment with primary treatment and about half of these also have secondary treatment (ERG 2008). In the United States, primary treatment is focused on solids removal, equalization, neutralization, and color reduction (EPA 1993b). The vast majority of pulp and paper mills with on-site treatment systems use mechanical clarifiers to remove suspended solids from the wastewater. About 10 percent of pulp and paper mills with treatment systems use settling ponds for primary treatment and these are more likely to be located at mills that do not perform secondary treatment (EPA 1993b).

Approximately 42 percent of the BOD passes on to secondary treatment, which consists of activated sludge, aerated stabilization basins, or non-aerated stabilization basins. Pulp and paper mill wastewater treated using anaerobic ponds or lagoons or unaerated ponds were classified as anaerobic (with an MCF of 0.8). Wastewater flow treated in systems with aerated stabilization basins or facultative lagoons was classified as partially anaerobic (with an MCF of 0.2, which is the *2006 IPCC Guidelines*-suggested MCF for shallow lagoons). Wastewater flow treated in systems with activated sludge systems or similarly aerated biological systems was classified as aerobic.

A time series of CH_4 emissions for 1990 through 2022 was developed based on paper and paperboard production data and market pulp production data. Market pulp production values were available directly for 1998, 2000

through 2003, and 2010 through 2021. Where market pulp data were unavailable, a percent of woodpulp that is market pulp was applied to woodpulp production values from FAOSTAT to estimate market pulp production (FAO 2023a). The percent of woodpulp that is market pulp for 1990 to 1997 was assumed to be the same as 1998, 1999 was interpolated between values for 1998 and 2000, 2000 through 2009 were interpolated between values for 2003 and 2010, and 2022 was forecasted from the rest of the time series. A time series of the overall wastewater outflow in units of cubic meters of wastewater per ton of total production (i.e., market pulp plus woodpulp) is presented in Table 7-25. Data for 1990 through 1994 varies based on data outlined in ERG (2013a) to reflect historical wastewater flow. Wastewater generation rates for 1995, 2000, and 2002 were estimated from the 2014 *American Forest and Paper Association* (AF&PA) *Sustainability Report* (AF&PA 2014). Wastewater generation rates for 2004, 2006, 2008, 2010, 2012, and 2014 were estimated from the 2016 AF&PA Sustainability Report (AF&PA 2016). Data for 2005 and 2016 were obtained from the 2018 AF&PA Sustainability Report (AF&PA 2018), data for 2018 were obtained from the 2020 AF&PA Sustainability Report (AF&PA 2020), and data for 2020 were obtained from a 2022 AF&PA sustainability update (AF&PA 2022). Data for intervening years were obtained by linear interpolation, while 2021-2022 were set equal to 2020. The average BOD concentration in raw wastewater was estimated to be 0.4 grams BOD/liter for 1990 to 1998, while 0.3 grams BOD/liter was estimated for 2014 through 2022 (EPA 1997b; EPA 1993b; World Bank 1999; Malmberg 2018). Data for intervening years were obtained by linear interpolation.

Table 7-25: Wastewater Outflow (m^3/ton) for Pulp, Paper, and Paperboard Mills

Wastewater Outflow (m^3/ton)	1990	2005	2018	2019	2020	2021	2022
Pulp and Paper	68	43	40	39	39	39	39

Sources: ERG (2013a), AF&PA (2014), AF&PA (2016), AF&PA (2018), AF&PA (2020); AF&PA (2022)

Pulp, Paper, and Paperboard Wastewater Treatment Effluent. Methane emissions from pulp, paper, and paperboard wastewater treatment effluent were estimated by multiplying the total BOD of the discharged wastewater effluent by an emission factor associated with the location of the discharge.

Equation 7-27: CH_4 Emissions from Pulp and Paper Discharge (U.S. Specific)

$$Emissions\ from\ Pulp\ and\ Paper\ Discharge\ \left(\text{U. S. Specific}, \frac{\text{kt CH}_4}{\text{year}}\right)$$
$$= (\text{TOW}_{\text{RLE,pulp}} \times \text{EF}_{\text{RLE}}) + (\text{TOW}_{\text{Other,pulp}} \times \text{EF}_{\text{Other}})$$

Equation 7-28: Total Organics in Pulp and Paper Effluent Discharged to Reservoirs, Lakes, Or Estuaries (U.S. Specific)

$$\text{TOW}_{\text{RLE,pulp}}\ (\frac{\text{Gg BOD}}{\text{year}}) = \text{TOW}_{\text{EFFLUENT,IND}} \times \text{Percent}_{\text{RLE,pulp}}$$

Equation 7-29: Total Organics in Pulp and Paper Effluent Discharged to Other Waterbodies (U.S. Specific)

$$\text{TOW}_{\text{Other,pulp}}\ (\frac{\text{Gg BOD}}{\text{year}}) = \text{TOW}_{\text{EFFLUENT,IND}} \times \text{Percent}_{\text{Other,pulp}}$$

where,

$TOW_{RLE,pulp}$	=	Total organics in pulp, paper, and paperboard manufacturing wastewater treatment effluent discharged to reservoirs, lakes, or estuaries (Gg BOD/year)
EF_{RLE}	=	Emission factor (discharge to reservoirs/lakes/estuaries) (0.114 kg CH_4/kg BOD) (IPCC 2019)
$TOW_{Other,pulp}$	=	Total organics in pulp, paper, and paperboard manufacturing wastewater treatment effluent discharged to other waterbodies (Gg BOD/year)
EF_{Other}	=	Emission factor (discharge to other waterbodies) (0.021 kg CH_4/kg BOD) (IPCC 2019)

$TOW_{EFFLUENT,IND}$ = Total organically degradable material in pulp, paper, and paperboard manufacturing wastewater effluent for inventory year (Gg BOD/year)

$Percent_{RLE,pulp}$ = Percent of wastewater effluent discharged to reservoirs, lakes, and estuaries (ERG 2021b)

$Percent_{Other,pulp}$ = Percent of wastewater effluent discharged to other waterbodies (ERG 2021b)

The percent of pulp, paper, and paperboard wastewater treatment effluent routed to reservoirs, lakes, or estuaries (3 percent) and other waterbodies (97 percent) were obtained from discussions with NCASI (ERG 2021b). Data for 2019 were assumed the same as the rest of the time series due to lack of available data. Default emission factors for reservoirs, lakes, and estuaries (0.114 kg CH_4/kg BOD) and other waterbodies (0.021 kg CH_4/kg BOD) were obtained from IPCC (2019).

Meat and Poultry Processing. The meat and poultry processing industry makes extensive use of anaerobic lagoons in sequence with screening, fat traps, and dissolved air flotation when treating wastewater on site. Although all meat and poultry processing facilities conduct some sort of treatment on site, about 33 percent of meat processing operations (EPA 2002) and 25 percent of poultry processing operations (U.S. Poultry 2006) perform on-site treatment in anaerobic lagoons. The IPCC default emission factor of 0.2 kg CH_4/kg COD for anaerobic lagoons were used to estimate the CH_4 produced from these on-site treatment systems.

Vegetables, Fruits, and Juices Processing. Treatment of wastewater from fruits, vegetables, and juices processing includes screening, coagulation/settling, and biological treatment (lagooning). The flows are frequently seasonal, and robust treatment systems are preferred for on-site treatment. About half of the operations that treat and discharge wastewater use lagoons intended for aerobic operation, but the large seasonal loadings may develop limited anaerobic zones. In addition, some anaerobic lagoons may also be used (Nemerow and Dasgupta 1991). Wastewater treated in partially anaerobic systems were assigned the IPCC default emission factor of 0.12 kg CH_4/kg BOD. Outflow and BOD data, presented in Table 7-26, were obtained from CAST (1995) for apples, apricots, asparagus, broccoli, carrots, cauliflower, cucumbers (for pickles), green peas, pineapples, snap beans, and spinach; EPA (1974) for potato and citrus fruit processing; and EPA (1975) for all other commodities.

Table 7-26: Wastewater Outflow (m^3/ton) and BOD Production (g/L) for U.S. Vegetables, Fruits, and Juices Production

Commodity	Wastewater Outflow (m^3/ton)	Organic Content in Untreated Wastewater (g BOD/L)
Vegetables		
Potatoes	10.27	1.765
Other Vegetables	9.85	0.751
Fruit		
Apples	9.08	8.16
Citrus Fruits	10.11	0.317
Non-citrus Fruits	12.59	1.226
Grapes (for wine)	2.78	1.831

Sources: CAST (1995); EPA (1974); EPA (1975).

Ethanol Production. Ethanol, or ethyl alcohol, is produced primarily for use as a fuel component, but is also used in industrial applications and in the manufacture of beverage alcohol. Ethanol can be produced from the fermentation of sugar-based feedstocks (e.g., molasses and beets), starch- or grain-based feedstocks (e.g., corn, sorghum, and beverage waste), and cellulosic biomass feedstocks (e.g., agricultural wastes, wood, and bagasse). Ethanol can also be produced synthetically from ethylene or hydrogen and carbon monoxide. However, synthetic ethanol comprises a very small percent of ethanol production in the United States. Currently, ethanol is mostly made from sugar and starch crops, but with advances in technology, cellulosic biomass is increasingly used as ethanol feedstock (DOE 2013).

Ethanol is produced from corn (or other sugar or starch-based feedstocks) primarily by two methods: wet milling and dry milling. Historically, the majority of ethanol was produced by the wet milling process, but now the majority is produced by the dry milling process. The dry milling process is cheaper to implement and is more efficient in terms of actual ethanol production (Rendleman and Shapouri 2007). The wastewater generated at ethanol production facilities is handled in a variety of ways. Dry milling facilities often combine the resulting evaporator condensate with other process wastewaters, such as equipment wash water, scrubber water, and boiler blowdown and anaerobically treat this wastewater using various types of digesters. Wet milling facilities often treat their steepwater condensate in anaerobic systems followed by aerobic polishing systems. Wet milling facilities may treat the stillage (or processed stillage) from the ethanol fermentation/distillation process separately or together with steepwater and/or wash water. Methane generated in anaerobic sludge digesters is commonly collected and either flared or used as fuel in the ethanol production process (ERG 2006b).

About 33 percent of wet milling facilities and 75 percent of dry milling facilities treat their wastewater anaerobically (ERG 2006b). A default emission factor of 0.2 kg CH_4/kg COD for anaerobic treatment was used to estimate the CH_4 produced from these on-site treatment systems. The amount of CH_4 recovered through the use of biomethanators was estimated, and a 99 percent destruction efficiency was used. Biomethanators are anaerobic reactors that use microorganisms under anaerobic conditions to reduce COD and organic acids and recover biogas from wastewater (ERG 2006b). For facilities using biomethanators, approximately 90 percent of BOD is removed during on-site treatment (ERG 2006b, 2008a). For all other facilities, the removal of organics was assumed to be equivalent to secondary treatment systems, or 85 percent (IPCC 2019).

Petroleum Refining. Petroleum refining wastewater treatment operations have the potential to produce CH_4 emissions from anaerobic wastewater treatment. EPA's Office of Air and Radiation performed an Information Collection Request (ICR) for petroleum refineries in 2011.[10] Facilities that reported using non-aerated surface impoundments or other biological treatment units (trickling filter, rotating biological contactor), which have the potential to lead to anaerobic conditions, were assigned the IPCC default emission factor of 0.05 kg CH_4/kg COD. In addition, the wastewater generation rate was determined to be 26.4 gallons per barrel of finished product, or 0.8 m^3/ton (ERG 2013b).

Breweries. Since 2010, the number of breweries has increased from less than 2,000 to more than 8,000 (Brewers Association 2021). This increase has primarily been driven by craft breweries, which have increased by over 250 percent during that period. Craft breweries were defined as breweries producing less than six million barrels of beer per year, and non-craft breweries produce greater than six million barrels. With their large amount of water use and high strength wastewater, breweries generate considerable CH_4 emissions from anaerobic wastewater treatment. However, because many breweries recover their CH_4, their emissions are much lower.

The Alcohol and Tobacco Tax and Trade Bureau (TTB) provides total beer production in barrels per year for different facility size categories from 2007 to 2021 (TTB 2022). Because data were unavailable for 2022, EPA extrapolated from 1990 to 2021 values. For years prior to 2007 where TTB data were not readily available, the Brewers Almanac (Beer Institute 2011) was used, along with an estimated percent of craft and non-craft breweries based on the breakdown of craft and non-craft for the years 2007 through 2020.

To determine the overall amount of wastewater produced, data on water use per unit of production and a wastewater-to-water ratio were used from the Benchmarking Report (Brewers Association 2016a) for both craft and non-craft breweries. Since brewing is a batch process, and different operations have varying organic loads, full-strength brewery wastewater can vary widely on a day-to-day basis. However, the organic content of brewery wastewater does not substantially change between craft and non-craft breweries. Some breweries may collect and discharge high strength wastewater from particular brewing processes (known as "side streaming") to a POTW,

[10] Available online at https://www.epa.gov/stationary-sources-air-pollution/comprehensive-data-collected-petroleum-refining-sector.

greatly reducing the organics content of the wastewater that is treated on site. Subsequently, the MCF for discharge to a POTW was assumed to be zero (ERG 2018b).

Breweries may treat some or all of their wastewater on site prior to discharge to a POTW or receiving water. On-site treatment operations can include physical treatment (e.g., screening, settling) which are not expected to contribute to CH_4 emissions, or biological treatment, which may include aerobic treatment or pretreatment in anaerobic reactors (ERG 2018b). The IPCC default emission factor of 0.2 kg CH_4/kg COD for anaerobic treatment and 0 for aerobic treatment were used to estimate the CH_4 produced from these on-site treatment systems (IPCC 2006). The amount of CH_4 recovered through anaerobic wastewater treatment was estimated, and a 99 percent destruction efficiency was used (ERG 2018b; Stier J. 2018). Very limited activity data are available on the number of U.S. breweries that are performing side streaming or pretreatment of wastewater prior to discharge.

Domestic Wastewater N_2O Emission Estimates

Domestic wastewater N_2O emissions originate from both septic systems and POTWs. Within these centralized systems, N_2O emissions can result from aerobic systems, including systems like constructed wetlands. Emissions will also result from discharge of centrally treated wastewater to waterbodies with nutrient-impacted/eutrophic conditions. The systems with emission estimates are:

- Septic systems (A);
- Centralized treatment aerobic systems (B), including aerobic systems (other than constructed wetlands) (B1), constructed wetlands only (B2), and constructed wetlands used as tertiary treatment (B3);
- Centralized anaerobic systems (C); and
- Centralized wastewater treatment effluent (D).

Methodological equations for each of these systems are presented in the subsequent subsections; total domestic N_2O emissions are estimated as follows:

Equation 7-30: Total Domestic N_2O Emissions from Wastewater Treatment and Discharge

$$\text{Total Domestic } N_2O \text{ Emissions from Wastewater Treatment and Discharge } (\text{kt}) = \text{A} + \text{B} + \text{C} + \text{D}$$

Table 7-27 presents domestic wastewater N_2O emissions for both septic and centralized systems, including emissions from centralized wastewater treatment effluent, in 2022.

Table 7-27: Domestic Wastewater N_2O Emissions from Septic and Centralized Systems (2022, kt, MMT CO_2 Eq. and Percent)

	N_2O Emissions (kt)	N_2O Emissions (MMT CO_2 Eq.)	% of Domestic Wastewater N_2O
Septic Systems	3	0.8	3.6%
Centrally-Treated Aerobic Systems	61	16.3	76.0%
Centrally-Treated Anaerobic Systems	+	+	+
Centrally-Treated Wastewater Effluent	16	4.4	20.4%
Total	**81**	**21.4**	**100%**

+ Does not exceed 0.5 kt, 0.05 MMT CO_2 Eq., or 0.5 percent.
Note: Totals may not sum due to independent rounding.

Emissions from Septic Systems:

Nitrous oxide emissions from domestic treatment depend on the nitrogen present, in this case, in the form of protein. Per capita protein consumption (kg protein/person/year) was determined by multiplying per capita annual food availability data and its protein content. Those data are then adjusted using a factor to account for the fraction of protein actually consumed. The methodological equations are:

Equation 7-31: Annual per Capita Protein Supply (U.S. Specific)

$$\text{Protein}_{\text{SUPPLY}}\ (\text{kg/person/year}) = \text{Protein}_{\text{per capita}}/1000 \times 365.25$$

Equation 7-32: Consumed Protein (IPCC 2019 [Eq. 6.10A])

$$\text{Protein}\ (\text{kg/person/year}) = \text{Protein}_{\text{SUPPLY}} \times \text{FPC}$$

Table 7-28: Variables and Data Sources for Protein Consumed

Variable	Variable Description	Units	Inventory Years: Source of Value
Protein			
$\text{Protein}_{\text{SUPPLY}}$	Annual per capita protein supply[a]	kg/person/year	1990-2022: Calculated
$\text{Protein}_{\text{per capita}}$	Daily per capita protein supply[a]	g/person/day	1990-2022: USDA (2015)
1000	Conversion factor	g to kg	Standard conversion
365.25	Conversion factor	Days in a year	Standard conversion
FPC	Fraction of Protein Consumed[a]	kg protein consumed / kg protein available	1990-2010: USDA (2015) 2011-2020: FAO (2022) and scaling factor 2021-2022: Forecasted from the rest of the time series

[a] Value of this activity data varies over the *Inventory* time series.

Nitrous oxide emissions from septic systems were estimated by multiplying the U.S. population by the percent of wastewater treated in septic systems (about 16 percent in 2022; U.S. Census Bureau 2019), consumed protein per capita (kg protein/person/year), the fraction of N in protein, the correction factor for additional nitrogen from household products, the factor for industrial and commercial co-discharged protein into septic systems, the factor for non-consumed protein added to wastewater and an emission factor and then converting the result to kt/year. The method selected is in accordance with IPCC methodological decision trees and available data. All factors were obtained from IPCC (2019).

U.S. population data were taken from historic U.S. Census Bureau national population totals data and include the populations of the United States and Puerto Rico (U.S. Census Bureau 2002; U.S. Census Bureau 2011; U.S. Census Bureau 2021b and 2022, Instituto de Estadísticas de Puerto Rico 2021). Population data for American Samoa, Guam, Northern Mariana Islands, and the U.S. Virgin Islands were taken from the U.S. Census Bureau International Database (U.S. Census Bureau 2023). Table 7-12 presents the total U.S. population for 1990 through 2022. The fraction of the U.S. population using septic systems, as well as centralized treatment systems (see below), is based on data from *American Housing Survey* (U.S. Census Bureau 2021a). The methodological equations are:

Equation 7-33: Total Nitrogen Entering Septic Systems (IPCC 2019 [Eq. 6.10])

$$\text{TN}_{\text{DOM}_{\text{SEPTIC}}}\left(\frac{\text{kg N}}{\text{year}}\right)$$

$$= (\text{US}_{\text{POP}} \times \text{T}_{\text{SEPTIC}}) \times \text{Protein} \times \text{F}_{\text{NPR}} \times \text{N}_{\text{HH}} \times \text{F}_{\text{NON-CON_septic}} \times \text{F}_{\text{IND-COM_septic}}$$

Equation 7-34: N_2O Emissions from Septic Systems (IPCC 2019 [Eq. 6.9])

$$A\left(\frac{\text{kt } N_2O}{\text{year}}\right) = TN_{DOM_SEPTIC} \times (EF_{SEPTIC}) \times 44/28 \times 1/10^6$$

Table 7-29: Variables and Data Sources for N_2O Emissions from Septic System

Variable	Variable Description	Units	Inventory Years: Source of Value
Emissions from Septic Systems			
TN_{DOM_SEPTIC}	Total nitrogen entering septic systems	kg N/year	1990-2022: Calculated
US_{POP}	U.S. population[a]	Persons	United States and Puerto Rico: 1990-1999: U.S. Census Bureau 2002; Instituto de Estadísticas de Puerto Rico 2021 2000-2009: U.S. Census Bureau 2011 2010-2019: U.S. Census Bureau (2021b) 2020-2022: U.S. Census Bureau (2022) U.S. Territories other than Puerto Rico: 1990-2022: U.S. Census Bureau (2023)
T_{SEPTIC}	Percent treated in septic systems[a]	%	Odd years from 1989 through 2021: U.S. Census Bureau (2021a) Data for intervening years obtained by linear interpolation 2022: Forecasted from the rest of the time series
F_{NPR}	Fraction of nitrogen in protein (0.16)	kg N/kg protein	1990-2022: IPCC (2019) Eq. 6.10
N_{HH}	Additional nitrogen from household products (1.17)	No units	1990-2022: IPCC (2019) Table 6.10a
$F_{NON\text{-}CON_septic}$	Factor for Non-Consumed Protein Added to Wastewater (1.13)	No units	
$F_{IND\text{-}COM_septic}$	Factor for Industrial and Commercial Co-Discharged Protein, septic systems (1)	No units	1990-2022: IPCC (2019)
EF_{SEPTIC}	Emission factor, septic systems (0.0045)	kg N_2O-N/kg N	1990-2022: IPCC (2019) Table 6.8a
44/28	Conversion factor	Molecular weight ratio of N_2O to N_2	Standard conversion
$1/10^6$	Conversion factor	kg to kt	Standard conversion

[a] Value of this activity data varies over the *Inventory* time series.

Emissions from Centrally Treated Aerobic and Anaerobic Systems:

Nitrous oxide emissions from POTWs depend on the total nitrogen entering centralized wastewater treatment. The total nitrogen entering centralized wastewater treatment was estimated by multiplying the U.S. population by the percent of wastewater collected for centralized treatment (about 84 percent in 2022), the consumed protein per capita, the fraction of N in protein, the correction factor for additional N from household products, the factor for industrial and commercial co-discharged protein into wastewater treatment, and the factor for non-consumed protein added to wastewater.

Equation 7-35: Total Nitrogen Entering Centralized Systems (IPCC 2019 [Eq. 10])

$$\mathrm{TN_{DOM_{CENTRAL}}}\left(\frac{\text{kg N}}{\text{year}}\right) = (\mathrm{US_{POP}} \times \mathrm{T_{CENTRALIZED}}) \times \text{Protein} \times \mathrm{F_{NPR}} \times \mathrm{N_{HH}} \times \mathrm{F_{NON-CON}} \times \mathrm{F_{IND-COM}}$$

Table 7-30: Variables and Data Sources for Non-Consumed Protein and Nitrogen Entering Centralized Systems

Variable	Variable Description	Units	Inventory Years: Source of Value
US_{POP}	U.S. population[a]	Persons	United States and Puerto Rico: 1990-1999: U.S. Census Bureau (2002); Instituto de Estadísticas de Puerto Rico (2021) 2000-2009: U.S. Census Bureau 2011 2010-2019: U.S. Census Bureau (2021b) 2020-2022: U.S. Census Bureau (2022) U.S. Territories other than Puerto Rico: 1990-2022: U.S. Census Bureau (2023)
$T_{CENTRALIZED}$	Percent collected[a]	%	Odd years from 1989 through 2021: U.S. Census Bureau (2021a) Data for intervening years obtained by linear interpolation 2022: Forecasted from the rest of the time series
Protein	Consumed protein per capita[a]	kg/person/year	1990-2022: Calculated
F_{NPR}	Fraction of nitrogen in protein (0.16)	kg N/kg protein	1990-2022: IPCC (2019), Eq. 6.10
N_{HH}	Factor for additional nitrogen from household products (1.17)	No units	1990-2022: IPCC (2019), Table 6.10a
$F_{NON-CON}$	Factor for U.S. specific non-consumed protein (1.13)	No units	

Variable	Variable Description	Units	Inventory Years: Source of Value
$F_{IND\text{-}COM}$	Factor for Industrial and Commercial Co-Discharged Protein (1.25)	No units	1990-2022: IPCC (2019) Table 6.11

[a] Value of this activity data varies over the *Inventory* time series.

Nitrous oxide emissions from POTWs were estimated by multiplying the total nitrogen entering centralized wastewater treatment, the relative percentage of wastewater treated by aerobic systems (other than constructed wetlands) and anaerobic systems, aerobic systems with constructed wetlands as the sole treatment, the respective emission factors for aerobic systems and anaerobic systems, and the conversion from N_2 to N_2O.

Table 7-34 presents the data for U.S. population, population served by centralized wastewater treatment plants, available protein, and protein consumed. The methodological equations are:

Equation 7-36: Total Domestic N_2O Emissions from Centrally Treated Aerobic Systems

$$Emissions\ from\ Centrally\ Treated\ Aerobic\ Systems\ (other\ than\ Constructed\ Wetlands)(B1) + Emissions\ from\ Centrally\ Treated\ Aerobic\ Systems\ (Constructed\ Wetlands\ Only)(B2) + Emissions\ from\ Centrally\ Treated\ Aerobic\ Systems\ (Constructed\ Wetlands\ used\ as\ Tertiary\ Treatment)$$

$$(B3)\ =\ B\ (kt\ N_2O/year)$$

where,

Equation 7-37: N_2O Emissions from Centrally Treated Aerobic Systems (other than Constructed Wetlands) (IPCC 2019 [Eq. 6.9])

$$\mathrm{B1\ (kt\ N_2O/year)} = [(\mathrm{TN_{DOM_CENTRAL}}) \times (\%\ \mathrm{aerobic_{OTCW}})] \times \mathrm{EF_{aerobic}} \times 44/28 \times 1/10^6$$

Table 7-31: Variables and Data Sources for N_2O Emissions from Centrally Treated Aerobic Systems (Other than Constructed Wetlands)

Variable	Variable Description	Units	Inventory Years: Source of Value
Emissions from Centrally Treated Aerobic Systems (Other than Constructed Wetlands) (kt N_2O/year)			
$TN_{DOM_CENTRAL}$	Total nitrogen entering centralized systems[a]	kg N/year	1990-2022: Calculated
% $aerobic_{OTCW}$	Flow to aerobic systems, other than constructed wetlands only / total flow to POTWs[a]	%	1990, 1991: Set equal to 1992 1992, 1996, 2000, 2004: EPA (1992, 1996, 2000, 2004), respectively Data for intervening years obtained by linear interpolation. 2005-2022: Forecasted from the rest of the time series
$EF_{aerobic}$	U.S.-specific emission factor – aerobic systems (0.015)	kg N_2O-N/kg N	1990-2022: IPCC (2022)
44/28	Conversion factor	Molecular weight ratio of N_2O to N_2	Standard conversion
$1/10^6$	Conversion factor	kg to kt	Standard conversion

[a] Value of this activity data varies over the *Inventory* time series.

Nitrous oxide emissions from constructed wetlands used as sole treatment include similar data and processes as aerobic systems other than constructed wetlands. See description above. Nitrous oxide emissions from

constructed wetlands used as tertiary treatment were estimated by multiplying the flow to constructed wetlands used as tertiary treatment, wastewater N concentration entering tertiary treatment, constructed wetlands emission factor, and converting to kt/year.

Equation 7-38: N_2O Emissions from Centrally Treated Aerobic Systems (Constructed Wetlands Only) (IPCC 2014 [Eq. 6.9])

$$B2\ \left(\frac{\text{kt } N_2O}{\text{year}}\right) = [(TN_{DOM_CENTRAL}) \times (\%\ \text{aerobic}_{CW})] \times EF_{CW} \times 44/28 \times 1/10^6$$

Equation 7-39: N_2O Emissions from Centrally Treated Aerobic Systems (Constructed Wetlands used as Tertiary Treatment) (U.S.-Specific)

$$B3\ \left(\frac{\text{kt } N_2O}{\text{year}}\right) = [(POTW_flow_CW) \times (N_{CW,INF}) \times 3.785 \times (EF_{CW})] \times 1/10^6 \times 365.25$$

Table 7-32: Variables and Data Sources for N_2O Emissions from Centrally Treated Aerobic Systems (Constructed Wetlands)

Variable	Variable Description	Units	Inventory Years: Source of Value
Emissions from Constructed Wetlands Only (kt N_2O/year)			
$TN_{DOM_CENTRAL}$	Total nitrogen entering centralized treatment[a]	kg N/year	1990-2022: Calculated
% $aerobic_{CW}$	Flow to aerobic systems, constructed wetlands used as sole treatment / total flow to POTWs[a]	%	1990, 1991: Set equal to 1992 1992, 1996, 2000, 2004, 2008, 2012: EPA (1992, 1996, 2000, 2004, 2008, and 2012) Data for intervening years obtained by linear interpolation. 2013-2022: Forecasted from the rest of the time series
EF_{CW}	Emission factor for constructed wetlands (0.0013)	kg N_2O-N/kg N	1990-2022: IPCC (2014) Table 6.7
44/28	Conversion factor	Molecular weight ratio of N_2O to N_2	Standard conversion
$1/10^6$	Conversion factor	kg to kt	Standard conversion
Emissions from Constructed Wetlands used as Tertiary Treatment (kt N_2O/year)			
POTW_flow_CW	Wastewater flow to POTWs that use constructed wetlands as tertiary treatment [a]	MGD	1990, 1991: Set equal to 1992 1992, 1996, 2000, 2004, 2008, 2012: EPA (1992, 1996, 2000, 2004, 2008, and 2012) Data for intervening years obtained by linear interpolation. 2013-2022: Forecasted from the rest of the time series

Variable	Variable Description	Units	Inventory Years: Source of Value
$N_{CW,INF}$	BOD concentration in wastewater entering the constructed wetland (25)	mg/L	1990-2022: Metcalf & Eddy (2014)
3.785	Conversion factor	liters to gallons	Standard conversion
EF_{CW}	Emission factor for constructed wetlands (0.0013)	kg N_2O-N/kg N	1990-2022: IPCC (2014) Table 6.7
$1/10^6$	Conversion factor	mg to kg	Standard conversion
365.25	Conversion factor	Days in a year	Standard conversion

[a] Value of this activity data varies over the *Inventory* time series.

Data sources and methodologies are similar to those described for aerobic systems, other than constructed wetlands. See discussion above.

Equation 7-40: N_2O Emissions from Centrally Treated Anaerobic Systems (IPCC 2019 [Eq. 6.9])

$$C\left(\frac{\text{kt } N_2O}{\text{year}}\right) = [(TN_{DOM_CENTRAL}) \times (\%\text{ anaerobic})] \times EF_{anaerobic} \times 44/28 \times 1/10^6$$

Table 7-33: Variables and Data Sources for N_2O Emissions from Centrally Treated Anaerobic Systems

Variable	Variable Description	Units	Inventory Years: Source of Value
Emissions from Centrally Treated Anaerobic Systems			
$TN_{DOM_CENTRAL}$	Total nitrogen entering centralized treatment[a]	kg N/year	1990-2022: Calculated
% anaerobic	Percent centralized wastewater that is anaerobically treated[a]	%	1990, 1991: Set equal to 1992 1992, 1996, 2000, 2004: (EPA 1992, 1996, 2000, 2004), respectively Data for intervening years obtained by linear interpolation. 2005-2022: Forecasted from the rest of the time series
$EF_{anaerobic}$	Emission factor for anaerobic reactors/deep lagoons (0)	kg N_2O-N/kg N	1990-2022: IPCC (2019) Table 6.8A
44/28	Conversion factor	Molecular weight ratio of N_2O to N_2	Standard conversion
$1/10^6$	Conversion factor	mg to kg	Standard conversion

[a] Value of this activity data varies over the *Inventory* time series.

Table 7-34: U.S. Population (Millions) Fraction of Population Served by Centralized Wastewater Treatment (percent), Protein Supply (kg/person-year), and Protein Consumed (kg/person-year)

Year	1990	2005	2018	2019	2020	2021	2022
Population	253	300	330	332	335	336	337
Centralized WWT Population (%)	75.6	78.8	82.9	83.6	84.2	84.8	83.6
Protein Supply	43.1	44.9	45.5	46	46.9	46.3	46.3
Protein Consumed	33.2	34.7	35.1	35.5	36.2	35.7	35.7

Sources: Population – U.S. Census Bureau 2002; U.S. Census Bureau 2011; U.S. Census Bureau (2021b); Instituto de Estadísticas de Puerto Rico (2021); U.S. Census Bureau (2022); U.S. Census Bureau (2023); WWTP Population – U.S. Census Bureau (2021a); Available Protein – USDA (2015), FAO (2022); Protein Consumed – FAO (2022).

Emissions from Discharge of Centralized Treatment Effluent:

Nitrous oxide emissions from the discharge of wastewater treatment effluent were estimated by multiplying the total nitrogen in centrally treated wastewater effluent by the percent of wastewater treated in primary, secondary, and tertiary treatment and the fraction of nitrogen remaining after primary, secondary, or tertiary treatment and then multiplying by the percent of wastewater volume routed to waterbodies with nutrient-impaired/eutrophic conditions and all other waterbodies (ERG 2021a) and emission factors for discharge to impaired waterbodies and other waterbodies from IPCC (2019). The methodological equations are:

Equation 7-41: N_2O Emissions from Centrally Treated Systems Discharge (U.S.-Specific)

$$D\left(\frac{\text{kt } N_2O}{\text{year}}\right) = [(N_{EFFLUENT,IMP} \times EF_{IMP}) + (N_{EFFLUENT,NONIMP} \times EF_{NONIMP})] \times 44/28 \times 1/10^6$$

where,

Equation 7-42: Total Organics in Centralized Treatment Effluent (IPCC 2019 [Eq. 6.8])

$$N_{EFFLUENT,DOM}\left(\frac{\text{kg N}}{\text{year}}\right)$$

$$= [TN_{DOM_CENTRAL}[11] \times \%\ \text{primary} \times (1 - N_{rem,PRIMARY})] + [TN_{DOM_CENTRAL} \times \%\ \text{secondary} \times (1 - N_{rem,SECONDARY})] + [TN_{DOM_CENTRAL} \times \%\ \text{tertiary} \times (1 - N_{rem,TERTIARY})]$$

Equation 7-43: Total Nitrogen in Effluent Discharged to Impaired Waterbodies (U.S.-Specific)

$$N_{EFFLUENT,IMP}\ (\text{kg N/year}) = (N_{EFFLUENT,DOM} \times \text{Percent}_{IMP})/1000$$

Equation 7-44: Total Nitrogen in Effluent Discharged to Nonimpaired Waterbodies (U.S.-Specific)

$$N_{EFFLUENT,NONIMP}\ (\text{kg N year}) = N_{EFFLUENT,DOM} \times \text{Percent}_{NONIMP})/1000$$

Table 7-35: Variables and Data Sources for N_2O Emissions from Centrally Treated Systems Discharge

Variable	Variable Description	Units	Source of Value
$N_{EFFLUENT,DOM}$	Total organics in centralized treatment effluent[a]	kg N/year	1990-2022: Calculated
44/28	Conversion factor	Molecular weight ratio of N_2O to N_2	Standard conversion
$1/10^6$	Conversion factor	kg to kt	Standard conversion
$TN_{DOM_CENTRAL}$	Total nitrogen entering centralized treatment[a]	kg N/year	1990-2022: Calculated
1000	Conversion factor	kg to kt	Standard Conversion
% primary	Percent of primary domestic centralized treatment[a]	%	1990,1991: Set equal to 1992. 1992, 1996, 2000, 2004, 2008, 2012: EPA (1992, 1996, 2000, 2004, 2008, and 2012), respectively
% secondary	Percent of secondary domestic centralized treatment[a]	%	
% tertiary	Percent of tertiary domestic centralized treatment[a]	%	

[11] See emissions from centrally treated aerobic and anaerobic systems for methodological equation calculating $TN_{DOM_CENTRAL}$.

Variable	Variable Description	Units	Source of Value
			Data for intervening years obtained by linear interpolation. 2013-2022: Forecasted from the rest of the time series
$N_{rem,PRIMARY}$	Fraction of nitrogen removed from primary domestic centralized treatment (0.1)	No units	1990-2022: IPCC (2019) Table 6.10c
$N_{rem,SECONDARY}$	Fraction of nitrogen removed from secondary domestic centralized treatment (0.4)	No units	
$N_{rem,TERTIARY}$	Fraction of nitrogen removed from tertiary domestic centralized treatment (0.9)	No units	
$N_{EFFLUENT,IMP}$	Total nitrogen in effluent discharged to impaired waterbodies	kg N/year	1990-2022: Calculated
$N_{EFFLUENT,NONIMP}$	Total nitrogen in effluent discharged to nonimpaired waterbodies	kg N/year	
EF_{IMP}	Emission factor (discharge to impaired waterbodies) (0.19)	kg N_2O-N/kg N	1990-2022: IPCC (2019) Table 6.8a
$EF_{NONIMPr}$	Emissions factor (discharge to nonimpaired waterbodies) (0.005)	kg N_2O-N/kg N	
$Percent_{IMP}$	Percent of wastewater discharged to impaired waterbodies[a]	%	1990-2010: Set equal to 2010 2010: ERG (2021a) 2011: Obtained by linear interpolation 2012: ERG (2021a) 2013-2022: Set equal to 2012
$Percent_{NONIMP}$	Percent of wastewater discharged to nonimpaired waterbodies[a]	%	

[a] Value for this activity data varies over the *Inventory* time series.

Industrial Wastewater N_2O Emission Estimates

Nitrous oxide emission estimates from industrial wastewater are estimated according to the methodology described in the *2019 Refinement*. U.S. industry categories that are likely to produce significant N_2O emissions from wastewater treatment were identified based on whether they generate high volumes of wastewater, whether there is a high nitrogen wastewater load, and whether the wastewater is treated using methods that result in N_2O emissions. The top four industries that meet these criteria and were added to the *Inventory* are meat and poultry processing; petroleum refining; pulp and paper manufacturing; and breweries (ERG 2021a). Wastewater treatment and discharge emissions for these sectors for 2022 are displayed in Table 7-36 below. Table 7-20 contains production data for these industries.

Table 7-36: Total Industrial Wastewater N_2O Emissions by Sector (2022, MMT CO_2 Eq. and Percent)

Industry	N_2O Emissions (MMT CO_2 Eq.)	% of Industrial Wastewater N_2O
Meat & Poultry	0.2	47.3%
Petroleum Refineries	0.1	30.5%
Pulp & Paper	0.1	21.4%
Breweries	+	0.7%
Total	**0.5**	**100%**

+ Does not exceed 0.5 MMT CO_2 Eq.

Note: Totals may not sum due to independent rounding.

Emissions from Industrial Wastewater Treatment Systems:

More recent research has revealed that emissions from nitrification or nitrification-denitrification processes at wastewater treatment, previously judged to be a minor source, may in fact result in more substantial emissions (IPCC 2019). N_2O is generated as a by-product of nitrification, or as an intermediate product of denitrification. Therefore, N_2O emissions are primarily expected to occur from aerobic treatment systems. To estimate these emissions, the total nitrogen entering aerobic wastewater treatment for each industry must be calculated. Then, the emission factor provided by the *2019 Refinement* is applied to the portion of wastewater that undergoes aerobic treatment.

The total nitrogen that enters each industry's wastewater treatment system is a product of the total amount of industrial product produced, the wastewater generated per unit of product, and the nitrogen expected to be present in each meter cubed of wastewater (IPCC equation 6.13).

Equation 7-45: Total Nitrogen in Industrial Wastewater

$$TN_{INDi} = P_i \times W_i \times TN_i$$

where,

TN_{INDi} = total nitrogen in wastewater for industry *i* for inventory year, kg TN/year
i = industrial sector
P_i = total industrial product for industrial sector *i* for inventory year, t/year
W_i = wastewater generated per unit of production for industrial sector *i* for inventory year, m^3/t product
Tni = total nitrogen in untreated wastewater for industrial sector *i* for inventory year, kg TN/m^3

For the four industries of interest, the total production and the total volume of wastewater generated has already been calculated for CH_4 emissions. For these new N_2O emission estimates, the total nitrogen in the untreated wastewater was determined by multiplying the annual industry production, shown in Table 7-20, by the average wastewater outflow, shown in Table 7-23 and the nitrogen loading in the outflow shown in Table 7-37.

Table 7-37: U.S. Industrial Wastewater Nitrogen Data

Industry	Wastewater Total N (kg N/ m^3)	Source for Total N
Pulp and Paper	0.30[a]	Cabrera (2017)
Meat Processing	0.19	IPCC (2019), Table 6.12
Poultry Processing	0.19	IPCC (2019), Table 6.12
Petroleum Refining	0.051	Kenari et al. (2010)
Breweries – Craft	0.055	IPCC (2019), Table 6.12
Breweries – NonCraft	0.055	IPCC (2019), Table 6.12

[a] Units are kilograms N per air-dried metric ton of production.

Nitrous oxide emissions from industry wastewater treatment are calculated by applying an emission factor to the percent of wastewater (and therefore nitrogen) that undergoes aerobic treatment (IPCC Equation 6.11).

Equation 7-46: N_2O Emissions from Industrial Wastewater Treatment Plants

$$N_2O\ Plants_{IND} = \left[\sum_i \left(T_{i,j} \times EF_{i,j} \times TN_{INDi}\right)\right] \times \frac{44}{28}$$

where,

$N_2O\ Plants_{IND}$ = N_2O emissions from industrial wastewater treatment plants for inventory year, kg N_2O/year
TN_{INDi} = total nitrogen in wastewater from industry *i* for inventory year, kg N/year
$T_{i,j}$ = degree of utilization of treatment/discharge pathway or system *j*, for each industry *i* for inventory year

i	=	industrial sector
j	=	each treatment/discharge pathway or system
$EF_{i,j}$	=	emission factor for treatment/discharge pathway or system j, kg N_2O-N/kg N. 0.015 kg N_2O-N/kg N (IPCC 2022)
44/28	=	conversion of kg N_2O-N into kg N_2O

For each industry, the degree of utilization (Ti,j)–the percent of wastewater that undergoes each type of treatment–was previously determined for CH_4 emissions and presented in Table 7-22.

Emissions from Industrial Wastewater Treatment Effluent:

Nitrous oxide emissions from industrial wastewater treatment effluent are estimated by multiplying the total nitrogen content of the discharged wastewater effluent by an emission factor associated with the location of the discharge. Where wastewater is discharged to aquatic environments with nutrient-impacted/eutrophic conditions (i.e., water bodies which are rich in nutrients and very productive in terms of aquatic animal and plant life), or environments where carbon accumulates in sediments such as lakes, reservoirs, and estuaries, the additional organic matter in the discharged wastewater is expected to increase emissions.

Equation 7-47: N_2O Emissions from Industrial Wastewater Treatment Effluent

$$\mathrm{N_2O\ Effluent_{IND}} = \mathrm{N_{EFFLUENT,IND}} \times \mathrm{EF_{EFFLUENT}} \times 44/28$$

where,

$N_2O\ Effluent_{IND}$	=	N_2O emissions from industrial wastewater discharge for inventory year (kg N_2O/year)
$N_{EFFLUENT,IND}$	=	Total nitrogen in industry wastewater effluent discharged to aquatic environments for inventory year (kg N/year)
$EF_{EFFLUENT}$	=	Tier 1 emission factor for wastewater discharged to aquatic environments (0.005 kg N_2O-N/kg N) (IPCC 2019)
44/28	=	Conversion of kg N_2O-N into kg N_2O

The total N in treated effluent was determined through use of a nutrient estimation tool developed by EPA's Office of Water (EPA 2019). The Nutrient Tool uses known nutrient discharge data within defined industrial sectors or subsectors, as reported on Discharge Monitoring Reports, to estimate nutrient discharges for facilities within that sector or subsector that do not have reported nutrient discharges but are likely to discharge nutrients. The estimation considers, within each sector or subsector, elements such as the median nutrient concentration and flow, as well as the percent of facilities within the sector or subsector that have reported discharges. Data from 2018 are available for the pulp, paper, and paperboard, meat and poultry processing, and petroleum refining industries. To complete the time series, an industry-specific percent removal of nitrogen was calculated using the total nitrogen in untreated wastewater. See Table 7-38.

Because data for breweries was not available, the removal of nitrogen was assumed to be equivalent to secondary treatment, or 40 percent (IPCC 2019). The Tier 1 emission factor (0.005 kg N_2O/kg N) from IPCC (2019) was used.

Table 7-38: Industrial Wastewater Nitrogen Discharged in 2018 by Sector (kg N)

Industry	N $Effluent_{IND}$ (kg N)	Industry-Specific N Removal Factor
Meat & Poultry	12,078,919	0.082
Petroleum Refineries	1,698,953	0.045
Pulp & Paper	18,809,623	1.08
Breweries[a]	1,604,878	NA

[a] Nitrogen discharged by breweries was estimated as 60 percent of untreated wastewater nitrogen.
NA (Not Available)
Source: ERG (2021a).

Uncertainty

The overall uncertainty associated with both the 2022 CH_4 and N_2O emission estimates from wastewater treatment and discharge was calculated using the *2006 IPCC Guidelines* Approach 2 methodology (IPCC 2006). Uncertainty associated with the parameters used to estimate CH_4 emissions include that of numerous input variables used to model emissions from domestic wastewater and emissions from wastewater from pulp and paper manufacturing, meat and poultry processing, fruits and vegetable processing, ethanol production, petroleum refining, and breweries. Uncertainty associated with the parameters used to estimate N_2O emissions include that of numerous input variables used to model emissions from domestic wastewater and emissions from wastewater from pulp and paper manufacturing, meat and poultry processing, petroleum refining, and breweries. Uncertainty associated with centrally treated constructed wetlands parameters including U.S. population served by constructed wetlands, and emission and conversion factors are from IPCC (2014), whereas uncertainty associated with POTW flow to constructed wetlands and influent BOD and nitrogen concentrations were based on expert judgment (ERG 2021b). The specified probability density functions (PDFs) are assumed to be normal for most activity data and emission factors, and due to lack of data, are based on expert judgement (ERG 2021c).

The results of this Approach 2 quantitative uncertainty analysis are summarized in Table 7-39. For 2022, methane emissions from wastewater treatment were estimated to be between 14.9 and 27.7 MMT CO_2 Eq. at the 95 percent confidence level (or in 19 out of 20 Monte Carlo stochastic simulations). This indicates a range of approximately 29 percent below to 33 percent above the 2022 emissions estimate of 20.8 MMT CO_2 Eq. Nitrous oxide emissions from wastewater treatment were estimated to be between 13.9 and 64.0 MMT CO_2 Eq., which indicates a range of approximately 36 percent below to 192 percent above the 2022 emissions estimate of 21.9 MMT CO_2 Eq.

Table 7-39: Approach 2 Quantitative Uncertainty Estimates for 2022 Emissions from Wastewater Treatment (MMT CO_2 Eq. and Percent)

Source	Gas	2022 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Wastewater Treatment	**CH_4**	**20.8**	**14.9**	**27.7**	**-29%**	**+33%**
Domestic	CH_4	13.6	8.8	19.3	-35%	+42%
Industrial	CH_4	7.2	4.2	11.4	-42%	+57%
Wastewater Treatment	**N_2O**	**21.9**	**13.9**	**64.0**	**-36%**	**+192%**
Domestic	N_2O	21.4	13.0	63.2	-39%	+195%
Industrial	N_2O	0.5	0.5	1.4	-0.7%	+201%

[a] Range of emission estimates predicted by Monte Carlo stochastic simulation for a 95 percent confidence interval.

QA/QC and Verification

General QA/QC procedures were applied to activity data, documentation, and emission calculations consistent with the *U.S. Inventory QA/QC Plan*, which is in accordance with Vol. 1 Chapter 6 of the *2006 IPCC Guidelines* (see Annex 8 for more details). This effort included a general or Tier 1 analysis, including the following checks:

- Checked for transcription errors in data input;
- Ensured references were specified for all activity data used in the calculations;
- Checked a sample of each emission calculation used for the source category;
- Checked that parameter and emission units were correctly recorded and that appropriate conversion factors were used;

- Checked for temporal consistency in time series input data for each portion of the source category;
- Confirmed that estimates were calculated and reported for all portions of the source category and for all years;
- Investigated data gaps that affected trends of emission estimates; and
- Compared estimates to previous estimates to identify significant changes.

Calculation-related QC (category-specific, Tier 2) was performed for a portion of the domestic wastewater treatment discharges methodology, which included assessing available activity data to ensure the most complete publicly data set was used and checking historical trends in the data to assist determination of best methodology for filling in the time series for data that are not available annually.

All transcription errors identified were corrected and documented. The QA/QC analysis did not reveal any systemic inaccuracies or incorrect input values.

Recalculations Discussion

Population data were updated using the same and latest data sources as the state-level emissions inventory to create consistency across *Inventory* estimates. These changes affected the years 2020 and 2021. Protein data were updated to reflect available protein values available for 2018 through 2020 (FAO 2022). Pulp, paper, and paperboard production data were updated to reflect revised values for 2021 (FAO 2023a). Updated red meat production values for 2021, were updated based on revised data (USDA 2023a). Fruits and vegetables production values were updated for the time series (ERG 2022; USDA 2023c). Ethanol production values for 2021 were based on revised data (RFA 2023a; RFA 2023b). Petroleum refining production values for 2021 were revised based on EIA (2023). Updated values for non-craft brewery wastewater generation were included for the years 2015 and 2020, affecting the values for 2016, 2018, 2019, and 2021 (BIER 2021).

Compared to the previous *Inventory* the cumulative effect of all these recalculations had a minor impact on the overall wastewater treatment emission estimates:

- Domestic wastewater treatment and discharge CH_4 emissions decreased on average 0.2 percent over the timeseries, with 1990 through 2019 not changing and the largest decrease of 3.1 percent (0.4MMT CO_2 Eq.) in 2021.
- Domestic wastewater treatment and discharge N_2O emissions increased an average 5.6 percent over the timeseries, with 1990 through 2017 not changing and the largest increase of 6.8 percent (1.4 MMT CO_2 Eq.) in 2020.
- Industrial wastewater treatment and discharge CH_4 emissions decreased on average 0.01 percent over the timeseries, with the smallest decrease of 0.003 percent (0.0 MMT CO_2 Eq.) in 2017 and largest decrease of 0.2 percent (0.01 MMT CO_2 Eq.) in 2020.
- Industrial wastewater treatment and discharge N_2O emissions increase an average 0.02 percent over the timeseries, with the smallest increase of 0.0 percent (0.0 MMT CO_2 Eq.) in 1990 to the largest increase of 0.6 percent (0.003 MMT CO_2 Eq.) in 2021.

Over the time series, the total emissions on average increased by 0.1 percent from the previous *Inventory*. The changes ranged from the smallest increase, 0.0005 percent (0.0002 MMT CO_2 Eq.), in 2017, to the largest decrease, 2.4 percent (1.0 MMT CO_2 Eq.), in 2020.

Planned Improvements

EPA notes the following improvements will continue to be investigated as time and resources allow, but there are no immediate plans to implement them until data are available or identified:

- Continue to investigate anaerobic sludge digester and biogas data compiled by the Water Environment Federation (WEF) in collaboration with other entities as a potential source of updated activity data. Due to lack of these data, the United States continues to use another method for estimating biogas produced. This method uses the standard 100 gallons/capita/day wastewater generation factor for the United States (Ten-State Standards), which EPA believes is reasonable to estimate national emissions. However, based on stakeholder input, some regions of the United States use markedly less water due to water conservation efforts so EPA plans to investigate updated sources for this method as well.
- Investigate additional sources for estimating wastewater volume discharged and discharge location for both domestic and industrial sources. For domestic wastewater, the goal would be to provide additional data points along the time series, while the goal for industrial wastewater would be to update the Tier 1 discharge methodology to a Tier 2 methodology.
- Investigate additional sources for domestic wastewater treatment type in place data.
- Continue to review whether sufficient data exist to develop U.S.-specific CH_4 or N_2O emission factors for domestic wastewater treatment systems, including whether emissions should be differentiated for systems that incorporate biological nutrient removal operations.
- Investigate additional data sources for improving the uncertainty of the estimate of N entering municipal treatment systems.
- Evaluate literature provided by expert review commenters for potential inclusion as updates, in particular focusing on the industrial N_2O emission factor for pulp and paper wastewater treatment.
- Evaluate the use of POTW BOD effluent discharge data from ICIS-NPDES.[12] Currently only half of POTWs report organics as BOD_5 so EPA would need to determine a hierarchy of parameters to appropriately sum all loads. Using these data could potentially improve the current methane emission estimates from domestic discharge, or at least provide a comparison to the current method for QA/QC.
- Evaluate the use of POTW N effluent discharge data from ICIS-NPDES. Currently only about 80 percent of POTWs report a form of N so EPA would need to determine an appropriate method to scale to the total POTW population. EPA is aware of a method for industrial sources and plans to determine if this method is appropriate for domestic sources. Using these data could potentially improve the current nitrous oxide emissions estimates from domestic discharge, or at least provide a comparison to the current method for QA/QC.

7.3 Composting (CRT Source Category 5B1)

Composting of organic waste, such as food waste, garden (yard) and park waste, and wastewater treatment sludge and/or biosolids, is common in the United States. Composting reduces the amount of methane-generating waste entering landfills, destroys pathogens in the waste, sequesters carbon, and provides a source of organic matter. Composting can also generate a saleable product and reduce the need for chemical fertilizers when the end product is used as a fertilizer or soil amendment. This source category assumes all composting facilities are commercial, large-scale anaerobic windrow composting facilities with yard trimmings as the main waste stream composted, which aligns with findings from full-scale compost infrastructure survey data published by BioCycle (2017, 2023). Of 200 major food waste composting facilities in the United States, 75 (38 percent) use the windrow method, 45 (23 percent) use the aerated static pile method, and the remainder use other methods. The BioCycle 2023 survey received responses from facilities using aerobic composting methods (e.g., aerated static piles, in-

[12] ICIS-NPDES refers to EPA's Integrated Compliance Information System – National Pollutant Discharge Elimination System.

vessel composting) are operational in the United States, however national estimates of the material processed by these facilities are not readily available; therefore, emissions estimates by composting method are not included in this source category. Residential backyard composting is also not included in this source category.

Composting naturally converts a large fraction of the degradable organic carbon in the waste material into carbon dioxide (CO_2) through aerobic processes without anthropogenic influence. With anthropogenic influences (e.g., at commercial or large on-site composting operations), anaerobic conditions can be created in sections of the compost pile when there is excessive moisture or inadequate aeration (or mixing) of the compost pile, resulting in the formation of methane (CH_4). Methane in aerobic sections of a windrow pile is generally oxidized by microorganisms, which convert the CH_4 to CO_2 emissions. Even though CO_2 emissions are generated, they are not included in net greenhouse gas emissions for composting. Consistent with the *2006 IPCC Guidelines*, net CO_2 flux from carbon stock changes in waste material are estimated and reported under the LULUCF sector. The estimated CH_4 released into the atmosphere ranges from less than 1 percent to a few percent of the initial carbon content in the material (IPCC 2006). Depending on how well the compost pile is managed, nitrous oxide (N_2O) emissions can also be produced. The formation of N_2O depends on the initial nitrogen content of the material and is mostly due to nitrogen oxide (NO_x) denitrification during the thermophilic and secondary mesophilic stages of composting (Cornell 2007). Emissions vary and range from less than 0.5 percent to 5 percent of the initial nitrogen content of the material (IPCC 2006). Animal manures are typically expected to generate more N_2O than, for example, yard waste, however data are limited.

From 1990 to 2022, the amount of waste composted in the United States increased from 3,810 kt to 23,042 kt (see Table 7-42). There was some fluctuation in the amount of waste composted between 2006 to 2009 where a peak of 20,063 kt composted was observed in 2008, which decreased to 18,838 kt composted the following year, presumably driven by the economic crisis of 2009 (data not shown). Since 2009, the amount of waste composted has gradually increased, and when comparing 2010 to 2022, a 26 percent increase in waste composted is observed. Emissions of CH_4 and N_2O from composting from 2010 to 2022 have increased by the same percentage.

In 2022, CH_4 emissions from composting (see Table 7-40 and Table 7-41) were 2.6 MMT CO_2 Eq. (92 kt), and N_2O emissions from composting were 1.8 MMT CO_2 Eq. (7 kt), representing consistent emissions trends over the past several years. Composted material primarily includes yard trimmings (grass, leaves, and tree and brush trimmings) and food scraps from the residential and commercial sectors (such as grocery stores; restaurants; and school, business, and factory cafeterias). The composted waste quantities reported here do not include small-scale backyard composting and agricultural composting mainly due to the lack of consistent and comprehensive national data. Additionally, it is assumed that backyard composting tends to be a more naturally managed process with less chance of generating anaerobic conditions and CH_4 and N_2O emissions. Agricultural composting is accounted for in Chapter 5, Section 5.4 (Agricultural Soil Management) of this *Inventory*, as most agricultural composting operations are assumed to land-apply the resultant compost to soils.

The growth in composting since the 1990s and specifically over the past decade may be attributable to the following factors: (1) the enactment of legislation by state and local governments that discouraged or banned the disposal of yard trimmings and/or food waste in landfills, (2) an increase in yard trimming collection and yard trimming drop off sites operated by local solid waste management districts/divisions, (3) an increased awareness of the environmental benefits of composting, and (4) loans or grant programs to establish or expand composting infrastructure.

Most bans or diversion laws on the disposal of yard trimmings were initiated in the early 1990s by state or local governments (U.S. Composting Council 2010). California, for example, enacted a waste diversion law for organics including yard trimmings and food scraps in 1999 (AB939) that required jurisdictions to divert 50 percent of the waste stream by 2000, or be subjected to fines. Currently, 20 states representing up to 42 percent of the nation's population have enacted legislation banning yard waste from landfill disposal (U.S. Composting Council 2022). Additional initiatives at the metro and municipal level also exist across the United States. Roughly 4,713 composting facilities exist in the United States with most (57.2 percent) composting yard trimmings only (BioCycle 2017).

In the last decade, bans and diversions for food waste have also become more common. As of 2022, eight states (California, Connecticut, Massachusetts, New Jersey, New York, Orgon, Vermont, Washington) and seven local governments (Austin, TX; Boulder, CO; Hennepin County, MN; Portland, OR; New York City, NY; San Francisco, CA; Seattle, WA) had implemented organic waste bans or mandatory recycling laws to help reduce organic waste entering landfills, with most having taken effect after 2013 (U.S. Composting Council 2022). In most cases, organic waste reduction in landfills is accomplished by following recycling guidelines, donating excess food for human consumption, or by sending waste to organics processing facilities (Harvard Law School and CET 2019). An example of an organic waste ban as implemented by California is the California Mandatory Recycling Law (AB1826), which requires companies to comply with organic waste recycling procedures if they produce a certain amount of organic waste and took effect on January 1, 2015 (Harvard Law School and CET 2019). In 2017, *BioCycle* released a report in which 27 of 43 states that responded to their organics recycling survey noted that food waste (collected residential, commercial, institutional, and industrial food waste) was recycled via anaerobic digestion and/or composting. These 27 states reported an estimated total of 1.8 million tons of food waste diverted from landfills in 2016 (BioCycle 2018b). A growing number of initiatives to encourage households and businesses to compost or beneficially reuse food waste also exist.

Table 7-40: CH_4 and N_2O Emissions from Composting (MMT CO_2 Eq.)

Activity	1990	2005	2018	2019	2020	2021	2022
CH_4	0.4	2.1	2.5	2.5	2.6	2.6	2.6
N_2O	0.3	1.5	1.8	1.8	1.8	1.8	1.8
Total	**0.7**	**3.6**	**4.3**	**4.3**	**4.4**	**4.4**	**4.4**

Note: Totals may not sum due to independent rounding.

Table 7-41: CH_4 and N_2O Emissions from Composting (kt)

Activity	1990	2005	2018	2019	2020	2021	2022
CH_4	15	75	90	91	92	92	92
N_2O	1	6	7	7	7	7	7

Methodology

Methane and N_2O emissions from composting depend on factors such as the type of waste composted, the amount and type of supporting material (such as wood chips and peat) used, temperature, moisture content (e.g., wet and fluid versus dry and crumbly), and aeration during the composting process.

The emissions shown in Table 7-40 and Table 7-41 were estimated using the IPCC default (Tier 1) methodology (IPCC 2006) in accordance with IPCC methodological decision trees and available data. Using this method, emissions are the product of an emission factor and the mass of organic waste composted (note: no CH_4 recovery is expected to occur at composting operations in the emission estimates presented):

Equation 7-48: Greenhouse Gas Emission Calculation for Composting

$$E_i = M \times EF_i$$

where,

E_i = CH_4 or N_2O emissions from composting, kt CH_4 or N_2O
M = mass of organic waste composted in kt
EF_i = emission factor for composting, 4 t CH_4/kt of waste treated (wet basis) and 0.3 t N_2O/kt of waste treated (wet basis) (IPCC 2006)
i = designates either CH_4 or N_2O

Per IPCC Tier 1 methodology defaults, the emission factors for CH_4 and N_2O assume a moisture content of 60 percent in the wet waste (IPCC 2006). While the moisture content of composting feedstock can vary significantly

by type, composting as a process ideally proceeds between 40 to 65 percent moisture (University of Maine 2016; Cornell 1996).

Estimates of the quantity of waste composted (M, wet weight as generated) are presented in Table 7-42 for select years. Estimates of the quantity composted for 1990 and 2005 were taken from EPA's *Advancing Sustainable Materials Management: Facts and Figures* 2015 (EPA 2018); estimates of the quantities composted for 2017 to 2018 were taken from EPA's *Advancing Sustainable Materials Management: 2018 Tables and Figures* (EPA 2020); the estimate of the quantity composted for 2019 to 2022 were extrapolated using the 2018 quantity composted and a ratio of the U.S. population growth for each year between 2018 and 2022 (U.S. Census Bureau 2021; U.S. Census Bureau 2022; U.S Census Bureau 2023). Estimates of waste composted by commercial facilities in Puerto Rico were provided for select years by EPA Region 2 (Kijanka 2020). This data includes amount of waste composted at three facilities in Puerto Rico for 2017, 2018, and 2019, ranging from approximately 1,200 kt to a high of 15,000 kt. The average waste composted for these years was used as the annual amount composted for the respective facility for years the facility was operational. The annual quantity of composted waste in Puerto Rico was forecasted for 2020, 2021, and 2022 using available data from prior years, assumed metro area population data near where each facility is located, and the Microsoft Excel FORECAST function to obtain annual composting estimates.

Table 7-42: U.S. Waste Composted (kt)

Activity	1990	2005	2018	2019	2020	2021	2022
Waste Composted	3,810	18,655	22,594	22,698	22,918	22,946	23,042

Uncertainty

The major uncertainty drivers are the assumption that all composting emissions come from commercial windrow facilities and the use of default emission factors (IPCC 2006) which is tied to a homogenous mixture of waste processed across the country (largely yard trimmings). Data presented by BioCycle (BioCycle 2017, 2023) confirm most composting operations use the windrow method and yard trimmings are the largest share of material composted across the country, but there are other composting methods used and waste characteristics will vary at a facility level. Additionally, there are composting operations in Puerto Rico and U.S. territories that are not explicitly included in the national quantity of material composted as reported in the EPA Sustainable Materials Management Reports because the methodological scope does not include Puerto Rico and U.S. territories. EPA took steps to include emissions from Puerto Rico and U.S. Territories beginning in the 1990 to 2020 *Inventory* and will continue to seek out additional data in future *Inventories*.

The estimated uncertainty from the *2006 IPCC Guidelines* is ±58 percent for the Tier 1 methodology and considers the individual emission factors applied to the default emission factors and activity data.

Emissions from composting in 2022 were estimated to range between 1.8 and 7.0 MMT CO_2 Eq., which indicates a range of 58 percent below to 58 percent above the 2022 emission estimate of each gas (see Table 7-43).

Table 7-43: Tier 1 Quantitative Uncertainty Estimates for Emissions from Composting (MMT CO_2 Eq. and Percent)

Source	Gas	2022 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate (MMT CO_2 Eq.)		Uncertainty Range Relative to Emission Estimate (%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Composting	CH_4	2.6	1.1	4.1	-58%	+58%
Composting	N_2O	1.8	0.8	2.9	-58%	+58%
Composting	**Total**	**4.4**	**1.8**	**7.0**	**-58%**	**+58%**

QA/QC and Verification

General QA/QC procedures were applied to data gathering and input, documentation, and calculations consistent with the *U.S. Inventory QA/QC Plan*, which is in accordance with Vol. 1 Chapter 6 of the *2006 IPCC Guidelines* (see Annex 8 for more details). No errors were found for the current *Inventory*.

Recalculations Discussion

No recalculations were performed for the 1990 to 2022 *Inventory*.

Planned Improvements

EPA recently completed a literature search on emission factors and composting systems and management techniques that were documented in a draft technical memorandum. The purpose of this literature review was to compile all published emission factors specific to various composting systems and composted materials in the United States to determine whether the emission factors used in the current methodology can be revised or expanded to account for geographical differences and/or differences in composting systems used. For example, outdoor composting processes in arid regions typically require the addition of moisture compared to similar composting processes in wetter climates. In general, there is a lack of facility-specific data on the management techniques and sum of material composted to enable the use of different emission factors. EPA will continue to seek out more detailed data on composting facilities to enable this improvement in the future.

Relatedly, EPA has received comments during previous *Inventory* cycles recommending that calculations for the composting sector be based on waste subcategories (i.e., leaves, grass and garden debris, food waste) and category-specific moisture contents. At this time, EPA is not aware of any available datasets which would enable estimations to be performed at this level of granularity. EPA will continue to search for data which could lead to the development of subcategory-specific composting emission factors to be used in future *Inventory* cycles.

EPA will also continue to seek out activity data including processing capacity and years of operation for commercial composting facilities in Puerto Rico (for additional years), Guam, and other U.S. Territories for inclusion in a future *Inventory*.

7.4 Anaerobic Digestion at Biogas Facilities (CRT Source Category 5B2)

Anaerobic digestion is a series of biological processes in the absence of oxygen in which microorganisms break down organic matter, producing biogas and digestate. The biogas primarily consists of CH_4, biogenic CO_2, and trace amounts of other gases such as N_2O (IPCC 2006) and is often combusted to produce heat and power, or further processed into renewable natural gas or for use as a transportation fuel. Digester gas contains approximately 65 percent CH_4 (a normal range is 55 percent to 65 percent) and approximately 35 percent CO_2 (WEF 2012; EPA 1993). Methane emissions may result from a fraction of the biogas that is lost during the process due to leakages and other unexpected events (0 to 10 percent of the amount of CH_4 generated, IPCC 2006), collected biogas that is not completely combusted, and entrained gas bubbles and residual gas potential in the digestate. Carbon dioxide emissions are biogenic in origin and should be reported as an informational item in the Energy Sector (IPCC 2006). Volume 5 Chapter 4 of the *2006 IPCC Guidelines* notes that at biogas plants where unintentional CH_4 emissions are flared, CH_4 emissions are likely to be close to zero.

Anaerobic digesters differ based on the operating temperature, feedstock type and moisture content, and mode of operation. The operating temperature dictates the microbial communities that live in the digester. Mesophilic

microbes are present at temperatures ranging from 85 to 100 degrees Fahrenheit while thermophilic microbes thrive at temperatures ranging from 122 to 140 degrees Fahrenheit (WEF 2012). Digesters may process one or more types of feedstock, including food waste; municipal wastewater solids; livestock manure; industrial wastewater and residuals; fats, oils, and grease; and other types of organic waste streams. Co-digestion (multiple feedstocks) is employed to increase methane production in cases where an organic matter type does not break down easily. In co-digestion, various organic wastes are decomposed in a singular anaerobic digester by using a combination of wastewater solids or manure and food waste from restaurants or food processing industry, a combination of manure and waste from energy crops or crop residues (EPA 2016), or alternative combinations of feedstock. The moisture content of the feedstock (wet or dry) impacts the amount of biogas generation. Wet anaerobic digesters process feedstock with a solids content of less than 15 percent while dry anaerobic digesters process feedstock with a solids content greater than 15 percent (EPA 2020). Digesters may also operate in batch or continuous mode, which affects the feedstock loading and removal. Batch anaerobic digesters are manually loaded with feedstock all at once and then manually emptied while continuous anaerobic digesters are continuously loaded and emptied with feedstock (EPA 2020).

The three main categories of anaerobic digestion facilities included in national greenhouse gas inventories include the following:

- Anaerobic digestion at biogas facilities, or stand-alone digesters, can be industry-dedicated digesters that process waste from on industry or industrial facility (typically food of beverage waste from manufacturing), or multi-source digesters that process feedstocks from various sources (e.g., municipal food scraps, manure, food processing waste). Some stand-alone digesters also co-digest other organics such as yard waste.
- On-farm digesters manage organic matter and reduce odor generated by farm animals or crops. On-farm digesters are found mainly at dairy, swine, and poultry farms where there is the highest potential for methane production to energy conversion. On-farm digesters may also accept food waste as feedstock for co-digestion.
- Digesters at water resource recovery facilities (WRRF) produce biogas through the treatment and reduction of wastewater solids. Some WRRF facilities may also accept and co-digest food waste.

This section focuses on stand-alone anaerobic digestion at biogas facilities. Emissions from on-farm digesters are included Chapter 5 (Agriculture) and AD facilities at WRRFs are included in Section 7.2.

From 1990 to 2022, the estimated amount of waste managed by stand-alone digesters in the United States increased from approximately 988 kt to 11,947 kt, an increase of 1,109 percent. As described in the Uncertainty section, no data sources present the annual amount of waste managed by these facilities prior to 2015 when the EPA began a comprehensive data collection survey. Thus, the emission estimates between 1990 and 2014, and for 2020 to 2022 are general estimates extrapolated from data collected for years 2015 to 2019 via the EPA surveys (EPA 2018, 2019, 2021, and 2023). The steady increase in the amount of waste processed over the time series is likely driven by increasing interest in using biogas produced from waste as a renewable energy source and other organics diversion goals.

In 2022, emissions from stand-alone anaerobic digestion at biogas facilities were approximately 13,380 MT CO_2 Eq. (0.5 kt) (see Table 7-44 and Table 7-45).

Table 7-44: CH_4 Emissions from Anaerobic Digestion at Biogas Facilities (MT CO_2 Eq.)

Activity	1990	2005	2018	2019	2020	2021	2022
CH_4 Generation	22,129	66,388	186,507	348,699	239,720	267,603	267,603
CH_4 Recovery	(21,023)	(63,069)	(177,182)	(331,264)	(227,734)	(254,223)	(254,223)
CH_4 Emissions	**1,106**	**3,319**	**9,325**	**17,435**	**11,986**	**13,380**	**13,380**

Notes: Parentheses indicate negative values. Totals may not sum due to independent rounding.

Table 7-45: CH_4 Emissions from Anaerobic Digestion at Biogas Facilities (kt CH_4)

Activity	1990	2005	2018	2019	2020	2021	2022
CH_4 Generation	1	2	7	12	9	10	10
CH_4 Recovery	(1)	(2)	(6)	(12)	(8)	(9)	(9)
CH_4 Emissions	**+**	**+**	**+**	**1**	**+**	**+**	**+**

+ Does not exceed 0.5 kt CH_4.

Notes: Parentheses indicate negative values. Totals may not sum due to independent rounding.

Methodology

Methane emissions from anaerobic digestion depend on factors such as the type of waste managed, the amount and type of supporting material (such as wood chips and peat) used, temperature, moisture content (e.g., wet and fluid versus dry and crumbly), aeration during the digestion process, unintentional leakages, and how the biogas generated is used/combusted (e.g., flared, used on-site, used off-site).

The emissions presented in Table 7-44 were estimated using the IPCC default (Tier 1) methodology (Volume 5, Chapter 4, IPCC 2006) given in Equation 7-49 below, which applies a default leakage factor of 5 percent to the CH_4 generated, which is the product of an emission factor and the mass of organic waste processed (Equation 7-50). Only CH_4 emissions are estimated because N_2O emissions are considered negligible (IPCC 2006). Some Tier 2 data are available (annual quantity of waste digested) for the later portion of the time series (2015 and later). The methods were selected in accordance with IPCC methodological decision trees and available data on organic waste processed.

Per the *2006 IPCC Guidelines*, emissions of CH_4 from anaerobic digestion facilities due to unintentional leakages during process disturbances or other unexpected events are generally between 0 to 10 percent of the amount of CH_4 generated. When facility-specific information or data are unavailable, a 5 percent leakage factor is recommended (IPCC 2006).

Equation 7-49: Methane Emissions Calculation for Anaerobic Digestion

$$CH_4\ Emissions = L \times (G_{CH4})$$

where,

CH_4 Emissions = total CH_4 emissions in inventory year, Gg CH_4
L = leakage factor, default assumed 5 percent (IPCC 2006)
G_{CH4} = total CH_4 generation in inventory year, Gg CH_4

Equation 7-50: Methane Generation Calculation for Anaerobic Digestion

$$G_{CH4} = \sum_i (M_i \times EF_i) \times 10^{-3}$$

where,

M_i = mass of organic waste treated by biological treatment type *i*, Gg, see Table 7-46
EF = emission factor for treatment *i*, g CH_4/kg waste treated, 0.8 Mg/Gg CH_4
i = anaerobic digestion

Per IPCC Tier 1 methodology defaults, the emission factor for CH_4 assumes a moisture content of 60 percent in the wet waste (IPCC 2006). Both liquid and solid wastes are processed by stand-alone digesters and the moisture content entering a digester may be higher. One emission factor, 0.8 Mg/Gg CH_4 is applied for the entire time series (IPCC 2006 Volume 5, Chapter 4, Table 4.1).

The annual quantity of waste digested is sourced from EPA surveys of anaerobic digestion facilities (EPA 2018, 2019, 2021, and 2023). The EPA was granted the authority to survey anaerobic digestion facilities that process food waste annually through an Information Collection Request (ICR No. 2533.01). The scope includes stand-alone and

co-digestion facilities (on-farm and water resource recovery facilities [WRRF]). Four reports with survey results have been published to date:

- *Anaerobic Digestion Facilities Processing Food Waste in the United States in 2015: Survey Results* (EPA 2018)
- *Anaerobic Digestion Facilities Processing Food Waste in the United States in 2016: Survey Results* (EPA 2019)
- *Anaerobic Digestion Facilities Processing Food Waste in the United States in (2017 & 2018): Survey Results* (EPA 2021)
- *Anaerobic Digestion Facilities Processing Food Waste in the United States in (2019): Survey Results* (EPA 2023).

These reports present aggregated survey data including the annual quantity of waste processed by digester type (i.e., stand-alone, on-farm, and WRRF); waste types accepted; biogas generation and end use; and more. The amount of waste digested as reported in the survey reports were assumed to be in wet weight; the majority of stand-alone digesters were found to be wet and mesophilic (EPA 2019).

The aggregated data presented in the EPA reports are underestimates of the actual amount of processed waste and biogas produced because (1) surveys rarely achieve a 100 percent response rate and some fraction of facilities in each survey year did not respond to the survey; (2) EPA focused the surveys on facilities that primarily process food waste, although non-food waste quantities processed were also collected and reported; and (3) while the EPA has done due diligence to identify all stand-alone digesters that process food waste, EPA may not have identified all facilities across the United States and its territories.

The annual quantity of waste digested at stand-alone digesters for 1990 to 2014 (only 1990 and 2005 are shown in Table 7-46) was estimated by multiplying the count of estimated operating facilities (as presented in Table 7-47) by the weighted average of waste digested in 2015 to 2019 collected through EPA's survey data (EPA 2018, 2019, 2021, 2023). Masked survey responses of food and non-food waste processed were shared with the *Inventory* team by the EPA team leading the EPA AD Data Collection Surveys. This provided an accurate count of the number of facilities that provided annual quantities of digested waste, which matters for the weighted average. The weighted average applied to the current *Inventory* is calculated as follows for 1990 to 2014:

Equation 7-50: Weighted Average of Waste Processed

$$Weighted\ Average\ Waste\ Processed = \sum_{year} \frac{W_{year} \times Fac_{year}}{Sum\ of\ All\ Fac}$$

where,

year = the year of data for the average waste processed and count of facilities in the numerator

W = total average waste processed in the respective survey year, food and non-food waste (short tons).

Fac = the number of facilities that reported an amount of waste processed in the respective survey year. Note the number of facilities that provided an annual quantity of waste processed data was internally shared and differs from the total number of facilities that responded to the EPA surveys as presented in EPA (2018, 2019, 2021, and 2023).

The number of facilities that reported annual quantities of waste digested to the EPA survey varies by year. The masked data provided by the EPA AD survey data collection team include data for 41, 44, 42, 43, and 18 facilities between 2015 to 2019, respectively. This data was used to calculate the weighted average of waste digested of 239,709 short tons.

Estimates of the quantity of waste digested for 1990 to 2014 are calculated by multiplying the weighted average of waste digested from the masked survey data by the count of operating facilities in each year. This calculation

assumes that each facility operates continuously from the first year of operation for the remainder of the time series. Additional efforts will be made to quantify the number of operating facilities and estimates of the total waste digested by year for future Inventories as described in the Planned Improvements section.

Estimates of the quantity digested for 2015 to 2019 were taken from EPA's AD survey data (EPA 2018, EPA 2019, EPA 2021, and EPA 2023). In the 1990 to 2022 *Inventory*, the quantity of liquid, non-food waste was converted to tons using a general conversion factor of 3.8 lbs/gallon.

The EPA (2023) report provides a significant increase in data granularity for stand-alone digesters compared to earlier reports because food waste processed by the beverage sector is included as tons of food waste processed as opposed to gallons of food waste processed in prior survey years. Detail on the sources and types of the liquid food and non-food waste was not available in the 2015 to 2018 data to reliably convert the data to tons. However, the 2019 data point provides some assurance that using a general conversion factor to convert liquid waste to tons yields a more comprehensive estimate of total waste processed at stand-alone AD facilities.

The estimate of waste digested for 2020 to 2022 were extrapolated using the average of the waste digested from the 2017 to 2019 survey data (EPA 2021, 2023) as a proxy. The average did not include data from 2015 and 2016 because there is a drop in the amount of waste digested by nearly 1 million tons between 2016 and 2017. The quantities digested between 2015 and 2016 are similar, and quantities digested between 2017 and 2018 are similar. The quantity digested for 2019 is nearly twice the amount of prior EPA survey years because food waste from the beverage sector were able to be accurately converted to tons. Estimates for 2020 to 2022 will be updated as future EPA survey reports are published.

Table 7-46: Estimated U.S. Waste Digested (kt) from 1990-2022

Activity	1990	2005	2018	2019	2020	2021	2022
Waste Digested	988	2,964	8,326	15,567	10,702	11,947	11,947

The estimated count of operating facilities is calculated by summing the count of digesters that began operating by year over the time series. The year a digester began operating is sourced from EPA (2021). This assumes all facilities are in operation from their first year of operation throughout the remainder of the time series, including facilities prior to 1990. This is likely an overestimate of facilities operating per year but does not necessarily translate to an overestimate in the amount of waste processed because a weighted average of waste processed for the surveyed facilities is applied to these years. The number of facilities in 1990 to 2014 are directly used in calculating the emissions for those years.

Table 7-47: Estimated Number of Stand-Alone AD Facilities Operating from 1990-2022

Year	1990	2005	2018	2019	2020	2021	2022
Estimated Count of Operational Facilities	4	12	68	68	68	68	68

Uncertainty

The methodology applied for the 1990 to 2014 emissions estimates should be considered a starting point to build on in future years if additional historical data become available. Five years of facility-provided data are available (2015 to 2019) while the rest of the time series is estimated based on an assumption of facility counts and the 2015 to 2019 weighted average annual waste digested as calculated from survey data. The major limitations, and uncertainty drivers in the emissions estimates, are related to the uncertainty in assumptions to ensure completeness across the time series and the limitations in the EPA AD survey data, as described below:

1. The EPA AD surveys (EPA 2018; EPA 2019; EPA 2021; EPA 2023) did not receive a 100 percent response rate, meaning that the survey data represent a portion, albeit the majority, of stand-alone digesters, and annual waste processed. The methodology applied here did not attempt to estimate waste digested by facilities that did not respond to the survey, which likely underestimates the quantity of waste digested and CH_4 emissions.

2. The EPA AD survey data (EPA 2018; EPA 2019) present both food and non-food waste digested. The non-food waste was reported as liquid (gallons) and solid (tons). The quantity of liquid waste managed for 2015 and 2016, which is used as a proxy for 1990 to 2014, was converted to tons using a general conversion factor of 3.8 lbs/gallon. This may slightly over- or underestimate the quantity of waste digested and CH_4 emissions between 1990 to 2018. This conversion was not made by EPA in the survey report (EPA 2018). However, EPA (2021) did convert the liquid waste managed to tons for 2017 and 2018 using the general conversion factor of 3.8 lbs/gallon.
3. The assumption required to estimate the activity data for 1990 to 2014 may overestimate the number of facilities in operation because it assumes that each facility operates from its start year for the entire time series (i.e. facility closures are not taken into account). This introduces a large amount of uncertainty in the estimates compared to years where there is directly reported survey data. It is unclear whether this under- or over-estimates the quantity of waste digested and CH_4 emissions.
4. The most recent EPA AD survey data (EPA 2023) includes waste processed by the beverage sector, which was not presented in prior survey years. No attempts were made to separately estimate and include this waste stream in years prior to 2019 (i.e. the EPA 2023 survey). This means that annual CH_4 estimates for 1990 to 2018 are underestimated.

The estimated uncertainty from the *2006 IPCC Guidelines* is ±54 percent for the Approach 1 methodology.

Emissions from anaerobic digestion at stand-alone biogas facilities in 2022 were estimated to be between 6,175 and 20,586 MT CO_2 Eq., which indicates a range of 54 percent below to 54 percent above the 2022 emission estimate of CH_4 (see Table 7-48). A ±20 percent uncertainty factor is applied to the annual amount of material digested (i.e., the activity data), which was developed with expert judgment (Bronstein 2021). A ±50 percent default uncertainty factor is applied to the CH_4 emission factor (IPCC 2006). Using the IPCC's error propagation equation (Equation 3.1 in IPCC 2006 Volume 1, Chapter 3), the combined uncertainty percentage is ±54 percent.

Table 7-48: Approach 1 Quantitative Uncertainty Estimates for Emissions from Anaerobic Digestion (MT CO_2 Eq. and Percent)

Source	Gas	2022 Emission Estimate (MT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate (MT CO_2 Eq.)		Uncertainty Range Relative to Emission Estimate (%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Anaerobic Digestion at Biogas Facilities	CH_4	13,380	6,175	20,586	-54%	+54%

QA/QC and Verification

General QA/QC procedures were applied to data gathering and input, documentation, and calculations consistent with the *U.S. Inventory QA/QC Plan*, which is in accordance with Vol. 1, Chapter 6 of the *2006 IPCC Guidelines* (see Annex 8 for more details). No errors were found for the current *Inventory*.

Recalculations Discussion

For the current *Inventory*, a methodological change was made whereby the CH_4 emissions are considered equal to leakage from the digester network of pipes. A leakage factor of 5 percent as recommended in IPCC 2006 is applied to the CH_4 generation estimate for all years in the time series. This methodological change applies to every year in the time series and significantly reduces annual CH_4 emissions estimates. Previously the EPA AD Survey data of amount of biogas produced at AD facilities was used for the amount of gas recovered, with the remaining gas assumed to be leaked or emitted. This method calculated higher emissions estimates, which showed most of the gas generated at an AD was emitted, instead of used in biogas projects. This was inconsistent with the EPA AD Survey findings that approximately 95 percent of stand-alone AD facilities use some or all biogas onsite and the

IPCC guidance on default leakage from AD facilities. EPA will further investigate the survey data for the biogas produced data point, since it indicates very low gas utilized as compared to this revised methodology.

The weighted average of waste digested was recalculated for the current *Inventory* to incorporate EPA AD survey data from 2017 to 2019. The recalculation increased the weighted average annual waste digested from 216,494 short tons to 272,249 short tons, an approximately 25 percent increase. The weighted average is applied to the estimated count of stand-along digesters operating between 1990 to 2014 and resulted in a 26 percent increase in the amount of waste digested annually.

Additional recalculations were also made for the waste processed in 2019 to 2021. In the previous *Inventory*, the amount of waste processed for 2019 to 2021 was extrapolated based on available survey data. With the publication of survey data for 2019 (EPA 2023), the values for 2019 were replaced and the extrapolation for years 2020 to 2022 were updated. Recalculations for the amount of waste processed resulted in increases of 88 percent in 2019, 30 percent in 2020, and 45 percent in 2021.

Despite the increase of waste processed across the time series, recalculations for this *Inventory* resulted in significant decreases to the emissions estimates as compared to the previous 1990 through 2021 *Inventory*. Emissions estimates were reduced by 93 percent annually between 1990 to 2014, and between 90 to 95 percent between 2015 to 2021. For example, the net emissions estimate in 2021 decreased from 6.1 kt to 0.48 kt. The decrease in emissions is driven by the methodological change described in the first paragraph.

Planned Improvements

EPA will continue to incorporate updated survey data from future EPA AD Data Collection Surveys when the survey data are published. These revisions will change the estimated emissions for 2020 to 2022. Additionally, quality control checks on the default emission factor used to determine CH_4 generation is in process.

EPA will also reassess how best to estimate annual waste processed using proxy data for years between the EPA AD Data Collection Survey reports as needed (e.g., for 2020, 2021, 2022). The methodology described here assumes the same average amount of waste is processed each year for 2020 through 2022.

EPA continues to seek out data sources to confirm the estimated number of operational facilities by year prior to 2015 and consider how best to estimate the quantity of waste processed per year by these facilities with the goal of better estimating the annual quantity of waste digested between 1990 to 2014. Available data will also be compiled where available for facilities that did not directly respond to the EPA AD Data Collection surveys for completeness.

7.5 Waste Incineration (CRT Source Category 5C1)

As stated earlier in this chapter, carbon dioxide (CO_2), nitrous oxide (N_2O), and methane (CH_4) emissions from the combustion of waste are accounted for in the Energy sector rather than in the Waste sector because almost all combustion of municipal solid waste (MSW) in the United States occurs at waste-to-energy facilities where useful energy is recovered. Similarly, the Energy sector also includes an estimate of emissions from burning waste tires and hazardous industrial waste, because virtually all of the combustion occurs in industrial and utility boilers that recover energy. The combustion of waste in the United States in 2022 resulted in 12.7 MMT CO_2 Eq. of emissions. For more details on emissions from the combustion of waste, see Section 3.3 of the Energy chapter.

Additional sources of emissions from waste combustion include non-hazardous industrial waste incineration and medical waste incineration. As described in Annex 5 of this report, data are not readily available for these sources and emission estimates are not provided.

An analysis of the likely level of medical waste incineration emissions was conducted based on a 2009 study of hospital/ medical/ infectious waste incinerator (HMIWI) facilities in the United States (RTI 2009). Based on that study's information of waste throughput and an analysis of the fossil-based composition of the waste, it was determined that annual greenhouse gas emissions for medical waste incineration would be below 500 kt CO_2 Eq. per year and considered insignificant for the purposes of inventory reporting under the Paris Agreement and the UNFCCC. More information on this analysis is provided in Annex 5.

Furthermore, an analysis was conducted on the likely level of sewage sludge incineration emissions based on the total amount of sewage sludge generated and assumed percent incineration. Based on assumed amount of sludge incinerated and non-CO_2 factors for solid biomass it was determined that annual greenhouse gas emissions for sewage sludge incineration would be below 500 kt CO_2 Eq. per year and considered insignificant for the purposes of inventory reporting under the Paris Agreement and the UNFCCC. More information on this analysis is provided in Annex 5.

7.6 Waste Sources of Precursor Greenhouse Gases

In addition to the main greenhouse gases addressed above, waste generating and handling processes are also sources of precursors to greenhouse gases. The reporting requirements of the Paris Agreement and the UNFCCC[13] request that information should be provided on precursor emissions, which include carbon monoxide (CO), nitrogen oxides (NO_x), non-methane volatile organic compounds (NMVOCs), and sulfur dioxide (SO_2). These gases are not direct greenhouse gases, but can indirectly impact Earth's radiative balance by altering the concentrations of other greenhouse gases (e.g., tropospheric ozone) and atmosphere aerosol (e.g., particulate sulfate). Total emissions of NO_x, CO, NMVOCs, and SO_2 from waste sources for the years 1990 through 2022 are provided in Table 7-49.

Table 7-49: Emissions of NO_x, CO, NMVOC, and SO_2 from Waste (kt)

Gas/Source	1990	2005	2018	2019	2020	2021	2022
NO_x	84	51	73	73	76	76	75
CO	1,028	1,178	1,182	1,182	1,342	1,343	1,343
NMVOCs	870	152	156	157	173	172	172
SO_2	36	20	23	23	33	32	31

Methodology and Time-Series Consistency

Emission estimates for 1990 through 2022 were obtained from data published on the National Emissions Inventory (NEI) Air Pollutant Emissions Trends Data website (EPA 2023a). For Table 7-49, NEI reported emissions of CO, NO_x, SO_2, and NMVOCs are recategorized from NEI Emissions Inventory System (EIS) sectors. The EIS sectors are mapped to categories more closely aligned with reporting sectors and categories under the Paris Agreement and the UNFCCC, based on discussions between the EPA *Inventory* and NEI staff (see crosswalk documented in Annex 6.3).[14] EIS sectors mapped to the waste sector categories in this report include: waste disposal and recycling

[13] See paragraph 51 of Annex to 18/CMA.1 available online at: https://unfccc.int/sites/default/files/resource/CMA2018_03a02E.pdf.

[14] The NEI estimates and reports emissions from six criteria air pollutants (CAPs) and 187 hazardous air pollutants (HAPs) in support of National Ambient Air Quality Standards. EPA reported CAP emission trends are grouped into 60 sectors and 15 Tier 1

(landfills; publicly owned treatment works; industrial wastewater; treatment, storage, and disposal facilities; waste incineration; and other).[15] As described in the NEI Technical Support Documentation (TSD) (EPA 2023b), emissions are estimated through a combination of emissions data submitted directly to the EPA by state, local, and tribal air agencies, as well as additional information added by the Agency from EPA emissions programs, such as the emission trading program, Toxics Release Inventory (TRI), and data collected during rule development or compliance testing. Within the NEI, there is only one EIS sector for waste generating and handling processes, so precursor estimates are aggregated in Table 7-49 for consistency with NEI reporting. Future presentations of this data may disaggregate emissions so it better maps to reporting categories under the Paris Agreement and the UNFCCC.

Methodological recalculations were applied to the entire time series to ensure time-series consistency from 1990 through 2022, which are described in detail in the NEI's TSD (EPA 2021). No quantitative estimates of uncertainty were calculated for this source category.

source categories, which broadly cover similar source categories to those presented in this chapter. For reporting precursor emissions in the common reporting tables (CRT), EPA has mapped and regrouped emissions of greenhouse gas precursors (CO, NO_x, SO_2, and NMVOCs) from NEI's EIS sectors to better align with NIR source categories, and to ensure consistency and completeness to the extent possible. See Annex 6.3 for more information on this mapping.

[15] Precursor emissions from waste incineration were reported in the Energy sector in the previous *Inventory* but are not disaggregated from the Waste sector in this report.

8. Other

The United States does not report any greenhouse gas emissions under the Intergovernmental Panel on Climate Change (IPCC) “Other” sector.

9. Recalculations and Improvements

Each year, many emission and sink estimates in the *Inventory of U.S. Greenhouse Gas Emissions and Sinks* are recalculated and revised through the use of better methods and/or data with the goal of improving inventory quality and reducing uncertainties, including improving the transparency, completeness, consistency, and overall usefulness of the report. In this effort, the United States follows the *2006 IPCC Guidelines* (IPCC 2006) and its refinements/supplements, which state:

> *"Both methodological changes and refinements over time are an essential part of improving inventory quality. It is good practice to change or refine methods when available data have changed; the previously used method is not consistent with the IPCC guidelines for that category; a category has become key; the previously used method is insufficient to reflect mitigation activities in a transparent manner; the capacity for inventory preparation has increased; improved inventory methods become available; and/or for correction of errors."*

When methodological changes have been implemented, the previous *Inventory's* time series (i.e., 1990 to 2021) is assessed and potentially recalculated to reflect the change, per guidance in IPCC (2006, 2019). Changes in historical data are often the result of changes in statistical data supplied by other agencies, and these changes do not necessarily impact the entire time series.

The results of all methodological changes and historical data updates made in the current *Inventory* in calculating CO_2-equivalent U.S. greenhouse gas emissions and sinks are presented in Figure 9-2, while impacts on both total and net emissions by gas are presented in Table 9-1 and Table 9-2. Collectively, these changes resulted in an average annual decrease of 114.8 million metric tons of carbon dioxide equivalent (MMT CO_2 Eq.) (1.9 percent) in net total emissions relative to the previously published *Inventory* (i.e., the 1990 to 2021 report) in units of MMT CO_2 Eq.

Figure 9-1: Impacts of Recalculations on Net Emissions

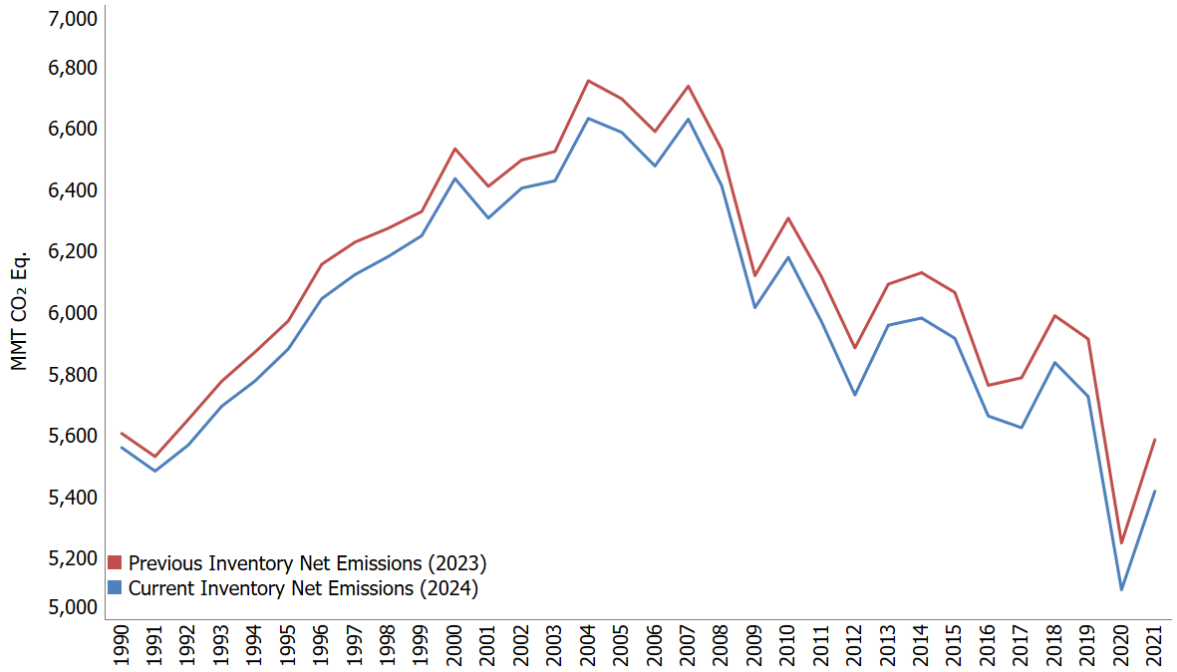


Table 9-1: Overall Impact of Recalculations by Gas Compared to Previous *Inventory*

Gas/Source	1990	2005	2018	2019	2020	2021	Average Annual Change
CO_2	10.7	(5.3)	(15.6)	(27.7)	(25.7)	(15.0)	(4.6)
CH_4[a]	3.0	4.4	(2.6)	(13.4)	(6.9)	(7.0)	0.5
N_2O[a]	1.9	3.4	9.3	6.1	2.3	4.9	3.9
HFCs and PFCs	34.0	14.8	6.8	7.2	6.1	5.7	21.2
Total Gross Emissions (Sources)	**49.6**	**17.3**	**(2.1)**	**(27.8)**	**(24.2)**	**(11.4)**	**21.0**
Change in LULUCF Total Net Flux[b]	(95.8)	(123.0)	(148.8)	(153.4)	(120.2)	(151.4)	(133.6)
LULUCF Emissions[c]	0.0	(3.5)	(1.6)	(6.2)	(8.0)	(4.9)	(2.2)
CH_4	(0.4)	(2.8)	(1.8)	(4.4)	(6.1)	(3.8)	(2.0)
N_2O	0.4	(0.7)	0.2	(1.8)	(1.9)	(1.1)	(0.2)
Change in LULUCF Sector Net Total[d]	(95.7)	(126.5)	(150.4)	(159.5)	(128.2)	(156.3)	(135.8)
Net Emissions (Sources and Sinks)	**(46.2)**	**(109.3)**	**(152.4)**	**(187.3)**	**(152.4)**	**(167.8)**	**(114.8)**

[a] Does not include CH_4 and N_2O emissions from LULUCF.

[b] LULUCF carbon stock change includes any C stock gains and losses from all land use and land use conversion categories

[c] LULUCF emissions include the CH_4 and N_2O emissions reported for peatlands remaining peatlands, forest fires, drained organic soils, grassland fires, and coastal wetlands remaining coastal wetlands; CH_4 emissions from land converted to coastal wetlands; and N_2O emissions from forest soils and settlement soils.

[d] The LULUCF sector net total is the net sum of all CH_4 and N_2O emissions to the atmosphere plus net carbon stock changes. More detail on the impacts of recalculations on the LULUCF sector can be found in Table 9-5.

Notes: Parentheses indicate negative values. Totals may not sum due to independent rounding.

Table 9-2: Overall Impact of Recalculations by Sector Compared to Previous *Inventory*

Gas/Source	1990	2005	2018	2019	2020	2021	Average Annual Change
Energy	16.8	1.6	(13.4)	(32.1)	(25.6)	(16.7)	(0.2)
IPPU	33.5	15.3	5.0	5.1	4.7	5.2	20.4
Agriculture	3.1	4.1	12.9	5.6	2.4	6.7	5.3
LULUCF	(95.8)	(126.5)	(150.4)	(159.5)	(128.2)	(156.3)	(135.8)
Waste	0.0	(0.1)	(0.5)	(0.2)	0.2	0.0	(0.1)
Total Gross Emissions (Sources)	**49.6**	**17.3**	**(2.1)**	**(27.8)**	**(24.2)**	**(11.4)**	**21.0**
Net Emissions (Sources and Sinks)	**(46.2)**	**(109.3)**	**(152.4)**	**(187.3)**	**(152.4)**	**(167.8)**	**(114.8)**

Notes: Parentheses indicate negative values. Totals may not sum due to independent rounding.

Table 9-4 and Table 9-5 include the category-level quantitative effects of methodological changes and historical data updates made in the current *Inventory* in calculating CO_2-equivalent U.S. greenhouse gas emissions by gas across all sectors. To understand the details of any specific recalculation or methodological improvement, see the Recalculations sections within each source/sink categories' section found in Chapters 3 through 7 of this report. A discussion of *Inventory* improvements in response to review processes is described in Annex 8.

Key Recalculations and Improvements for 1990-2022 *Inventory*

The current *Inventory* includes new categories that improve completeness of the national estimates. Specifically, the current report includes CO_2 emissions from ceramics production and non-metallurgical magnesia production within other process use of carbonates category, fluorinated gases from fluorochemical production other than HCFC-22 within the fluorochemical production category, and managed forest land in Hawaii and several U.S. Territories.[1] The report also now includes SF_6 and PFCs from product uses.

The following source and sink categories underwent the most significant methodological and historical data changes. A brief summary of the recalculations and/or improvements undertaken are provided for these categories.

Table 9-3: Key Recalculations

Sector	Category	Reason for Recalculation or Improvement	Impact of Recalculation on 2021 Value	Average Impact over Time Series	
				Percent	(MMT CO_2 Eq.)
LULUCF	Forest Land Remaining Forest Land (CO_2)	Accuracy. Use of new and updated data and methods from the USFS Forest Inventory and Analysis program, see details in Chapter 6.2.	148.8	+21.7%	159.1
LULUCF	Land Converted to Grassland (CO_2)	Accuracy. Use of new activity data and methods from FIA, USDA-NRCS NRI and DayCent model, see details in Chapter 6.7.	49.2	-237.1%	53.1
LULUCF	Land Converted to Cropland (CO_2)	Accuracy. Use of new activity data and methods from FIA, USDA-NRCS NRI and DayCent model, see details in Chapter 6.5.	21.6	-36.6%	20.7

[1] American Samoa, Guam, Northern Marianas Islands, U.S. Virgin Islands, and Puerto Rico.

LULUCF	Grassland Remaining Grassland (CO_2)	Accuracy. Use of new data from USDA-NRCS NRI, and re-calibration of the DayCent model, see details in Chapter 6.6.	0.6	+1,850.1%	10.7
Energy	Non-Energy Use of Fuels (CO_2)	Accuracy and Consistency. Use of new, updated, and recategorized data from U.S. International Trade Commission, EIA and other data sources (ACC), see details in Chapter 3.2.	28.6	-8.2%	10.1
LULUCF	Land Converted to Settlements (CO_2)	Accuracy. Use of new data from USDA-NRCS NRI, FIA, and extended time series, see details in Chapter 6.11.	12.8	-9.3%	7.7
IPPU	Fluorochemical Production (HFCs)	Completeness. Inclusion of new subcategory fluorochemical production other than HCFC-22, see details in Chapter 4.14 and 4.15.	1.7	+58.7%	6.8
Energy	Fossil Fuel Combustion (CO_2)	Accuracy and Consistency. Use of updated data and alignment of methodology from EIA, see details in Chapter 3.1.	15.2	+0.1%	5.8
LULUCF	Cropland Remaining Cropland (CO_2)	Accuracy. Use of new data from USDA-NRCS NRI and the OpTIS remote-sensing data, and methods to extend time series, see details in Chapter 6.4.	13.0	+26.4%	4.2
Agriculture	Agricultural Soil Management (N_2O)	Accuracy. Use of updated time series data for land representation, re-calibration of DayCent model, and updated cropland management parameters, see details in Chapter 5.4.	3.9	+1.1%	3.3
Energy	Petroleum Systems (CH_4)	Accuracy. Use of additional data from GHGRP, see details in Chapter 3.6.	1.5	-4.6%	2.5
LULUCF	Wetlands Remaining Wetlands (CO_2)	Accuracy. Use of new data and updated emissions factors, see details in Chapter 1.8.	2.3	+2.2%	2.4

Figure 9-2: Impacts of Recalculations to U.S. Greenhouse Gas Emissions and Sinks by Sector

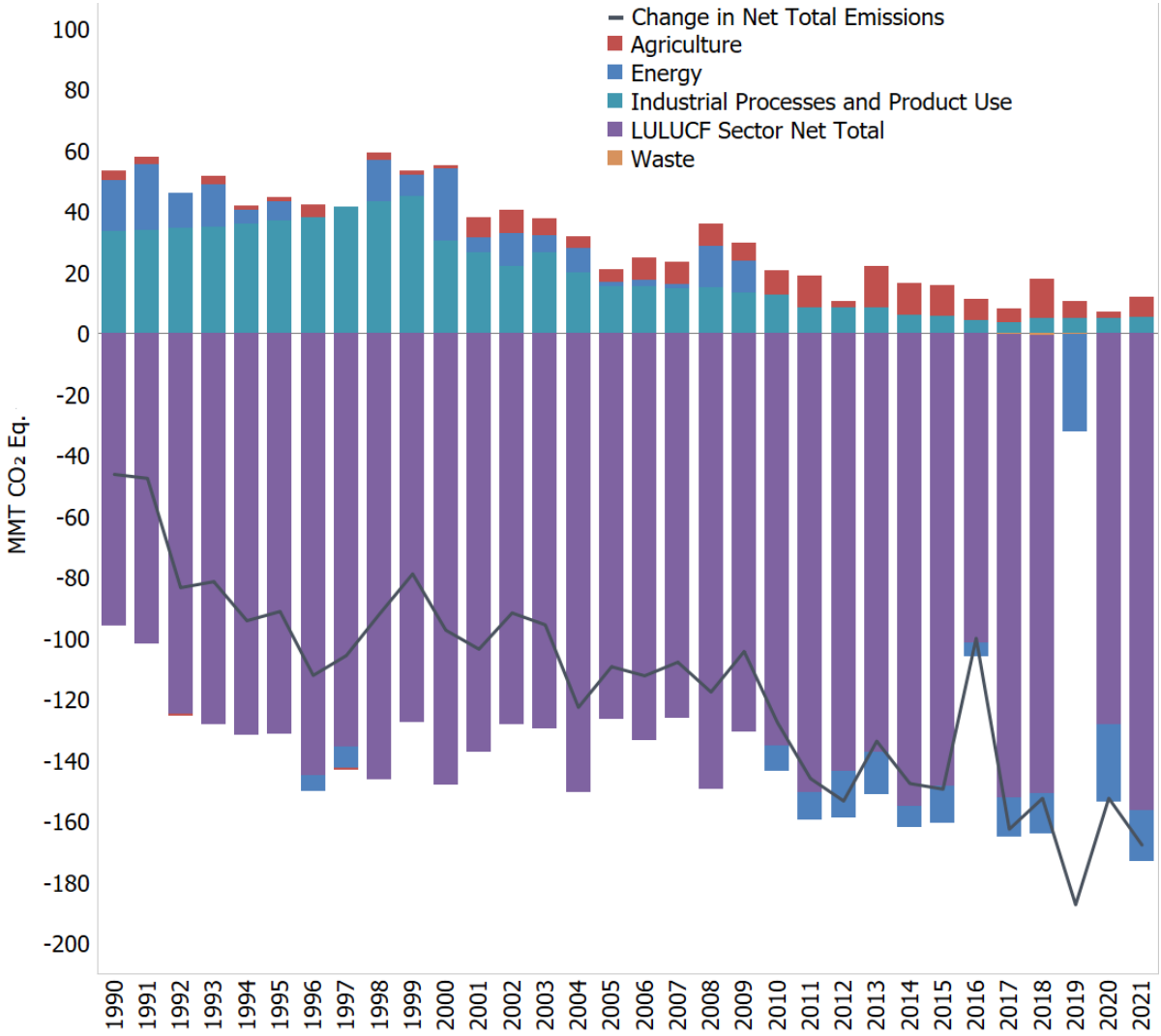


Table 9-4: Revisions to U.S. Greenhouse Gas Emissions (MMT CO_2 Eq.)

Gas/Source	1990	2005	2018	2019	2020	2021	Average Annual Change
CO_2	**10.7**	**(5.3)**	**(15.6)**	**(27.7)**	**(25.7)**	**(15.0)**	**(4.6)**
Fossil Fuel Combustion	*24.0*	*(3.2)*	*(1.7)*	*(3.3)*	*(3.2)*	*15.2*	*5.8*
Electric Power Sector	NC	NC	NC	NC	+	+	+
Transportation	NC	NC	0.2	0.2	0.3	1.1	0.1
Industrial	24.0	(3.2)	(3.1)	(6.1)	(5.9)	4.8	5.2
Residential	(+)	+	0.7	1.5	1.6	4.7	0.3
Commercial	(+)	+	0.5	1.0	0.8	4.5	0.2
U.S. Territories	(+)	(+)	(+)	(+)	(+)	(+)	(+)
Non-Energy Use of Fuels	(13.3)	(3.9)	(11.1)	(21.1)	(21.5)	(28.6)	(10.1)
Natural Gas Systems	0.2	1.3	(+)	(+)	0.3	(0.4)	0.4
Cement Production	NC	NC	NC	NC	NC	NC	NC

Lime Production	NC	NC	NC	NC	NC	NC	NC
Other Process Uses of Carbonates[a]	0.9	1.0	0.6	0.6	0.6	0.6	0.8
Glass Production	0.3	(+)	NC	NC	NC	NC	+
Soda Ash Production	NC	NC	NC	NC	NC	NC	NC
Carbon Dioxide Consumption	NC	NC	NC	NC	NC	NC	NC
Incineration of Waste	NC	NC	NC	NC	NC	NC	NC
Titanium Dioxide Production	NC	NC	NC	(0.1)	0.1	NC	+
Aluminum Production	NC	NC	NC	NC	NC	NC	NC
Iron and Steel Production & Metallurgical Coke Production	+	+	+	+	+	0.2	+
Ferroalloy Production	NC	NC	NC	NC	NC	NC	NC
Ammonia Production	NC	NC	NC	NC	NC	(+)	(+)
Urea Consumption for Non-Agricultural Purposes	NC	NC	+	(+)	(+)	1.6	0.1
Phosphoric Acid Production	NC	NC	NC	NC	NC	(+)	(+)
Petrochemical Production	(1.5)	(0.5)	(2.1)	(2.2)	(1.9)	(2.5)	(1.4)
Carbide Production and Consumption	NC	NC	NC	NC	NC	NC	NC
Lead Production	NC	NC	NC	NC	(+)	(+)	(+)
Zinc Production	NC	NC	NC	NC	NC	+	+
Petroleum Systems	0.1	(+)	(1.3)	(1.4)	(0.1)	(0.5)	(0.1)
Abandoned Oil and Gas Wells	+	+	+	+	+	+	+
Magnesium Production and Processing	+	+	NC	NC	NC	(+)	+
Liming	NC	NC	NC	NC	(+)	(0.7)	(+)
Urea Fertilization	NC	NC	(+)	+	+	+	(+)
Coal Mining	(+)	(+)	(+)	(+)	(+)	(+)	(+)
Substitution of Ozone Depleting Substances	NC	NC	NC	NC	NC	NC	NC
Biomass and Biodiesel Consumption[b]	*NC*	*NC*	*(+)*	*(+)*	*(9.9)*	*(12.3)*	*(0.7)*
International Bunker Fuels[c]	*NC*	*NC*	*NC*	*NC*	*NC*	*NC*	*NC*
CH_4[d]	**3.0**	**4.4**	**(2.6)**	**(13.4)**	**(6.9)**	**(7.0)**	**0.5**
Stationary Combustion	+	(+)	+	+	(0.8)	(0.9)	(+)
Mobile Combustion	+	(0.1)	(+)	(+)	(+)	(+)	(0.1)
Coal Mining	NC	(0.4)	NC	(+)	NC	(+)	(+)
Abandoned Underground Coal Mines	NC	NC	NC	NC	NC	(0.1)	(+)
Natural Gas Systems	3.7	6.9	(4.0)	(4.9)	(5.0)	(6.8)	1.9
Petroleum Systems	(1.9)	(2.7)	(1.6)	(7.7)	(1.2)	(1.5)	(2.5)
Abandoned Oil and Gas Wells	0.1	0.2	0.2	0.1	0.2	0.3	0.2
Petrochemical Production	(0.2)	(0.1)	(0.3)	(0.4)	(0.3)	(0.4)	(0.2)
Carbide Production and Consumption	NC	NC	NC	NC	NC	NC	NC
Iron and Steel Production & Metallurgical Coke Production	NC	NC	NC	NC	+	(+)	+
Ferroalloy Production	NC	NC	NC	NC	NC	NC	NC
Enteric Fermentation	+	+	(+)	(+)	0.1	1.5	0.1
Manure Management	0.1	0.1	1.2	0.9	0.2	0.4	0.3
Rice Cultivation	1.0	0.4	2.5	(1.2)	1.0	1.5	1.0
Field Burning of Agricultural Residues	0.1	0.2	0.1	0.2	0.1	0.1	0.1
Landfills	NC	(+)	(0.4)	(0.3)	(0.7)	(0.6)	(+)
Wastewater Treatment	(+)	(+)	(+)	(+)	(0.4)	(0.4)	(+)
Composting	NC	NC	NC	NC	NC	NC	NC
Anaerobic Digestion at Biogas Facilities	(+)	(+)	(0.2)	(0.2)	(0.2)	(0.2)	(0.1)
Incineration of Waste	NC	NC	NC	NC	NC	NC	NC
International Bunker Fuels[c]	NC	NC	NC	NC	NC	NC	NC
N_2O[d]	**1.9**	**3.4**	**9.3**	**6.1**	**2.3**	**4.9**	**3.9**
Stationary Combustion	0.1	(+)	(+)	(+)	(0.1)	(0.1)	+
Mobile Combustion	+	+	0.1	0.1	+	0.1	0.1
Adipic Acid Production	NC	NC	(+)	NC	NC	NC	(+)

Nitric Acid Production	NC	NC	NC	NC	NC	NC	NC
Manure Management	1.0	0.7	(0.6)	(0.6)	(0.6)	(0.3)	0.5
Agricultural Soil Management	0.8	2.6	9.7	6.3	1.6	3.9	3.3
Field Burning of Agricultural Residues	+	+	+	+	+	+	+
Wastewater Treatment	NC	NC	+	0.3	1.4	1.1	0.1
N_2O from Product Uses	NC	NC	NC	NC	NC	NC	NC
Caprolactam, Glyoxal, and Glyoxylic Acid Production	NC	NC	NC	NC	(+)	(+)	(+)
Incineration of Waste	NC	NC	NC	NC	NC	NC	NC
Composting	NC	NC	NC	NC	NC	NC	NC
Electronics Industry	NC	NC	+	+	+	+	+
Natural Gas Systems	+	+	+	+	+	+	+
Petroleum Systems	(+)	(+)	+	(+)	(+)	(+)	(+)
International Bunker Fuels[c]	*NC*	*NC*	*NC*	*NC*	*NC*	*NC*	*NC*
HFCs, PFCs, SF_6 and NF_3	**34.0**	**14.8**	**6.8**	**7.2**	**6.1**	**5.7**	**21.2**
HFCs	**8.7**	**5.4**	**3.0**	**2.7**	**2.1**	**1.9**	**6.9**
Substitution of Ozone Depleting Substances	NC	0.1	0.1	0.1	0.1	0.2	0.1
Fluorochemical Production[e]	8.7	5.3	2.9	2.6	2.0	1.7	6.8
Electronics Industry	(+)	(+)	(+)	+	(+)	+	+
Magnesium Production and Processing	NC	NC	NC	NC	NC	NC	NC
PFCs	**17.7**	**4.2**	**3.1**	**3.3**	**2.7**	**2.8**	**9.3**
Aluminum Production	NC	NC	NC	NC	NC	+	+
Fluorochemical Production	17.5*	4.0*	2.9*	3.0*	2.5*	2.6*	9.1*
Electronics Industry	(+)	+	0.1	0.1	0.1	+	+
Substitution of Ozone Depleting Substances	NC	+	(+)	(+)	(+)	(+)	(+)
SF_6 and PFCs from Other Product Use	0.1*	0.1*	0.2*	0.2*	0.2*	0.1*	0.1*
Electrical Equipment	+	(+)	NC	(+)	+	(+)	(+)
SF_6	**7.4**	**4.7**	**0.5**	**0.6**	**0.6**	**0.4**	**4.6**
Electrical Equipment	NC	+	(0.2)	(+)	+	+	(+)
SF_6 and PFCs from Other Product Use	1.3*	1.3*	0.8*	0.6*	0.5*	0.4*	1.2*
Fluorochemical Production	5.8*	3.3*	+	+	+	+	3.3*
Electronics Industry	NC	+	+	+	+	(+)	+
Magnesium Production and Processing	0.2	0.1	NC	NC	NC	+	0.1
NF_3	**0.3**	**0.6**	**0.1**	**0.6**	**0.7**	**0.5**	**0.5**
Electronics Industry	NC	NC	+	+	+	(+)	+
Fluorochemical Production	0.3*	0.6*	0.1*	0.6*	0.7*	0.5*	0.5*
Total Gross Emissions (Sources)	**49.6**	**17.3**	**(2.1)**	**(27.8)**	**(24.2)**	**(11.4)**	**21.0**
Percent Change in Total Emissions	**0.8%**	**0.2%**	**0.0%**	**-0.4%**	**-0.4%**	**(+)**	**0.3%**
Change in LULUCF Sector Net Total[f]	(95.8)	(126.5)	(150.4)	(159.5)	(128.2)	(156.3)	(135.8)
Net Emissions (Sources and Sinks)	**(46.2)**	**(109.3)**	**(152.4)**	**(187.3)**	**(152.4)**	**(167.8)**	**(114.8)**
Percent Change in Net Emissions	**-0.8%**	**-1.6%**	**-2.5%**	**-3.2%**	**-2.9%**	**-3.0%**	**-1.9%**

NC (No Change)

+ Absolute value does not exceed 0.05 MMT CO_2 Eq. or 0.05 percent.

* Indicates a new source for the current *Inventory* year. Emissions from new sources are captured in net emissions and percent change totals.

[a] Category includes emissions from ceramics production (new subcategory, not estimated in the previous *Inventory*), other uses of soda ash, and non-metallurgical magnesia (new subcategory, not estimated in the previous *Inventory*) in the current *Inventory.*

[b] Emissions from biomass and biofuel consumption are not included specifically in summing Energy sector totals. Net carbon fluxes from changes in biogenic carbon reservoirs are accounted for in the estimates for LULUCF.

[c] Emissions from international bunker fuels are not included in totals.

[d] LULUCF emissions of CH_4 and N_2O are reported separately from gross emissions totals in Table 9-4. LULUCF emissions include the CH_4 and N_2O emissions reported for peatlands remaining peatlands, forest fires, drained organic soils, grassland

fires, and coastal wetlands remaining coastal wetlands; CH_4 emissions from land converted to coastal wetlands; and N_2O emissions from forest soils and settlement soils.

[e] This category was reported as HCFC-22 production in the 1990 to 2021 *Inventory*.

[f] The LULUCF sector net total is the net sum of all CH_4 and N_2O emissions to the atmosphere plus net carbon stock changes. More detail on the impacts of recalculations on the LULUCF sector can be found in Table 9-5.

Notes: Totals may not sum due to independent rounding. Parentheses indicate negative values.

Table 9-5: Revisions to U.S. Greenhouse Gas Emissions and Removals (Net Flux) from Land Use, Land-Use Change, and Forestry (MMT CO_2 Eq.)

Land-Use Category	1990	2005	2017	2018	2019	2020	Average Annual Change
Forest Land Remaining Forest Land	**(153.1)**	**(164.6)**	**(170.4)**	**(169.0)**	**(162.4)**	**(153.4)**	**(160.7)**
Changes in Forest Carbon Stocks[a]	(153.3)	(161.8)	(169.1)	(163.8)	(154.6)	(148.8)	(159.1)
Non-CO_2 Emissions from Forest Fires[b]	0.3	(2.8)	(1.3)	(5.1)	(7.7)	(4.5)	(1.6)
N_2O Emissions from Forest Soils[c]	+	(+)	(+)	(+)	(+)	(+)	(+)
Non-CO_2 Emissions from Drained Organic Soils[d]	NC	NC	NC	NC	NC	NC	NC
Land Converted to Forest Land	**(1.8)**	**(1.7)**	**(2.1)**	**(2.0)**	**(2.0)**	**(2.1)**	**(1.8)**
Changes in Forest Carbon Stocks[e]	(1.8)	(1.7)	(2.1)	(2.0)	(2.0)	(2.1)	(1.8)
Cropland Remaining Cropland	**18.1**	**(2.6)**	**(1.2)**	**(4.9)**	**14.5**	**(13.0)**	**(4.2)**
Changes in Mineral and Organic Soil Carbon Stocks	18.1	(2.6)	(1.2)	(4.9)	14.5	(13.0)	(4.2)
Land Converted to Cropland	**(9.4)**	**(20.1)**	**(24.4)**	**(24.9)**	**(27.4)**	**(21.6)**	**(20.7)**
Changes in all Ecosystem Carbon Stocks[f]	(9.4)	(20.1)	(24.4)	(24.9)	(27.4)	(21.6)	(20.7)
Grassland Remaining Grassland	**15.7**	**13.2**	**17.8**	**14.2**	**10.5**	**0.9**	**10.8**
Changes in Mineral and Organic Soil Carbon Stocks	15.7	13.0	17.3	14.5	10.0	0.6	10.7
Non-CO_2 Emissions from Grassland Fires[g]	0.1	0.1	0.5	(0.3)	0.4	0.3	0.1
Land Converted to Grassland	**41.9**	**61.9**	**49.4**	**48.7**	**54.6**	**49.2**	**53.1**
Changes in all Ecosystem Carbon Stocks[f]	41.9	61.9	49.4	48.7	54.6	49.2	53.1
Wetlands Remaining Wetlands	**(4.7)**	**(3.7)**	**(3.7)**	**(3.7)**	**(3.7)**	**(3.7)**	**(3.9)**
Changes in Organic Soil Carbon Stocks in Peatlands	NC	NC	(0.1)	(0.1)	(0.1)	(0.2)	(+)
Changes in Biomass, DOM, and Soil Carbon Stocks in Coastal Wetlands	(2.4)	(2.4)	(2.3)	(2.3)	(2.3)	(2.3)	(2.4)
CH_4 Emissions from Coastal Wetlands Remaining Coastal Wetlands	NC	NC	NC	NC	NC	NC	NC
N_2O Emissions from Coastal Wetlands Remaining Coastal Wetlands	NC	NC	NC	NC	NC	NC	NC
Non-CO_2 Emissions from Peatlands Remaining Peatlands	NC	NC	(+)	(+)	(+)	(+)	(+)
CH_4 Emissions from Flooded Land Remaining Flooded Land	(2.3)	(1.3)	(1.2)	(1.2)	(1.2)	(1.2)	(1.5)
Land Converted to Wetlands	**3.9**	**0.4**	**(0.1)**	**(0.1)**	**0.1**	**0.1**	**1.1**
Changes in Biomass, DOM, and Soil Carbon Stocks in Land Converted to Coastal Wetlands	(+)	(+)	(+)	(+)	(+)	(+)	(+)
CH_4 Emissions from Land Converted to Coastal Wetlands	NC	NC	NC	NC	NC	NC	NC
Changes in Land Converted to Flooded Land	2.2	0.3	(+)	(+)	0.1	0.1	0.6
CH_4 Emissions from Land Converted to Flooded Land	1.8	0.2	(+)	(+)	+	+	0.5
Settlements Remaining Settlements	**(1.4)**	**(1.4)**	**(6.0)**	**(7.1)**	**(0.2)**	**0.2**	**(1.8)**
Changes in Organic Soil Carbon Stocks	(1.4)	(2.1)	(1.6)	(1.3)	(0.7)	(0.4)	(1.8)

Changes in Settlement Tree Carbon Stocks	(0.2)	0.4	(4.9)	(6.2)	0.1	+	(0.3)
Changes in Yard Trimming and Food Scrap Carbon Stocks in Landfills	NC	NC	NC	NC	NC	0.1	+
N_2O Emissions from Settlement Soils[h]	0.3	0.3	0.5	0.5	0.5	0.5	0.4
Land Converted to Settlements	**(5.2)**	**(7.9)**	**(9.7)**	**(10.9)**	**(12.2)**	**(12.8)**	**(7.7)**
Changes in all Ecosystem Carbon Stocks[f]	(5.2)	(7.9)	(9.7)	(10.9)	(12.2)	(12.8)	(7.7)
Change in LULUCF Total Net Flux[i]	**(95.8)**	**(123.0)**	**(148.8)**	**(153.4)**	**(120.2)**	**(151.4)**	**(133.6)**
Change in LULUCF Emissions[j]	**+**	**(3.6)**	**(1.6)**	**(6.2)**	**(8.0)**	**(4.9)**	**(2.2)**
CH_4	(0.4)	(2.8)	(1.8)	(4.4)	(6.1)	(3.8)	(2.0)
N_2O	0.4	(0.7)	0.2	(1.8)	(1.9)	(1.1)	(0.2)
Change in LULUCF Sector Net Total[k]	**(95.8)**	**(126.6)**	**(150.4)**	**(159.5)**	**(128.2)**	**(156.3)**	**(135.8)**
Percent Change in LULUCF Sector Net Total	**-10.9%**	**-16.2%**	**-19.7%**	**-22.7%**	**-16.5%**	**-20.7%**	**-17.0%**

NC (No Change)

+ Absolute value does not exceed 0.05 MMT CO_2 Eq. or 0.05 percent.

[a] Includes the net changes to carbon stocks stored in all forest ecosystem pools (estimates include carbon stock changes from drained organic soils from both forest land remaining forest land and land converted to forest land) and harvested wood products.

[b] Estimates include CH_4 and N_2O emissions from fires on both forest land remaining forest land and land converted to forest land.

[c] Estimates include N_2O emissions from N fertilizer additions on both forest land remaining forest land and land converted to forest land.

[d] Estimates include CH_4 and N_2O emissions from drained organic soils on both forest land remaining forest land and land converted to forest land. Carbon stock changes from drained organic soils are included with the forest land remaining forest land forest ecosystem pools.

[e] Includes the net changes to carbon stocks stored in all forest ecosystem pools.

[f] Includes changes in mineral and organic soil carbon stocks for all land use conversions to cropland, grassland, and settlements, respectively. Also includes aboveground/belowground biomass, dead wood, and litter carbon stock changes for conversion of forest land to cropland, grassland, and settlements.

[g] Estimates include CH_4 and N_2O emissions from fires on both grassland remaining grassland and land converted to grassland.

[h] Estimates include N_2O emissions from N fertilizer additions on both settlements remaining settlements and land converted to settlements because it is not possible to separate the activity data at this time.

[i] LULUCF carbon stock change includes any C stock gains and losses from all land use and land use conversion categories.

[j] LULUCF emissions include the CH_4 and N_2O emissions reported for peatlands remaining peatlands, forest fires, drained organic soils, grassland fires, and coastal wetlands remaining coastal wetlands; CH_4 emissions from land converted to coastal wetlands, flooded land remaining flooded land, and land converted to flooded land; and N_2O emissions from forest soils and settlement soils.

[k] The LULUCF sector net total is the net sum of all LULUCF CH_4 and N_2O emissions to the atmosphere plus LULUCF net carbon stock changes in units of MMT CO_2 Eq.

Notes: Totals may not sum due to independent rounding. Parentheses indicate negative values.

10. References and Abbreviations

Executive Summary

BEA (2024) *2022 Comprehensive Revision of the National Income and Product Accounts: Current-dollar and "real" GDP, 1929–2022*. Bureau of Economic Analysis (BEA), U.S. Department of Commerce, Washington, D.C. Available online at: http://www.bea.gov/national/index.htm#gdp.

EIA (2024) *Monthly Energy Review, February 2024.* Energy Information Administration, U.S. Department of Energy, Washington, D.C. DOE/EIA-0035(2023/11).

IEA (2022) *Energy related CO_2 emissions, 2022,* International Energy Agency, Paris. Available online at: https://www.iea.org/reports/co2-emissions-in-2022.

IPCC (2021) *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change.* [Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 2391 pp. doi:10.1017/9781009157896.

IPCC (2019) *2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories.* Calvo Buendia, E., Tanabe, K., Kranjc, A., Baasansuren, J., Fukuda, M., Ngarize, S., Osako, A., Pyrozhenko, Y., Shermanau, P. and Federici, S. (eds). Published: IPCC, Switzerland.

IPCC (2013) *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. [Stocker, T.F., D. Qin, G.-K., Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1535 pp.

IPCC (2007) *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. [S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds.)]. Cambridge University Press. Cambridge, United Kingdom 996 pp.

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change. [H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (eds.)]. Hayama, Kanagawa, Japan.

National Academies of Sciences, Engineering, and Medicine (2018) *Improving characterization of anthropogenic methane emissions in the United States*. Washington, DC: The National Academies Press. Available online at: https://doi.org/10.17226/24987.

National Research Council (2010) *Verifying greenhouse gas emissions: methods to support international climate agreements*. Washington, DC: The National Academies Press. Available online at: https://doi.org/10.17226/12883.

NOAA/ESRL (2024a) *Trends in Atmospheric Carbon Dioxide*. Available online at: https://gml.noaa.gov/ccgg/trends/. 05 January 2024.

NOAA/ESRL (2024b) *Trends in Atmospheric Methane.* Available online at: https://gml.noaa.gov/ccgg/trends_ch4/. 05 January 2024.

NOAA/ESRL (2024c) *Trends in Atmospheric Nitrous Oxide.* Available online at: https://gml.noaa.gov/ccgg/trends_n2o/. 05 January 2024.

UNFCCC (2014) *Report of the Conference of the Parties on its Nineteenth Session, Held in Warsaw from 11 to 23 November 2013*. (FCCC/CP/2013/10/Add.3). January 31, 2014. Available online at: http://unfccc.int/resource/docs/2013/cop19/eng/10a03.pdf.

U.S. Census Bureau (2024) U.S. Census Bureau International Database (IDB). Available online at: https://www.census.gov/programs-surveys/international-programs.html.

Introduction

IPCC (2021) *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change.* [Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 2391 pp. doi:10.1017/9781009157896.

IPCC (2014) *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Edenhofer, O., R. Pichs-Madruga, Y. Sokona, J. Minx, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlomer, C. von Stechow, and T. Zwickel (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1435 pp.

IPCC (2013) *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1535 pp.

IPCC (2007*) Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. [S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds.)]. Cambridge University Press. Cambridge, United Kingdom 996 pp.

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change. [H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (eds.)]. Hayama, Kanagawa, Japan.

IPCC (2001) *Climate Change 2001: The Scientific Basis. Intergovernmental Panel on Climate Change.* [J.T. Houghton, Y. Ding, D.J. Griggs, M. Noguer, P.J. van der Linden, X. Dai, C.A. Johnson, and K. Maskell (eds.)]. Cambridge University Press. Cambridge, United Kingdom.

IPCC/TEAP (2005) *Special Report: Safeguarding the Ozone Layer and the Global Climate System, Chapter 4: Refrigeration*. 2005. Available online at: https://www.ipcc.ch/site/assets/uploads/2018/03/sroc04-1.pdf.

Meinhausen, M., et al. (2017) *Historical Greenhouse Gas Concentrations for Climate Modeling (CMIP6).* Available online at: https://gmd.copernicus.org/articles/10/2057/2017/.

NOAA (2017) Vital Signs of the Planet. Available online at: http://climate.nasa.gov/causes/. Accessed on 9 January 2017.

NOAA/ESRL (2024a) *Trends in Atmospheric Carbon Dioxide*. Available online at: https://gml.noaa.gov/ccgg/trends/gr.html. March 26, 2024.

NOAA/ESRL (2024b) *Trends in Atmospheric Methane.* Available online at: https://gml.noaa.gov/ccgg/trends_ch4/. March 26, 2024.

NOAA/ESRL (2024c) *Trends in Atmospheric Nitrous Oxide.* Available online at: https://gml.noaa.gov/ccgg/trends_n2o/. March 26, 2024.

NOAA/ESRL (2024d) *Trends in Atmospheric Sulfur Hexafluoride*. Available online at: https://gml.noaa.gov/ccgg/trends_sf6/. March 26, 2024.

Rigby, M., et al. (2010) *History of Atmospheric SF_6 from 1973 to 2008.* Available online at: www.atmos-chem-phys.net/10/10305/2010. March 23, 2024.

UNEP/WMO (1999) Information Unit on Climate Change. Framework Convention on Climate Change. Available online at: http://unfccc.int.

UNFCCC (2014) *Report of the Conference of the Parties on its nineteenth session, held in Warsaw from 11 to 23 November 2013*. (FCCC/CP/2013/10/Add.3). January 31, 2014. Available online at: http://unfccc.int/resource/docs/2013/cop19/eng/10a03.pdf.

USGCRP (2017) *Climate Science Special Report: Fourth National Climate Assessment, Volume I.* [Wuebbles, D.J., D.W. Fahey, K.A. Hibbard, D.J. Dokken, B.C. Stewart, and T.K. Maycock (eds.)]. U.S. Global Change Research Program, Washington, DC, USA, 470 pp, doi: 10.7930/J0J964J6. Available online at: https://science2017.globalchange.gov/.

WMO/UNEP (2018) Scientific Assessment of Ozone Depletion: 2018. Available online at: https://csl.noaa.gov/assessments/ozone/2018.

Trends in Greenhouse Gas Emissions

BEA (2024) 2022 *Comprehensive Revision of the National Income and Product Accounts: Current-dollar and "real" GDP, 1929–2022*. Bureau of Economic Analysis (BEA), U.S. Department of Commerce, Washington, D.C. Available online at: http://www.bea.gov/national/index.htm#gdp.

EIA (2024) *Monthly Energy Review, February 2024.* Energy Information Administration, U.S. Department of Energy, Washington, D.C. DOE/EIA-0035(2023/11).

EIA (2020) *Fuel Oil and Kerosene Sales.* Energy Information Administration, U.S. Department of Energy. Washington, D.C. Available online at: http://www.eia.gov/petroleum/fueloilkerosene.

EPA (2023a) "Criteria pollutants National Tier 1 for 1970 – 2023." National Emissions Inventory (NEI) Air Pollutant Emissions Trends Data. Office of Air Quality Planning and Standards, March 2024. Available online at: https://www.epa.gov/air-emissions-inventories/air-pollutant-emissions-trends-data.

EPA (2023b) *2023 EPA Automotive Trends Report.* Office of Transportation and Air Quality, U.S. Environmental Protection Agency. Available online at: https://www.epa.gov/automotive-trends/download-automotive-trends-report.

IPCC (2021) *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change.* [Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 2391 pp. doi:10.1017/9781009157896.

IPCC (2019) *2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories.* Calvo Buendia, E., Tanabe, K., Kranjc, A., Baasansuren, J., Fukuda, M., Ngarize, S., Osako, A., Pyrozhenko, Y., Shermanau, P. and Federici, S. (eds). Published: IPCC, Switzerland.

IPCC (2013) *Climate Change 2013: The Physical Science Basis.* Contribution of Working Group I to the *Fifth Assessment Report* of the Intergovernmental Panel on Climate Change. [Stocker, T.F., D. Qin, G.-K., Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1535 pp.

IPCC (2007) *Climate Change 2007: The Physical Science Basis*. Contribution of Working Group I to the *Fourth Assessment Report* of the Intergovernmental Panel on Climate Change. [S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds.)]. Cambridge University Press. Cambridge, United Kingdom 996 pp.

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change. [H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (eds.)]. Hayama, Kanagawa, Japan.

U.S. Census Bureau (2024) U.S. Census Bureau International Database (IDB). Available online at: https://www.census.gov/programs-surveys/international-programs.html.

U.S. Department of Agriculture, National Agricultural Statistics Service (USDA/NASS) (2023) Farm Production Expenditures Annual Summary. National Agricultural Statistics Service, U.S. Department of Agriculture, Washington DC. Available online at: https://usda.library.cornell.edu/concern/publications/qz20ss48r?locale=en.

Energy

EIA (2024) *Monthly Energy Review, February 2024*, Energy Information Administration, U.S. Department of Energy, Washington, DC. DOE/EIA-0035(2024/02).

IEA (2022) *Energy related CO_2 emissions, 2022*, International Energy Agency, Paris. Available online at: https://www.iea.org/reports/co2-emissions-in-2022.

Carbon Dioxide Emissions from Fossil Fuel Combustion

AAR (2008 through 2022) *Railroad Facts.* Policy and Economics Department, Association of American Railroads, Washington, D.C. Private communication with Dan Keen.

AISI (2004 through 2021) *Annual Statistical Report*, American Iron and Steel Institute, Washington, D.C.

APTA (2007 through 2020) *Public Transportation Fact Book.* American Public Transportation Association, Washington, D.C. Available online at: http://www.apta.com/resources/statistics/Pages/transitstats.aspx.

APTA (2006) *Commuter Rail National Totals.* American Public Transportation Association, Washington, D.C.

BEA (2024) *2022 Comprehensive Revision of the National Income and Product Accounts: Current-dollar and "real" GDP, 1929–2022*. Bureau of Economic Analysis (BEA), U.S. Department of Commerce, Washington, D.C. Available online at: http://www.bea.gov/national/index.htm#gdp.

BEA (1991 through 2015) Unpublished BE-36 survey data. Bureau of Economic Analysis, U.S. Department of Commerce. Washington, D.C.

Benson, D. (2002 through 2004) Unpublished data. Upper Great Plains Transportation Institute, North Dakota State University and American Short Line & Regional Railroad Association.

Browning (2022a) Addressing the Time Series Inconsistency in FHWA Data. Memorandum from ICF to Sarah Roberts, Office of Transportation and Air Quality, U.S. Environmental Protection Agency. September 2022.

Browning (2022b) Updated Methodology for Estimating CH_4 and N_2O Emissions from Highway Vehicle Alternative Fuel Vehicles. Memorandum from ICF to Sarah Roberts, Office of Transportation and Air Quality, U.S. Environmental Protection Agency. November 2022.

Browning, L. (2020) *GHG Inventory EF Development Using Certification Data.* Technical Memo, September 2020.

Browning, L. (2019) Updated On-highway CH_4 and N_2O Emission Factors for GHG Inventory. Memorandum from ICF to Sarah Roberts, Office of Transportation and Air Quality, U.S. Environmental Protection Agency. September 2019.

Browning, L. (2018a) Updated Methodology for Estimating Electricity Use from Highway Plug-In Electric Vehicles. Technical Memo, October 2018.

Browning, L. (2018b) Updated Non-Highway CH_4 and N_2O Emission Factors for U.S. GHG Inventory. Technical Memo, November 2018.

Browning, L. (2017) Updated Methodology for Estimating CH_4 and N_2O Emissions from Highway Vehicle Alternative Fuel Vehicles. Technical Memo, October 2017.

Coffeyville Resources Nitrogen Fertilizers (2012) Nitrogen Fertilizer Operations. Available online at: http://coffeyvillegroup.com/NitrogenFertilizerOperations/index.html.

Dakota Gasification Company (2006) *CO_2 Pipeline Route and Designation Information*. Bismarck, ND.

DHS (2008) Email Communication. Elissa Kay, Department of Homeland Security and Joe Aamidor, ICF International. January 11, 2008.

DLA Energy (2022) Unpublished data from the Fuels Automated System (FAS). Defense Logistics Agency Energy, U.S. Department of Defense. Washington, D.C.

DOC (1991 through 2022) Unpublished Report of Bunker Fuel Oil Laden on Vessels Cleared for Foreign Countries. Form-563. Foreign Trade Division, Bureau of the Census, U.S. Department of Commerce. Washington, D.C.

DOE (1991 through 2020) *Transportation Energy Data Book*. *Edition 40*. Office of Transportation Technologies, Center for Transportation Analysis, Energy Division, Oak Ridge National Laboratory. ORNL-6978. Personal Communication between Stacy Davis (DOE) and Deep Shah (ICF) for sharing selected tables from the pre-release version.

DOE (2012) *2010 Worldwide Gasification Database*. National Energy Technology Laboratory and Gasification Technologies Council. Available online at: http://www.netl.doe.gov/technologies/coalpower/gasification/worlddatabase/index.html. Accessed on 15 March 2012.

DOT (1991 through 2023) *Airline Fuel Cost and Consumption*. U.S. Department of Transportation, Bureau of Transportation Statistics, Washington, D.C. DAI-10. Available online at: http://www.transtats.bts.gov/fuel.asp.

Eastman Gasification Services Company (2011) Project Data on Eastman Chemical Company's Chemicals-from-Coal Complex in Kingsport, TN.

EIA (2024a) *Monthly Energy Review, February 2024,* Energy Information Administration, U.S. Department of Energy, Washington, DC. DOE/EIA-0035 (2024/02).

EIA (2024b) International Energy Statistics 1980-2022. Energy Information Administration, U.S. Department of Energy. Washington, D.C. Available online at: https://www.eia.gov/beta/international/.

EIA (2024c) *Quarterly Coal Report: January – September 2023*. Energy Information Administration, U.S. Department of Energy. Washington, D.C. DOE/EIA-0121.

EIA (2023a) *Natural Gas Annual 2022.* Energy Information Administration, U.S. Department of Energy. Washington, D.C. DOE/EIA-0131(20).

EIA (2023b). *Petroleum Supply Annual 2022*. Energy Information Administration, U.S. Department of Energy. Washington, D.C. Available online at: https://www.eia.gov/petroleum/.

EIA (2023c) Form EIA-923 detailed data with previous form data (EIA-906/920), Energy Information Administration, U.S. Department of Energy. Washington, DC. DOE/EIA. November 2023.

EIA (2023d) *Annual Coal Report 2022*. Energy Information Administration, U.S. Department of Energy. Washington, D.C. DOE/EIA-0584.

EIA (2022) "Energy use in homes." *Use of energy explained.* Available online at: https://www.eia.gov/energyexplained/use-of-energy/homes.php.

EIA (2020a) Glossary. Energy Information Administration, U.S. Department of Energy, Washington, D.C. Available online at: https://www.eia.gov/tools/glossary/?id=electricity.

EIA (2020b) "Natural gas prices, production, consumption, and exports increased in 2019." *Today in Energy*. Available online at: https://www.eia.gov/todayinenergy/detail.php?id=37892.

EIA (2018) "Both natural gas supply and demand have increased from year-ago levels." Today in Energy. Available online at: https://www.eia.gov/todayinenergy/detail.php?id=37193.

EIA (2009a) *Emissions of Greenhouse Gases in the United States 2008, Draft Report.* Office of Integrated Analysis and Forecasting, Energy Information Administration, U.S. Department of Energy. Washington, D.C. DOE-EIA-0573 (2009).

EIA (2009b) *Manufacturing Consumption of Energy (MECS) 2006*. U.S. Department of Energy, Energy Information Administration, Washington, D.C. Released July 2009.

EIA (2008) *Historical Natural Gas Annual, 1930 – 2008*. Energy Information Administration, U.S. Department of Energy. Washington, D.C.

EIA (2007) Personal Communication. Joel Lou, Energy Information Administration and Aaron Beaudette, ICF International. *Residual and Distillate Fuel Oil Consumption for Vessel Bunkering (Both International and Domestic) for American Samoa, U.S. Pacific Islands, and Wake Island*. October 24, 2007.

EIA (2002) *Alternative Fuels Data Tables*. Energy Information Administration, U.S. Department of Energy. Washington, D.C. Available online at: https://www.eia.gov/renewable/.

EIA (2001) *U.S. Coal, Domestic and International Issues*. Energy Information Administration, U.S. Department of Energy. Washington, D.C. March 2001.

EIA (1990-2001) *State Energy Data System*. Energy Information Administration, U.S. Department of Energy. Washington, D.C.

Environment and Climate Change Canada (2022) Personal Communication between Environment and Climate Change Canada and Vincent Camobreco for imported CO_2. March 2022.

EPA (2024) Acid Rain Program Dataset 1996-2022. Office of Air and Radiation, Office of Atmospheric Programs, U.S. Environmental Protection Agency, Washington, D.C.

EPA (2023) The 2023 EPA Automotive Trends Report: Greenhouse Gas Emissions, Fuel Economy, and Technology since 1975. Office of Transportation and Air Quality, U.S. Environmental Protection Agency. Available online at: https://www.epa.gov/automotive-trends.

EPA (2022) *Motor Vehicle Emissions Simulator (MOVES3)*. Office of Transportation and Air Quality, U.S. Environmental Protection Agency, Washington, D.C. Available online at: https://www.epa.gov/moves.

EPA (2021) The Emissions & Generation Resource Integrated Database (eGRID) 2019 Technical Support Document. Clean Air Markets Division, Office of Atmospheric Programs, U.S. Environmental Protection Agency, Washington, D.C. Available Online at: https://www.epa.gov/sites/default/files/2021-02/documents/egrid2019_technical_guide.pdf

EPA (2020) EPA Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-2019: Updated Gasoline and Diesel Fuel CO_2 Emission Factors – Memo.

EPA (2010) Carbon Content Coefficients Developed for EPA's Mandatory Reporting Rule. Office of Air and Radiation, Office of Atmospheric Programs, U.S. Environmental Protection Agency, Washington, D.C.

Erickson, T. (2003) *Plains CO_2 Reduction (PCOR) Partnership*. Presented at the Regional Carbon Sequestration Partnership Meeting Pittsburgh, Pennsylvania, Energy and Environmental Research Center, University of North Dakota. November 3, 2003.

FAA (2024) Personal Communication between FAA and John Steller, Mausami Desai, and Vincent Camobreco for aviation emissions estimates from the Aviation Environmental Design Tool (AEDT). March 2024.

FHWA (1996 through 2023) *Highway Statistics*. Federal Highway Administration, U.S. Department of Transportation, Washington, D.C. Report FHWA-PL-96-023-annual. Available online at: http://www.fhwa.dot.gov/policy/ohpi/hss/hsspubs.htm.

FHWA (2015) *Off-Highway and Public-Use Gasoline Consumption Estimation Models Used in the Federal Highway Administration*, Publication Number FHWA-PL-17-012. Available online at: https://www.fhwa.dot.gov/policyinformation/pubs/pl17012.pdf.

Fitzpatrick, E. (2002) *The Weyburn Project: A Model for International Collaboration*.

FRB (2022) *Industrial Production and Capacity Utilization*. Federal Reserve Statistical Release, G.17, Federal Reserve Board. Available online at: http://www.federalreserve.gov/releases/G17/table1_2.htm.

Gaffney, J. (2007) Email Communication. John Gaffney, American Public Transportation Association and Joe Aamidor, ICF International. December 17, 2007.

IPCC (2013) *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change.* [Stocker, T.F., D. Qin, G.K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1535 pp.

IPCC (2007) *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change.* [S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds.)]. Cambridge University Press. Cambridge, United Kingdom, 996 pp.

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change. [H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (eds.)]. Hayama, Kanagawa, Japan.Marland, G. and A. Pippin (1990) "United States Emissions of Carbon Dioxide to the Earth's Atmosphere by Economic Activity." *Energy Systems and Policy,* 14(4):323.

NREL (2023) "NREL Researchers Reveal How Buildings Across United States Do—and Could—Use Energy." Available online at: https://www.nrel.gov/news/features/2023/nrel-researchers-reveal-how-buildings-across-the-united-

states-do-and-could-use-energy.html#:~:text=Buildings%20are%20responsible%20for%2040,building%20stock%20is%20also%20essential.

SAIC/EIA (2001) *Monte Carlo Simulations of Uncertainty in U.S. Greenhouse Gas Emission Estimates*. *Final Report*. Prepared by Science Applications International Corporation (SAIC) for Office of Integrated Analysis and Forecasting, Energy Information Administration, U.S. Department of Energy. Washington, D.C. June 22, 2001.

U.S. Aluminum Association (USAA) (2008 through 2021) U*.S. Primary Aluminum Production*. U.S. Aluminum Association, Washington, D.C.

USAF (1998) Fuel Logistics Planning. U.S. Air Force: AFPAM23-221. May 1, 1998.

U.S. Census Bureau (2001 through 2011) *Current Industrial Reports Fertilizer Materials and Related Products: Annual Summary*. Available online at: https://www.census.gov/data/tables/time-series/econ/cir/mq325b.html.

United States Geological Survey (USGS) (2020a) *2020 Mineral Commodity Summaries: Aluminum*. U.S. Geological Survey, Reston, VA.

USGS (2021b) *2021 Mineral Commodity Summary: Titanium and Titanium Dioxide*. U.S. Geological Survey, Reston, VA.

USGS (2019) *2017 Mineral Yearbook: Aluminum.* U.S. Geological Survey, Reston, VA

USGS (2014 through 2021a) *Mineral Industry Surveys: Silicon*. U.S. Geological Survey, Reston, VA.

USGS (2014 through 2021b) *Mineral Commodity Summary, Lead*. U.S. Geological Survey, Reston, VA.

USGS (2014 through 2019) *Minerals Yearbook: Nitrogen [Advance Release*]. Available online at: http://minerals.usgs.gov/minerals/pubs/commodity/nitrogen/.

USGS (1991 through 2020) *Minerals Yearbook – Iron and Steel Scrap*. U.S. Geological Survey, Reston, VA.

USGS (1991 through 2015a) *Minerals Yearbook: Manufactured Abrasives Annual Report*. U.S. Geological Survey, Reston, VA. Available online at: http://minerals.usgs.gov/minerals/pubs/commodity/abrasives/.

USGS (1991 through 2015b) *Minerals Yearbook: Titanium*. U.S. Geological Survey, Reston, VA.

USGS (1991 through 2015c) *Minerals Yearbook: Silicon Annual Report*. U.S. Geological Survey, Reston, VA. Available online at: http://minerals.usgs.gov/minerals/pubs/commodity/silicon/.

USGS (1996 through 2013) *Minerals Yearbook: Silicon*. U.S. Geological Survey, Reston, VA.

USGS (1995 through 2013) *Minerals Yearbook: Lead Annual Report*. U.S. Geological Survey, Reston, VA.

USGS (1995, 1998, 2000, 2001, 2002, 2007) *Minerals Yearbook: Aluminum Annual Report*. U.S. Geological Survey, Reston, VA.

Stationary Combustion (excluding CO_2)

EIA (2024a) *Monthly Energy Review, February 2024*. Energy Information Administration, U.S. Department of Energy. Washington, D.C. DOE/EIA-0035(2024/02).

EIA (2024b) *International Energy Statistics 1980-2022*. Energy Information Administration, U.S. Department of Energy. Washington, D.C. Available online at: https://www.eia.gov/international/data/world.

EPA (2024) Acid Rain Program Dataset 1996-2022. Office of Air and Radiation, Office of Atmospheric Programs, U.S. Environmental Protection Agency, Washington, D.C.

EPA (2022) *MOtor Vehicle Emissions Simulator (MOVES3)*. Office of Transportation and Air Quality, U.S. Environmental Protection Agency, Washington, D.C. Available online at: https://www.epa.gov/moves.

EPA (1997) Compilation of Air Pollutant Emission Factors, AP-42. Office of Air Quality Planning and Standards, U.S. Environmental Protection Agency. Research Triangle Park, NC. October 1997.

FHWA (1996 through 2023) *Highway Statistics*. Federal Highway Administration, U.S. Department of Transportation, Washington, D.C. Report FHWA-PL-96-023-annual. Available online at: http://www.fhwa.dot.gov/policy/ohpi/hss/hsspubs.htm.

IPCC (2013) *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change.* [Stocker, T.F., D. Qin, G.K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1535 pp.

IPCC (2007). *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change.* [S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds.)]. Cambridge University Press. Cambridge, United Kingdom, 996 pp.

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change. [H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (eds.)]. Hayama, Kanagawa, Japan.SAIC/EIA (2001) *Monte Carlo Simulations of Uncertainty in U.S. Greenhouse Gas Emission Estimates*. *Final Report*. Prepared by Science Applications International Corporation (SAIC) for Office of Integrated Analysis and Forecasting, Energy Information Administration, U.S. Department of Energy. Washington, D.C. June 22, 2001.

Mobile Combustion (excluding CO_2)

AAR (2008 through 2023) *Railroad Facts.* Policy and Economics Department, Association of American Railroads, Washington, D.C. Private communication with Dan Keen.

ANL (2022) *The Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation Model (GREET2022)*. Argonne National Laboratory. October 2022. Available online at: https://greet.es.anl.gov.

APTA (2007 through 2023) *Public Transportation Fact Book.* American Public Transportation Association, Washington, D.C. Available online at: http://www.apta.com/resources/statistics/Pages/transitstats.aspx.

APTA (2006) *Commuter Rail National Totals.* American Public Transportation Association, Washington, D.C. Available online at: http://www.apta.com/research/stats/rail/crsum.cfm.

BEA (1991 through 2015) Unpublished BE-36 survey data. Bureau of Economic Analysis, U.S. Department of Commerce. Washington, D.C.

Benson, D. (2002 through 2004) Personal communication. Unpublished data developed by the Upper Great Plains Transportation Institute, North Dakota State University and American Short Line & Regional Railroad Association.

Browning (2022a) Addressing the Time Series Inconsistency in FHWA Data. Memorandum from ICF to Sarah Roberts, Office of Transportation and Air Quality, U.S. Environmental Protection Agency. September 2022.

Browning (2022b) Updated Methodology for Estimating CH_4 and N_2O Emissions from Highway Vehicle Alternative Fuel Vehicles. Memorandum from ICF to Sarah Roberts, Office of Transportation and Air Quality, U.S. Environmental Protection Agency. November 2022.

Browning (2020) *GHG Inventory EF Development Using Certification Data*. Memorandum from ICF to Sarah Roberts, Office of Transportation and Air Quality, U.S. Environmental Protection Agency. September 2020.

Browning, L. (2019) Updated On-highway CH_4 and N_2O Emission Factors for GHG Inventory. Memorandum from ICF to Sarah Roberts and Justine Geidosch, Office of Transportation and Air Quality, U.S. Environmental Protection Agency. September 2019.

Browning, L. (2018) Updated Non-Highway CH_4 and N_2O Emission Factors for U.S. GHG Inventory. Technical Memorandum from ICF International to Sarah Roberts and Justine Geidosch, Office of Transportation and Air Quality, U.S. Environmental Protection Agency. November 2018.

Browning, L. (2005) Personal communication with Lou Browning, "Emission control technologies for diesel highway vehicles specialist," ICF International.

BTS (2023) *Amtrak Fuel Consumption and Travel.* Bureau of Transportation Statistics, Washington, DC. Available online at: https://www.bts.gov/content/amtrak-fuel-consumption-and-travel-1.

DLA Energy (2022) Unpublished data from the Defense Fuels Automated Management System (DFAMS). Defense Energy Support Center, Defense Logistics Agency, U.S. Department of Defense. Washington, D.C.

DOC (1991 through 2022) Unpublished Report of Bunker Fuel Oil Laden on Vessels Cleared for Foreign Countries. Form-563. Foreign Trade Division, Bureau of the Census, U.S. Department of Commerce. Washington, D.C.

DOE (1993 through 2022) *Transportation Energy Data Book Edition 40*. Office of Transportation Technologies, Center for Transportation Analysis, Energy Division, Oak Ridge National Laboratory. Personal Communication between Stacy Davis (DOE) and Deep Shah (ICF) for sharing selected tables from the pre-release version.

DOT (1991 through 2023) Airline *Fuel Cost and Consumption*. U.S. Department of Transportation, Bureau of Transportation Statistics, Washington, D.C. DAI-10. Available online at: http://www.transtats.bts.gov/fuel.asp.

EIA (2024) *Monthly Energy Review, February 2024,* Energy Information Administration, U.S. Department of Energy, Washington, D.C. DOE/EIA-0035(2024/02).

EIA (2023) *Natural Gas Annual 2022*. Energy Information Administration, U.S. Department of Energy, Washington, D.C. DOE/EIA-0131(22).

EIA (1991 through 2022) *Fuel Oil and Kerosene Sales.* Energy Information Administration, U.S. Department of Energy. Washington, D.C. Available online at: http://www.eia.gov/petroleum/fueloilkerosene.

EIA (2007) Personal Communication. Joel Lou, Energy Information Administration and Aaron Beaudette, ICF International. *Residual and Distillate Fuel Oil Consumption for Vessel Bunkering (Both International and Domestic) for American Samoa, U.S. Pacific Islands, and Wake Island*. October 24, 2007.

EIA (2002) *Alternative Fuels Data Tables*. Energy Information Administration, U.S. Department of Energy, Washington, D.C. Available online at: http://www.eia.doe.gov/fuelrenewable.html.

EPA (2023) Annual Certification Test Results Report. Office of Transportation and Air Quality, U.S. Environmental Protection Agency. Available online at: https://www.epa.gov/compliance-and-fuel-economy-data/annual-certification-test-data-vehicles-and-engines.

EPA (2022a) *Motor Vehicle Emissions Simulator (MOVES3)*. Office of Transportation and Air Quality, U.S. Environmental Protection Agency. Available online at: https://www.epa.gov/moves.

EPA (2022b) Confidential Engine Family Sales Data Submitted to EPA by Manufacturers. Office of Transportation and Air Quality, U.S. Environmental Protection Agency.

EPA (2004) *Mobile6.2 Vehicle Emission Modeling Software*. Office of Mobile Sources, U.S. Environmental Protection Agency, Ann Arbor, Michigan.

EPA (1999) *Emission Facts: The History of Reducing Tailpipe Emissions.* Office of Mobile Sources. May 1999. EPA 420-F-99-017. Available online at: https://www.epa.gov/nscep.

EPA (1998) *Emissions of Nitrous Oxide from Highway Mobile Sources: Comments on the Draft Inventory of U.S. Greenhouse Gas Emissions and Sinks, 1990–1996*. Office of Mobile Sources, Assessment and Modeling Division, U.S. Environmental Protection Agency. August 1998. EPA420-R-98-009.

EPA (1994a) *Automobile Emissions: An Overview.* Office of Mobile Sources. August 1994. EPA 400-F-92-007. Available online at: https://www.epa.gov/nscep.

EPA (1994b) *Milestones in Auto Emissions Control.* Office of Mobile Sources. August 1994. EPA 400-F-92-014. Available online at: https://www.epa.gov/nscep.

Esser, C. (2003 through 2004) Personal Communication with Charles Esser, Residual and Distillate Fuel Oil Consumption for Vessel Bunkering (Both International and Domestic) for American Samoa, U.S. Pacific Islands, and Wake Island.

FAA (2022) Personal Communication between FAA and John Steller, Mausami Desai and Vincent Camobreco for aviation emission estimates from the Aviation Environmental Design Tool (AEDT). March 2022.

FHWA (1996 through 2023) *Highway Statistics*. Federal Highway Administration, U.S. Department of Transportation, Washington, D.C. Report FHWA-PL-96-023-annual.

FTA (2023) National Transit Database "Fuel and Energy by Mode and TOS" table. Available online at: https://data.transportation.gov/.

Gaffney, J. (2007) Email Communication. John Gaffney, American Public Transportation Association and Joe Aamidor, ICF International. December 17, 2007.

IPCC (2006) 2006 *IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change. [H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (eds.)]. Hayama, Kanagawa, Japan.

ICF (2006) *Revised Gasoline Vehicle EFs for LEV and Tier 2 Emission Levels.* Memorandum from ICF International to John Davies, Office of Transportation and Air Quality, U.S. Environmental Protection Agency. November 2006.

ICF (2004) *Update of Methane and Nitrous Oxide Emission Factors for On-Highway Vehicles*. Final Report to U.S. Environmental Protection Agency. February 2004.

RailInc (2014 through 2023) *RailInc Short line and Regional Traffic Index.* Carloads Originated Year-to-Date. November 2023. Available online at: https://public.railinc.com/.

Whorton, D. (2006 through 2014) Personal communication, Class II and III Rail energy consumption, American Short Line and Regional Railroad Association.

Carbon Emitted from Non-Energy Uses of Fossil Fuels

ACC (2023a) "U.S. Resin Production & Sales 2022 vs. 2021." Available online at: https://www.americanchemistry.com/chemistry-in-america/data-industry-statistics/statistics-on-the-plastic-resins-industry/resources/pips-resin-sales-and-production-cy-figures-2022-vs-2021.

ACC (2023b) *Guide to the Business of Chemistry, 2023*, American Chemistry Council. Available online at: https://www.americanchemistry.com/chemistry-in-america/data-industry-statistics/resources/2023-guide-to-the-business-of-chemistry.

ACC (2022) "U.S. Resin Production & Sales 2021 vs. 2020." Available online at: https://www.americanchemistry.com/chemistry-in-america/data-industry-statistics/statistics-on-the-plastic-resins-industry.

ACC (2021) "U.S. Resin Production & Sales 2020 vs. 2019." Available online at: https://www.americanchemistry.com/chemistry-in-america/chemistry-in-everyday-products/plastics.

ACC (2020) "U.S. Resin Production & Sales 2019 vs. 2018." Available online at: https://www.americanchemistry.com/chemistry-in-america/chemistry-in-everyday-products/plastics.

ACC (2019) "U.S. Resin Production & Sales 2018 vs. 2017." Available online at: https://www.americanchemistry.com/chemistry-in-america/chemistry-in-everyday-products/plastics.

ACC (2018) “U.S. Resin Production & Sales 2017 vs. 2016.” Available online at: https://www.americanchemistry.com/chemistry-in-america/chemistry-in-everyday-products/plastics.

ACC (2017) “U.S. Resin Production & Sales 2016 vs. 2015.”

ACC (2016) “U.S. Resin Production & Sales 2015 vs. 2014.”

ACC (2015) “PIPS Year-End Resin Statistics for 2014 vs. 2013: Production, Sales and Captive Use.” Available online at: https://www.americanchemistry.com/chemistry-in-america/data-industry-statistics/statistics-on-the-plastic-resins-industry/resin-report-subscriptions.

ACC (2014) "U.S. Resin Production & Sales: 2013 vs. 2012,” American Chemistry Council. Available online at: http://www.americanchemistry.com/Jobs/EconomicStatistics/Plastics-Statistics/Production-and-Sales-Data-by-Resin.pdf.

ACC (2013) “U.S. Resin Production & Sales: 2012 vs. 2011,” American Chemistry Council. Available online at: http://www.americanchemistry.com/Jobs/EconomicStatistics/Plastics-Statistics/Production-and-Sales-Data-by-Resin.pdf.

ACC (2003-2011) “PIPS Year-End Resin Statistics for 2010: Production, Sales and Captive Use.” Available online at: http://www.americanchemistry.com/Jobs/EconomicStatistics/Plastics-Statistics/Production-and-Sales-Data-by-Resin.pdf.

Bank of Canada (2023) Financial Markets Department Year Average of Exchange Rates. Available online at: https://www.bankofcanada.ca/rates/exchange/annual-average-exchange-rates/#download.

Bank of Canada (2022) Financial Markets Department Year Average of Exchange Rates. Available online at: https://www.bankofcanada.ca/rates/exchange/annual-average-exchange-rates/#download.

Bank of Canada (2021) Financial Markets Department Year Average of Exchange Rates. Available online at: https://www.bankofcanada.ca/rates/exchange/annual-average-exchange-rates/#download.

Bank of Canada (2020) Financial Markets Department Year Average of Exchange Rates. Available online at: https://www.bankofcanada.ca/rates/exchange/annual-average-exchange-rates/#download.

Bank of Canada (2019) Financial Markets Department Year Average of Exchange Rates. Available online at: https://www.bankofcanada.ca/rates/exchange/annual-average-exchange-rates/#download.

Bank of Canada (2018) Financial Markets Department Year Average of Exchange Rates. Available online at: https://www.bankofcanada.ca/rates/exchange/annual-average-exchange-rates/.

Bank of Canada (2017) Financial Markets Department Year Average of Exchange Rates. Available online at: https://www.bankofcanada.ca/rates/exchange/legacy-noon-and-closing-rates/.

Bank of Canada (2016) Financial Markets Department Year Average of Exchange Rates. Available online at: https://www.bankofcanada.ca/rates/exchange/legacy-noon-and-closing-rates/.

Bank of Canada (2014) Financial Markets Department Year Average of Exchange Rates. Available online at: https://www.bankofcanada.ca/rates/exchange/legacy-noon-and-closing-rates/.

Bank of Canada (2013) Financial Markets Department Year Average of Exchange Rates. Available online at: https://www.bankofcanada.ca/rates/exchange/legacy-noon-and-closing-rates/.

Bank of Canada (2012) Financial Markets Department Year Average of Exchange Rates. Available online at: https://www.bankofcanada.ca/rates/exchange/legacy-noon-and-closing-rates/.

CIAC (2022). 2022 Economic Review of Chemistry. Available online at: https://canadianchemistry.ca/wp-content/uploads/2022/06/2022-Economic-Review-of-Chemistry23732_removed.pdf.

EIA (2024) *Monthly Energy Review, February 2024.* Energy Information Administration, U.S. Department of Energy, Washington, D.C. DOE/EIA-0035 (2024/02). Available online at: https://www.eia.gov/totalenergy/data/monthly/pdf/mer.pdf.

EIA (2021) *EIA Manufacturing Consumption of Energy (MECS) 2018.* U.S. Department of Energy, Energy Information Administration, Washington, D.C.

EIA (2020) Glossary. Energy Information Administration, U.S. Department of Energy, Washington, D.C. Available online at: https://www.eia.gov/tools/glossary/index.php?id=N#nat_Gas_Liquids.

EIA (2019) Personal communication between EIA and ICF on November 11, 2019.

EIA (2017) *EIA Manufacturing Consumption of Energy (MECS) 2014.* U.S. Department of Energy, Energy Information Administration, Washington, D.C.

EIA (2013) *EIA Manufacturing Consumption of Energy (MECS) 2010.* U.S. Department of Energy, Energy Information Administration, Washington, D.C.

EIA (2010) *EIA Manufacturing Consumption of Energy (MECS) 2006.* U.S. Department of Energy, Energy Information Administration, Washington, D.C.

EIA (2005) *EIA Manufacturing Consumption of Energy (MECS) 2002.* U.S. Department of Energy, Energy Information Administration, Washington, D.C.

EIA (2001) *EIA Manufacturing Consumption of Energy (MECS) 1998.* U.S. Department of Energy, Energy Information Administration, Washington, D.C.

EIA (1997) *EIA Manufacturing Consumption of Energy (MECS) 1994.* U.S. Department of Energy, Energy Information Administration, Washington, D.C.

EIA (1994) *EIA Manufacturing Consumption of Energy (MECS) 1991.* U.S. Department of Energy, Energy Information Administration, Washington, D.C.

EPA (2023) EPA's Emissions Inventory System (EIS) to National Inventory Report (NIR) Mapping file EIS_NIR_mapping.xlsx. U.S. Environmental Protection Agency. Washington, D.C.

EPA (2021) *Resource Conservation and Recovery Act (RCRA) Info*, Biennial Report, GM Form (Section 2- Onsite Management) and WR Form.

EPA (2019) *Advancing Sustainable Materials Management: 2016 and 2017 Data Tables*. Office of Land and Emergency Management, U.S. Environmental Protection Agency. Washington, D.C. Available online at: https://www.epa.gov/sites/production/files/2019-11/documents/2016_and_2017_facts_and_figures_data_tables_0.pdf.

EPA (2018a) Advancing Sustainable Materials Management: Facts and Figures 2015, Assessing Trends in Material Generation, Recycling and Disposal in the United States. Washington, D.C.

EPA (2018b) *Resource Conservation and Recovery Act (RCRA) Info*, Biennial Report, GM Form (Section 2- Onsite Management) and WR Form.

EPA (2017) EPA's Pesticides Industry Sales and Usage, 2008 – 2012 Market Estimates. Available online at: https://www.epa.gov/sites/production/files/2017-01/documents/pesticides-industry-sales-usage-2016_0.pdf. Accessed September 2017.

EPA (2016a) Advancing Sustainable Materials Management: 2014 Facts and Figures Fact Sheet. Office of Solid Waste and Emergency Response, U.S. Environmental Protection Agency, Washington, D.C. Available online at: https://www.epa.gov/sites/production/files/2016-11/documents/2014_smmfactsheet_508.pdf.

EPA (2016b) *Resource Conservation and Recovery Act (RCRA) Info*, Biennial Report, GM Form (Section 2- Onsite Management) and WR Form.

EPA (2015) *Resource Conservation and Recovery Act (RCRA) Info*, Biennial Report, GM Form (Section 2- Onsite Management) and WR Form.

EPA (2014a) Municipal Solid Waste in the United States: 2012 Facts and Figures. Office of Solid Waste and Emergency Response, U.S. Environmental Protection Agency, Washington, D.C. Available online at: https://www.epa.gov/sites/default/files/2015-09/documents/2012_msw_dat_tbls.pdf.

EPA (2014b) Chemical Data Access Tool (CDAT). U.S. Environmental Protection Agency, June 2014. Available online at: https://edg.epa.gov/metadata/catalog/search/resource/details.page?uuid=%7B2D73C764-6919-404D-8C9B-61869B3330D6%7D. Accessed January 2015.

EPA (2013a) Municipal Solid Waste in the United States: 2011 Facts and Figures. Office of Solid Waste and Emergency Response, U.S. Environmental Protection Agency, Washington, D.C. Available online at: http://www.epa.gov/epaoswer/non-hw/muncpl/msw99.htm.

EPA (2013b) *Resource Conservation and Recovery Act (RCRA) Info*, Biennial Report, GM Form (Section 2- Onsite Management) and WR Form.

EPA (2011) EPA's Pesticides Industry Sales and Usage, 2006 and 2007 Market Estimates. Available online at: https://www.epa.gov/pesticides/pesticides-industry-sales-and-usage-2006-and-2007-market-estimates. Accessed January 2012.

EPA (2009) Biennial Reporting System (BRS) Database. U.S. Environmental Protection Agency, Envirofacts Warehouse. Washington, D.C. Available online at: https://www.epa.gov/enviro/br-search. Data for 2001-2007 are current as of Sept. 9, 2009.

EPA (2004) EPA's Pesticides Industry Sales and Usage, 2000 and 2001 Market Estimates. Available online at: https://nepis.epa.gov/Exe/ZyPURL.cgi?Dockey=3000659P.TXT. Accessed September 2006.

EPA (2002) EPA's Pesticides Industry Sales and Usage, 1998 and 1999 Market Estimates, Table 3.6. Available online at https://nepis.epa.gov/Exe/ZyPURL.cgi?Dockey=200001G5.TXT. Accessed July 2003.

EPA (2001) AP 42, Volume I, Fifth Edition. Chapter 11: Mineral Products Industry. Available online at: http://www.epa.gov/ttn/chief/ap42/ch11/index.html.

EPA (2000a) *Biennial Reporting System (BRS)*. U.S. Environmental Protection Agency, Envirofacts Warehouse. Washington, D.C. Available online at: https://www.epa.gov/enviro/br-search.

EPA (2000b) *Toxics Release Inventory, 1998*. U.S. Environmental Protection Agency, Office of Environmental Information, Office of Information Analysis and Access, Washington, D.C. Available online at: https://enviro.epa.gov/triexplorer/tri_release.chemical.

EPA (1999) EPA's Pesticides Industry Sales and Usage, 1996-1997 Market Estimates. Available online at: https://nepis.epa.gov/Exe/ZyPURL.cgi?Dockey=200001IL.TXT.

EPA (1998) EPA's Pesticides Industry Sales and Usage, 1994-1995 Market Estimates. Available online at: http://www.epa.gov/oppbead1/pestsales/95pestsales/market_estimates1995.pdf.

FEB (2013) Fiber Economics Bureau, as cited in C&EN (2013) Lackluster Year for Chemical Output: Production stayed flat or dipped in most world regions in 2012. Chemical &Engineering News, American Chemical Society, 1 July. Available online at: http://www.cen-online.org.

FEB (2012) Fiber Economics Bureau, as cited in C&EN (2012) Too Quiet After the Storm: After a rebound in 2010, chemical production hardly grew in 2011. Chemical & Engineering News, American Chemical Society, 2 July. Available online at: http://www.cen-online.org.

FEB (2011) Fiber Economics Bureau, as cited in C&EN (2011) *Output Ramps up in all Regions*. Chemical Engineering News, American Chemical Society, 4 July. Available online at: http://www.cen-online.org.

FEB (2010) Fiber Economics Bureau, as cited in C&EN (2010) *Output Declines in U.S., Europe*. Chemical & Engineering News, American Chemical Society, 6 July. Available online at: http://www.cen-online.org.

FEB (2009) Fiber Economics Bureau, as cited in C&EN (2009) *Chemical Output Slipped In Most Regions* Chemical & Engineering News, American Chemical Society, 6 July. Available online at: http://www.cen-online.org.

FEB (2007) Fiber Economics Bureau, as cited in C&EN (2007) *Gains in Chemical Output Continue*. Chemical & Engineering News, American Chemical Society. July 2, 2007. Available online at: http://www.cen-online.org.

FEB (2005) Fiber Economics Bureau, as cited in C&EN (2005) *Production: Growth in Most Regions* Chemical & Engineering News, American Chemical Society, 11 July. Available online at: http://www.cen-online.org.

FEB (2003) Fiber Economics Bureau, as cited in C&EN (2003) *Production Inches Up in Most Countries,* Chemical & Engineering News, American Chemical Society, 7 July. Available online at: http://www.cen-online.org.

FEB (2001) Fiber Economics Bureau, as cited in ACS (2001) *Production: slow gains in output of chemicals and products lagged behind U.S. economy as a whole* Chemical & Engineering News, American Chemical Society, 25 June. Available online at: http://pubs.acs.org/cen.

Financial Planning Association (2006) Canada/US Cross-Border Tools: US/Canada Exchange Rates. Available online at: http://www.fpanet.org/global/planners/US_Canada_ex_rates.cfm. Accessed on August 16, 2006.

Gosselin, Smith, and Hodge (1984) "Clinical Toxicology of Commercial Products." Fifth Edition, Williams & Wilkins, Baltimore.

ICIS (2016) “Production issues force US melamine plant down” Available online at: https://www.icis.com/resources/news/2016/05/03/9994556/production-issues-force-us-melamine-plant-down/.

ICIS (2008) “Chemical profile: Melamine” Available online at: https://www.icis.com/resources/news/2008/12/01/9174886/chemical-profile-melamine/. Accessed November 2017.

IISRP (2003) “*IISRP Forecasts Moderate Growth in North America to 2007*” International Institute of Synthetic Rubber Producers, Inc. New Release. Available online at: http://www.iisrp.com/press-releases/2003-Press-Releases/IISRP-NA-Forecast-03-07.html.

IISRP (2000) "Synthetic Rubber Use Growth to Continue Through 2004, Says IISRP and RMA" International Institute of Synthetic Rubber Producers press release.

INEGI (2006) Producción bruta total de las unidades económicas manufactureras por Subsector, Rama, Subrama y Clase de actividad. Available online at: http://www.inegi.gob.mx/est/contenidos/espanol/proyectos/censos/ce2004/tb_manufacturas.asp. Accessed on August 15, 2006.

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change. [H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (eds.)]. Hayama, Kanagawa, Japan.

Marland, G., and R.M. Rotty (1984) “Carbon dioxide emissions from fossil fuels: A procedure for estimation and results for 1950-1982,” Tellus 36b:232-261.

NPRA (2002) North American Wax - A Report Card. Available online at: http://www.npra.org/members/publications/papers/lubes/LW-02-126.pdf.

U.S. Census Bureau (2021) 2017 Economic Census. Available online at: https://www.census.gov/data/tables/2017/econ/economic-census/naics-sector-31-33.html. Accessed October 2021.

U.S. Census Bureau (2014) 2012 Economic Census. Available online at: http://www.census.gov/econ/census/schedule/whats_been_released.html. Accessed November 2014.

U.S. Census Bureau (2009) *Soap and Other Detergent Manufacturing: 2007*.

U.S. Census Bureau (2004) *Soap and Other Detergent Manufacturing: 2002*. Issued December 2004. EC02-31I-325611 (RV). Available online at: http://www.census.gov/prod/ec02/ec0231i325611.pdf.

U.S. Census Bureau (1999) *Soap and Other Detergent Manufacturing: 1997*. Available online at: http://www.census.gov/epcd/www/ec97stat.htm.

U.S. International Trade Commission (2023) "Interactive Tariff and Trade DataWeb: Quick Query." Available online at: http://dataweb.usitc.gov/. Accessed September 2023.

USTMA (2022) "2021 U.S. Scrap Tire Management Summary." U.S. Tire Manufacturers Association, Washington, DC. October 2022. Available online at: https://www.ustires.org/sites/default/files/21%20US%20Scrap%20Tire%20Management%20Report%20101722.pdf.

USTMA (2020) "2019 U.S. Scrap Tire Management Summary." U.S. Tire Manufacturers Association, Washington, DC. October 2020. Available online at: https://www.ustires.org/sites/default/files/2019%20USTMA%20Scrap%20Tire%20Management%20Summary%20Report.pdf.

USTMA (2018) "2017 U.S. Scrap Tire Management Summary." U.S. Tire Manufacturers Association, Washington, DC. July 2018. Available online at: https://www.tyrepress.com/wp-content/uploads/2018/07/USTMA_scraptire_summ_2017_07_11_2018.pdf.

USTMA (2016) "2015 U.S. Scrap Tire Management Summary." U.S. Tire Manufacturers Association. August 2016. Available online at: https://www.ustires.org/sites/default/files/MAR_028_USTMA.pdf.

USTMA (2014) "2013 U.S. Scrap Tire Management Summary." U.S. Tire Manufacturers Association. November 2014. Available online at: https://www.ustires.org/sites/default/files/MAR_027_USTMA.pdf.

USTMA (2013) "U.S. Scrap Tire Management Summary 2005-2009." U.S. Tire Manufacturers Association. October 2011; Updated September 2013. Available online at: https://www.ustires.org/sites/default/files/MAR_025_USTMA.pdf.

USTMA (2012) "Scrap Tire Markets: Facts and Figures – Scrap Tire Characteristics." U.S. Tire Manufacturers Association. Accessed 18 on January 2012.

Incineration of Waste

ArSova, Ljupka, Rob van Haaren, Nora Goldstein, Scott M. Kaufman, and Nickolas J. Themelis (2008) "16th Annual BioCycle Nationwide Survey: The State of Garbage in America" *BioCycle*, JG Press, Emmaus, PA. December.

Bahor, B (2009) Covanta Energy's public review comments re: *Draft Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2007.* Submitted via email on April 9, 2009 to Leif Hockstad, U.S. EPA.

De Soete, G.G. (1993) "Nitrous Oxide from Combustion and Industry: Chemistry, Emissions and Control." In A. R. Van Amstel, (ed.) Proc. of the International Workshop Methane and Nitrous Oxide: Methods in National Emission Inventories and Options for Control, Amersfoort, NL. February 3-5, 1993.

Energy Recovery Council (2018) Energy Recovery Council. *2018 Directory of Waste to Energy Facilities*. Ted Michaels and Karunya Krishnan. October 2018. Available online at: http://energyrecoverycouncil.org/wp-content/uploads/2019/10/ERC-2018-directory.pdf.

Energy Recovery Council (2009) "2007 Directory of Waste-to-Energy Plants in the United States." Accessed on September 29, 2009.

EIA (2019) EIA St. Louis Federal Reserve's Economic Data (FRED) Consumer Price Index for All Urban Consumers: Education and Communication (CPIEDUSL). Available online at: https://www.eia.gov/opendata/excel/.

EIA (2017) *MSW Incineration for Heating or Electrical Generation, December 2017,* Energy Information Administration, U.S. Department of Energy, Washington, DC. DOE/EIA-0035. Available online at: https://www.eia.gov/opendata/?src=-f3.

EPA (2022) Greenhouse Gas Reporting Program (GHGRP). 2022 Envirofacts. Available online at: https://ghgdata.epa.gov/ghgp/main.do.

EPA (2020a) Advancing Sustainable Materials Management: 2018 Data Tables. Office of Land and Emergency Management, U.S. Environmental Protection Agency. Washington, D.C. Available online at: https://www.epa.gov/sites/production/files/2020-11/documents/2018_ff_fact_sheet.pdf.

EPA (2020b) Greenhouse Gas Reporting Program (GHGRP). 2020 Envirofacts. Available online at: https://ghgdata.epa.gov/ghgp/main.do.

EPA (2019) Advancing Sustainable Materials Management: 2016 and 2017 Data Tables. Office of Land and Emergency Management, U.S. Environmental Protection Agency. Washington, D.C. Available online at: https://www.epa.gov/sites/production/files/2019-11/documents/2016_and_2017_facts_and_figures_data_tables_0.pdf.

EPA (2018a) Advancing Sustainable Materials Management: 2015 Data Tables. Office of Land and Emergency Management, U.S. Environmental Protection Agency. Washington, D.C. Available online at: https://www.epa.gov/sites/production/files/2018-07/documents/smm_2015_tables_and_figures_07252018_fnl_508_0.pdf.

EPA (2018b) Greenhouse Gas Reporting Program Data. Washington, DC: U.S. Environmental Protection Agency. Available online at: https://www.epa.gov/ghgreporting/ghg-reporting-program-data-sets.

EPA (2016) *Advancing Sustainable Materials Management: 2014 Fact Sheet*. Office of Land and Emergency Management, U.S. Environmental Protection Agency. Washington, D.C. Available online at: https://www.epa.gov/sites/production/files/2016-11/documents/2014_smmfactsheet_508.pdf.

EPA (2015) *Advancing Sustainable Materials Management: Facts and Figures 2013 – Assessing Trends in Material Generation, Recycling and Disposal in the United States.* Office of Solid Waste and Emergency Response, U.S. Environmental Protection Agency. Washington, D.C. Available online at: http://www3.epa.gov/epawaste/nonhaz/municipal/pubs/2013_advncng_smm_rpt.pdf.

EPA (2007, 2008, 2011, 2013, 2014) *Municipal Solid Waste in the United States: Facts and Figures*. Office of Solid Waste and Emergency Response, U.S. Environmental Protection Agency. Washington, D.C. Available online at: http://www.epa.gov/osw/nonhaz/municipal/msw99.html.

EPA (2006) *Solid Waste Management and Greenhouse Gases: A Life-Cycle Assessment of Emissions and Sinks*. Office of Solid Waste and Emergency Response, U.S. Environmental Protection Agency. Washington, D.C.

EPA (2000) *Characterization of Municipal Solid Waste in the United States: Source Data on the 1999 Update.* Office of Solid Waste, U.S. Environmental Protection Agency. Washington, D.C. EPA530-F-00-024.

Goldstein, N. and C. Madtes (2001) "13th Annual BioCycle Nationwide Survey: The State of Garbage in America." *BioCycle*, JG Press, Emmaus, PA. December 2001.

IPCC (2013) *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Stocker, T.F., D. Qin, G.K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1535 pp.

IPCC (2007) *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change.* [S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds.)]. Cambridge University Press. Cambridge, United Kingdom, 996 pp.

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change. [H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (eds.)]. Hayama, Kanagawa, Japan.

Kaufman, et al. (2004) "14th Annual BioCycle Nationwide Survey: The State of Garbage in America 2004" Biocycle, JG Press, Emmaus, PA. January 2004.

Schneider, S. (2007) E-mail between Shelly Schneider of Franklin Associates (a division of ERG) and Sarah Shapiro of ICF International, January 10, 2007.

Shin, D. (2014) Generation and Disposition of Municipal Solid Waste (MSW) in the United States–A National Survey. Thesis. Columbia University, Department of Earth and Environmental Engineering, January 3, 2014.

Simmons, et al. (2006) "15th Nationwide Survey of Municipal Solid Waste Management in the United States: The State of Garbage in America." BioCycle, JG Press, Emmaus, PA. April 2006.

USTMA (2022) "2021 U.S. Scrap Tire Management Summary." U.S. Tire Manufacturers Association, Washington, DC. October 2022. Available online at: https://www.ustires.org/sites/default/files/21%20US%20Scrap%20Tire%20Management%20Report%20101722.pdf.

USTMA (2020) "2019 U.S. Scrap Tire Management Summary." U.S. Tire Manufacturers Association, Washington, DC. October 2020. Available online at: https://www.ustires.org/sites/default/files/2019%20USTMA%20Scrap%20Tire%20Management%20Summary%20Report.pdf.

USTMA (2018) "2017 U.S. Scrap Tire Management Summary." U.S. Tire Manufacturers Association, Washington, DC. July 2018. Available online at: https://www.tyrepress.com/wp-content/uploads/2018/07/USTMA_scraptire_summ_2017_07_11_2018.pdf.

USTMA (2016) "2015 U.S. Scrap Tire Management Summary." U.S. Tire Manufacturers Association. August 2016. Available online at: https://www.ustires.org/sites/default/files/MAR_028_USTMA.pdf.

USTMA (2014) "2013 U.S. Scrap Tire Management Summary." U.S. Tire Manufacturers Association. November 2014. Available online at: https://www.ustires.org/sites/default/files/MAR_027_USTMA.pdf.

USTMA (2013) "U.S. Scrap Tire Management Summary 2005-2009." U.S. Tire Manufacturers Association. October 2011; Updated September 2013. Available online at: https://www.ustires.org/sites/default/files/MAR_025_USTMA.pdf.

USTMA (2012a) "Rubber FAQs." U.S. Tire Manufacturers Association. Accessed on 19 November 2014.

USTMA (2012b) "Scrap Tire Markets: Facts and Figures – Scrap Tire Characteristics." U.S. Tire Manufacturers Association. Accessed 18 on January 2012.

van Haaren, Rob, Themelis, N., and Goldstein, N. (2010) "The State of Garbage in America." BioCycle, October 2010. Volume 51, Number 10, pg. 16-23.

Coal Mining

AAPG (1984) *Coalbed Methane Resources of the United States.* AAPG Studies in Geology Series #17.

Creedy, D.P. (1993) Methane Emissions from Coal Related Sources in Britain: Development of a Methodology. *Chemosphere,* 26: 419-439.

DMME (2023) *DGO Data Information System*. Department of Mines, Minerals and Energy of Virginia. Available online at https://www.dmme.virginia.gov/dgoinquiry/frmmain.aspx.

EIA (2023) *Annual Coal Report 2022*. Table 1. Energy Information Administration, U.S. Department of Energy. Washington, D.C. DOE/EIA-0584.

El Paso (2009) Shoal Creek Mine Plan, El Paso Exploration & Production.

EPA (2023) Greenhouse Gas Reporting Program (GHGRP) 2022 Subpart FF: Underground Coal Mines.

EPA (2005) *Surface Mines Emissions Assessment.* Draft. U.S. Environmental Protection Agency.

EPA (1996) *Evaluation and Analysis of Gas Content and Coal Properties of Major Coal Bearing Regions of the United States*. EPA/600/R-96-065. U.S. Environmental Protection Agency.

ERG (2023). Correspondence between ERG and Buchanan Mine.

Geological Survey of Alabama State Oil and Gas Board (GSA) (2023) Well Records Database. Available online at http://www.gsa.state.al.us/ogb/database.aspx.

IEA (2022) *Coal 2022*, International Energy Agency, Paris, License: CC BY 4.0. Available online at: https://www.iea.org/reports/coal-2022.

IPCC (2019) *2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories.* Calvo Buendia, E., Tanabe, K., Kranjc, A., Baasansuren, J., Fukuda, M., Ngarize S., Osako, A., Pyrozhenko, Y., Shermanau, P. and Federici, S. (eds). Published: IPCC, Switzerland.

IPCC (2013) *Climate Change 2013: The Physical Science Basis*. Contribution of Working Group I to the *Fifth Assessment Report* of the Intergovernmental Panel on Climate Change [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1535 pp.

IPCC (2011) *Use of Models and Facility-Level Data in Greenhouse Gas Inventories*. Report of IPCC Expert Meeting on Use of Models and Measurements in Greenhouse Gas Inventories 9-11 August 2010, Sydney, Australia. Eds: Eggleston H.S., Srivastava N., Tanabe K., Baasansuren J., Fukuda M. IGES.

IPCC (2007) *Climate Change 2007: The Physical Science Basis*. Contribution of Working Group I to the *Fourth Assessment Report* of the Intergovernmental Panel on Climate Change [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 996 pp.

JWR (2010) *No. 4 & 7 Mines General Area Maps.* Walter Energy: Jim Walter Resources.

King, Brian (1994) *Management of Methane Emissions from Coal Mines: Environmental, Engineering, Economic and Institutional Implication of Options.* Neil and Gunter Ltd.

McElroy OVS (2023) Marshall County VAM Abatement Project Offset Verification Statement submitted to California Air Resources Board, August 2023.

MSHA (2023) Data Transparency at MSHA. Mine Safety and Health Administration. Available online at http://www.msha.gov/.

Mutmansky, Jan M. and Yanbei Wang (2000) Analysis of Potential Errors in Determination of Coal Mine Annual Methane Emissions. *Mineral Resources Engineering,* 9(4).

Saghafi, Abouna (2013) *Estimation of Fugitive Emissions from Open Cut Coal Mining and Measurable Gas Content.* 13th Coal Operators' Conference, University of Wollongong, The Australian Institute of Mining and Metallurgy & Mine Managers Association of Australia. 306-313.

USBM (1986) *Results of the Direct Method Determination of the Gas Contents of U.S. Coal Basins*. Circular 9067. U.S. Bureau of Mines.

West Virginia Geological & Economic Survey (WVGES) (2023) Oil & Gas Production Data. Available online at http://www.wvgs.wvnet.edu/www/datastat/datastat.htm.

Abandoned Underground Coal Mines

CMOP (2023) EPA's Coalbed Methane Outreach Program, Map of US Coal Mine Methane Current Projects and Potential Opportunities. Available online at: https://www.epa.gov/cmop/map-us-coal-mine-methane-current-projects-and-potential-opportunities.

COGIS (2018) Colorado Oil and Gas Information System. Colorado Oil and Gas Commission, Department of Natural Resources. Available online at https://cogcc.state.co.us/data.html.

EPA (2004) Methane Emissions Estimates & Methodology for Abandoned Coal Mines in the U.S. Draft Final Report. Washington, D.C. April 2004.

GMI (2021) Global Methane Initiative, International Coal Mine Methane Database. Available online at: https://www.globalmethane.org/resources/details.aspx?resourceid=1981.

IPCC (2013) *Climate Change 2013: The Physical Science Basis*. Contribution of Working Group I to the *Fifth Assessment Report* of the Intergovernmental Panel on Climate Change [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1535 pp.

IPCC (2007) *Climate Change 2007: The Physical Science Basis*. Contribution of Working Group I to the *Fourth Assessment Report* of the Intergovernmental Panel on Climate Change [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 996 pp.

MSHA (2023) U.S. Department of Labor, Mine Health & Safety Administration, Mine Data Retrieval System. Available online at: https://www.msha.gov/mine-data-retrieval-system..

Petroleum Systems

API (1992) *Global Emissions of Methane from Petroleum Sources*. American Petroleum Institute, Health and Environmental Affairs Department, Report No. DR140, February 1992.

BOEM (2023a) BOEM Platform Structures Online Query. Available online at: https://www.data.boem.gov/Platform/PlatformStructures/Default.aspx.

BOEM (2023b) BOEM Oil and Gas Operations Reports - Part A (OGOR-A). Production Data for 1947 to 2022. Download "Production Data" online at: https://www.data.boem.gov/Main/RawData.aspx.

BOEM (2023c) BOEM Oil and Gas Operations Reports - Part A (OGOR-A). Production Data for 1996 to 2022. Available online at: https://www.data.boem.gov/Main/OGOR-A.aspx.

BOEM (2023d) BOEM Oil and Gas Operations Reports - Part B (OGOR-B). Flaring volumes for 1996 to 2022. Available online at: https://www.data.boem.gov/Main/OGOR-B.aspx.

EIA (2023) Crude Oil Production. Energy Information Administration.

Enverus (2023) September 2023 Download. Enverus, Inc.

EPA (2023) *Greenhouse Gas Reporting Program*. U.S. Environmental Protection Agency. Data reported as of August 18, 2023.

EPA (2017) *2017 Nonpoint Oil and Gas Emission Estimation Tool*, Version 1.2. Prepared for U.S. Environmental Protection Agency by Eastern Research Group, Inc. (ERG). October 2019.

EPA (1999) *Estimates of Methane Emissions from the U.S. Oil Industry (Draft Report).* Prepared by ICF International. Office of Air and Radiation, U.S. Environmental Protection Agency. October 1999.

EPA (1997) *Compilation of Air Pollutant Emission Factors, AP-42*. Office of Air Quality Planning and Standards, U.S. Environmental Protection Agency. Research Triangle Park, NC. October 1997.

EPA/GRI (1996) *Methane Emissions from the Natural Gas Industry*. Prepared by Radian. U.S. Environmental Protection Agency. April 1996.

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change. [H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (eds.)]. Hayama, Kanagawa, Japan.

Natural Gas Systems

AHS (2022) U.S. Census Bureau's *American Housing Survey* (AHS). https://www.census.gov/programs-surveys/ahs.html.

CBECS (2023) Energy Information Administration's Commercial Buildings Energy Consumption Survey (CBECS). https://www.eia.gov/consumption/commercial.

CenSARA (2012) *2011 Oil and Gas Emission Inventory Enhancement Project for CenSARA States*. Prepared by ENVIRON International Corporation and Eastern Research Group, Inc. (ERG). Central States Air Resources Agencies (CenSARA). December 2012.

Cusworth, D.H., Duren, R.M., Thorpe, A.K., Pandey S., Maasakkers, J.D., Aben, I., et al. (2021). *Multisatellite imaging of a gas well blowout enables quantification of total methane emissions.* Geophysical Research Letters, 48, e2020GL090864. https://doi.org/10.1029/2020GL090864.

EIA (2023a) Natural Gas Gross Withdrawals and Production. Energy Information Administration.

EIA (2023b) October 2021 *Monthly Energy Review*. Energy Information Administration. https://www.eia.gov/totalenergy/data/monthly/archive/00352110.pdf.

Enverus (2023) September 2023 Download. Enverus, Inc.

EPA (2023a) MOVES3. https://www.epa.gov/moves/latest-version-motor-vehicle-emission-simulator-moves.

EPA (2023b) *Greenhouse Gas Reporting Program- Subpart W – Petroleum and Natural Gas Systems*. Environmental Protection Agency. Data reported as of August 18, 2023.

EPA (2022) Nonpoint Oil & Gas Emission estimation Tool.

EPA (1977) *Atmospheric Emissions from Offshore Oil and Gas Development and Production*. Office of Air Quality Planning and Standards, Research Triangle Park, NC. PB272268. June 1977.

Evans, D.J. & Chadwick, R.A. (2009) (eds) "Underground Gas Storage: Worldwide Experiences and Future Development in the UK and Europe." *The Geological Society,* London, Special Publications, 313: 173–216. https://doi.org/10.1144/SP313.12.

FERC (2023) Form No. 2, Major Natural Gas Pipeline Annual Report. Federal Energy Regulatory Commission. https://ferc.gov/industries-data/natural-gas/industry-forms.

Fischer et al. (2018) "An Estimate of Natural Gas Methane Emissions from California Homes." *Environmental Science & Technology* 2018, *52 (17)*, 10205–10213. https://pubs.acs.org/doi/10.1021/acs.est.8b03217.

GRI/EPA (1996) *Methane Emissions from the Natural Gas Industry*. Prepared by Harrison, M., T. Shires, J. Wessels, and R. Cowgill, eds., Radian International LLC for National Risk Management Research Laboratory, Air Pollution Prevention and Control Division, Research Triangle Park, NC. EPA-600/R-96-080a.

GTI (2019) *Classification of Methane Emissions from Industrial Meters, Vintage vs Modern Plastic Pipe, and Plastic-lined Steel and Cast-Iron Pipe*. June 2019. Gas Technology Institute and U.S. Department of Energy GTI Project Number 22070. DOE project Number ED-FE0029061.

GTI (2001) Gas Resource Database: Unconventional Natural Gas and Gas Composition Databases. Second Edition. GRI-01/0136.

Illinois Office of Oil and Gas Resource Management (2022) State-level natural gas production quantities.

Indiana Division of Oil & Gas (2022) State-level natural gas production quantities.

Kansas Department of Health and Environment (2022) County-level produced water quantities.

Lamb, et al. (2015) "Direct Measurements Show Decreasing Methane Emissions from Natural Gas Local Distribution Systems in the United States." *Environmental Science & Technology, Vol. 49* 5161-5169.

Lavoie et al. (2017) "Assessing the Methane Emissions from Natural Gas-Fired Power Plants and Oil Refineries." *Environmental Science & Technology*. 2017 Mar 21;51(6):3373-3381. doi: 10.1021/acs.est.6b05531.

Li, H Z et al. (2022) "A national estimate of U.S. underground natural gas storage incident emissions." *Environmental Research Letters*. 17: 084013. https://doi.org/10.1088/1748-9326/ac8069.

Maasakkers, Joannes D., Mark Omara, Ritesh Gautam, Alba Lorente, Sudhanshu Pandey, Paul Tol, Tobias Borsdorff, Sander Houweling, Ilse Aben (2022). *Reconstructing and quantifying methane emissions from the full duration of a 38-day natural gas well blowout using space-based observations.* Remote Sensing of Environment. https://doi.org/10.1016/j.rse.2021.112755.

Ohio Environmental Protection Agency (2022) Well-level produced water quantities.

Oklahoma Department of Environmental Quality (2022) Well-level produced water quantities.

Pandey, S., Gautam, R., Houweling, S., van der Gon, H. D., Sadavarte, P., Borsdorff, T., et al. (2019). *Satellite observations reveal extreme methane leakage from a natural gas well blowout*. Proceedings of the National Academy of Sciences, 116, 26376– 26381. https://doi.org/10.1073/pnas.1908712116.

PHMSA (2022a) Gas Distribution Annual Data. Pipeline and Hazardous Materials Safety Administration, U.S. Department of Transportation, Washington, DC. Available online at: https://www.phmsa.dot.gov/data-and-statistics/pipeline/annual-report-mileage-gas-distribution-systems.

PHMSA (2022b) Underground Natural Gas STAR, Part C. Pipeline and Hazardous Materials Safety Administration, U.S. Department of Transportation, Washington, DC. https://www.phmsa.dot.gov/data-and-statistics/pipeline/gas-distribution-gas-gathering-gas-transmission-hazardous-liquids.

West Virginia Department of Environmental Protection (2020) State-level natural gas production quantities.

Zimmerle et al. (2019) "Characterization of Methane Emissions from Gathering Compressor Stations." October 2019. Available at https://mountainscholar.org/handle/10217/195489.

Zimmerle et al. (2015) "Methane Emissions from the Natural Gas Transmission and Storage System in the United States." *Environmental Science and Technology, Vol. 49* 9374–9383.

Abandoned Oil and Gas Wells

Alaska Oil and Gas Conservation Commission, Available online at: https://www.commerce.alaska.gov/web/aogcc/Data.aspx.

Arkansas Geological & Conservation Commission, "List of Oil & Gas Wells - Data From November 1, 1936 to January 1, 1955."

The Derrick's Handbook of Petroleum: A Complete Chronological and Statistical Review of Petroleum Developments From 1859 to 1898 (V.1), (1898-1899) (V.2).

Enverus (2023) October 2023 Download. Enverus, Inc.

Florida Department of Environmental Protection - Oil and Gas Program, Available online at: https://floridadep.gov/water/oil-gas.

Geological Survey of Alabama, Oil & Gas Board, Available online at: https://www.gsa.state.al.us/ogb/.

GRI/EPA (1996) *Methane Emissions from the Natural Gas Industry*. Prepared by Harrison, M., T. Shires, J. Wessels, and R. Cowgill, eds., Radian International LLC for National Risk Management Research Laboratory, Air Pollution Prevention and Control Division, Research Triangle Park, NC. EPA-600/R-96-080a.

GTI (2001) Gas Resource Database: Unconventional Natural Gas and Gas Composition Databases. Second Edition. GRI-01/0136.

Interstate Oil and Gas Compact Commission (2021). IDLE AND ORPHAN OIL AND GAS WELLS: STATE AND PROVINCIAL REGULATORY STRATEGIES 2021. Available online at: https://iogcc.ok.gov/sites/g/files/gmc836/f/iogcc_idle_and_orphan_wells_2021_final_web.pdf.

Kang, et al. (2016) "Identification and characterization of high methane-emitting abandoned oil and gas wells." *PNAS*, vol. 113 no. 48, 13636–13641, doi: 10.1073/pnas.1605913113.

Oklahoma Geological Survey. "Oklahoma Oil: Past, Present, and Future." Oklahoma Geology Notes, v. 62 no. 3, 2002 pp. 97-106.

Pennsylvania Department of Environmental Protection, Oil and Gas Reports - Oil and Gas Operator Well Inventory. Available online at: http://www.depreportingservices.state.pa.us/ReportServer/Pages/ReportViewer.aspx?/Oil_Gas/OG_Well_Inventory.

International Bunker Fuels

Anderson, B.E., et al. (2011) *Alternative Aviation Fuel Experiment (AAFEX)*, NASA Technical Memorandum, in press.

ASTM (1989) *Military Specification for Turbine Fuels, Aviation, Kerosene Types*, NATO F-34 (JP-8) and NATO F-35. February 10, 1989.

DHS (2008) Personal Communication with Elissa Kay, Residual and Distillate Fuel Oil Consumption (International Bunker Fuels). Department of Homeland Security, Bunker Report. January 11, 2008.

DLA Energy (2023) Unpublished data from the Defense Fuels Automated Management System (DFAMS). Defense Energy Support Center, Defense Logistics Agency, U.S. Department of Defense. Washington, D.C.

DOC (1991 through 2022) Unpublished Report of Bunker Fuel Oil Laden on Vessels Cleared for Foreign Countries. Form-563. Foreign Trade Division, Bureau of the Census, U.S. Department of Commerce. Washington, D.C.

DOT (1991 through 2013) Fuel Cost and Consumption. Federal Aviation Administration, Bureau of Transportation.

Statistics, U.S. Department of Transportation. Washington, D.C. DAI-10.

EIA (2024) *Monthly Energy Review, February 2024,* Energy Information Administration, U.S. Department of Energy, Washington, D.C. DOE/EIA-0035(2024/02).

EPA (2020) EPA Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-2019: Updated Gasoline and Diesel Fuel CO_2 Emission Factors – Memo.

FAA (2024) Personal Communication between FAA and John Steller, Mausami Desai, and Vincent Camobreco for aviation emissions estimates from the Aviation Environmental Design Tool (AEDT). March 2024.

IPCC (2013) *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change.* [Stocker, T.F., D. Qin, G.K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1535 pp.

IPCC (2007) *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change.* [S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds.)]. Cambridge University Press. Cambridge, United Kingdom, 996 pp.

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change. [H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (eds.)]. Hayama, Kanagawa, Japan.USAF (1998) Fuel Logistics Planning. U.S. Air Force pamphlet AFPAM23-221, May 1, 1998.

IPCC/UNEP/OECD/IEA (1997) *Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories*. 31 Intergovernmental Panel on Climate Change, United Nations Environment Programme, Organization for Economic 32 Co-Operation and Development, International Energy Agency, Paris, France.

Wood Biomass and Biofuel Consumption

EIA (2024a) *Monthly Energy Review, February 2024*. Energy Information Administration, U.S. Department of Energy. Washington, D.C. DOE/EIA-0035(2024/02).

EIA (2024b) Biofuels explained: Use of biomass-based diesel fuel. Energy Information Administration, U.S. Department of Energy. Washington, D.C. Available online at: https://www.eia.gov/energyexplained/biofuels/use-of-biodiesel.php.

EPA (2023). Greenhouse Gas Reporting Program (GHGRP). 2022 Envirofacts. Available online at: https://ghgdata.epa.gov/ghgp/main.do.

EPA (2010) Carbon Content Coefficients Developed for EPA's Mandatory Reporting Rule. Office of Air and Radiation, Office of Atmospheric Programs, U.S. Environmental Protection Agency, Washington, D.C.

Lindstrom, P. (2006) Personal Communication. Perry Lindstrom, Energy Information Administration and Jean Kim, ICF International.

Energy Sources of Precursor Greenhouse Gases

EPA (2023a) EPA's Emissions Inventory System (EIS) to National Inventory Report (NIR) Mapping file EIS_NIR_mapping.xlsx. U.S. Environmental Protection Agency. Washington, D.C.

EPA (2023b) "Criteria pollutants National Tier 1 for 1970 – 2023." National Emissions Inventory (NEI) Air Pollutant Emissions Trends Data. Office of Air Quality Planning and Standards, March 2024. Available online at: https://www.epa.gov/air-emissions-inventories/air-pollutant-emissions-trends-data.

EPA (2023c) "2020 National Emissions Inventory Technical Support Document: Introduction." Office of Air Quality Planning and Standards, March 2023. Available online at: https://www.epa.gov/system/files/documents/2023-01/NEI2020_TSD_Section1_Introduction.pdf.

Industrial Processes and Product Use

EPA (2014) *Greenhouse Gas Reporting Program. Developments on Publication of Aggregated Greenhouse Gas Data, November 25, 2014*. See http://www.epa.gov/ghgreporting/confidential-business-information-ghg-reporting.

EPA (2002) Quality Assurance/Quality Control and Uncertainty Management Plan for the U.S. Greenhouse Gas Inventory: Procedures Manual for Quality Assurance/Quality Control and Uncertainty Analysis, U.S. Greenhouse

Gas Inventory Program, U.S. Environmental Protection Agency, Office of Atmospheric Programs, EPA 430-R-02-007B, June 2002.

IPCC (2011) *Use of Models and Facility-Level Data in Greenhouse Gas Inventories* (Report of IPCC Expert Meeting on Use of Models and Measurements in Greenhouse Gas Inventories 9-11 August 2010, Sydney, Australia) eds.: Eggleston H.S., Srivastava N., Tanabe K., Baasansuren J., Fukuda M., Pub. IGES, Japan 2011.

IPCC (2007) *Climate Change 2007: The Physical Science Basis*. Contribution of Working Group I to the *Fourth Assessment Report* of the Intergovernmental Panel on Climate Change. [S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds.)]. Cambridge University Press. Cambridge, United Kingdom 996 pp.

Cement Production

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change. [H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (eds.)]. Hayama, Kanagawa, Japan.

U.S. Bureau of Mines (1990 through 1993) *Minerals Yearbook: Cement Annual Report.* U.S. Department of the Interior, Washington, D.C.

U.S. Environmental Protection Agency (EPA) (2015) *Greenhouse Gas Reporting Program Report Verification*. Available online at https://www.epa.gov/sites/production/files/2015-07/documents/ghgrp_verification_factsheet.pdf.

U.S. EPA (2023) Greenhouse Gas Reporting Program (GHGRP). Aggregation of Reported Facility Level Data under Subpart H -National Level Clinker Production from Cement Production for Calendar Years 2014 through 2022. Office of Air and Radiation, Office of Atmospheric Programs, U.S. Environmental Protection Agency, Washington, D.C.

United States Geological Survey (USGS) (2023a) *2021 Minerals Yearbook – Cement (Advance Release Tables)*. U.S. Geological Survey, Reston, VA. July 2023.

USGS (2023b) *Mineral Commodity Summaries: Cement*. U.S. Geological Survey, Reston, VA. January 2023.

USGS (2023c) *Mineral Industry Surveys, Cement in December 2022*. U.S. Geological Survey, Reston, VA. (March 2023).

USGS (1995 through 2014) *Minerals Yearbook - Cement*. U.S. Geological Survey, Reston, VA.

Van Oss (2013a) 1990 through 2012 Clinker Production Data Provided by Hendrik van Oss (USGS) via email on November 8, 2013.

Van Oss (2013b) Personal communication. Hendrik van Oss, Commodity Specialist of the U.S. Geological Survey and Gopi Manne, Eastern Research Group, Inc. October 28, 2013.

Lime Production

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change. [H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (eds.)]. Hayama, Kanagawa, Japan.

Males, E. (2003) Memorandum from Eric Males, National Lime Association to William N. Irving & Leif Hockstad, Environmental Protection Agency. March 6, 2003.

Miner, R. and B. Upton (2002) Methods for estimating greenhouse gas emissions from lime kilns at kraft pulp mills. Energy. Vol. 27 (2002), p. 729-738.

RTI (2023) Expert judgment, RTI International. March 30, 2023.

Seeger (2013) Memorandum from Arline M. Seeger, National Lime Association to Leif Hockstad, Environmental Protection Agency. March 15, 2013.

U.S. Environmental Protection Agency (EPA) (2023) Greenhouse Gas Reporting Program (GHGRP). Aggregation of Reported Facility Level Data under Subpart S-National Lime Production for Calendar Years 2010 through 2022. Office of Air and Radiation, Office of Atmospheric Programs, U.S. Environmental Protection Agency, Washington, D.C.

United States Geological Survey (USGS) (2023a) (1996 through 2023) *Mineral Commodities Summary: Lime*. U.S. Geological Survey, Reston, VA (January 2023). Latest edition was updated in 2023 for 2022. Applicable editions are available at: https://www.usgs.gov/centers/national-minerals-information-center/lime-statistics-and-information.

USGS (2023b) (*2002 through 2021) Minerals Yearbook Annual Tables: Lime*. U.S. Geological Survey, Reston, VA (January 2023). Latest edition was updated in 2023 for 2021 tables. Applicable editions are available at: https://www.usgs.gov/centers/national-minerals-information-center/lime-statistics-and-information.

USGS (2021) *(1991 through 2018) Minerals Yearbook: Lime*. U.S. Geological Survey, Reston, VA (October 2021). Latest edition was updated in 2021 for 2018. Applicable editions are available at: https://www.usgs.gov/centers/national-minerals-information-center/lime-statistics-and-information. See "Archive" for editions prior to 1993.

USGS (2012) *2012* Expert Elicitation. Michael Miller, U.S. Geological Survey (2012).

Glass Production

Federal Reserve (2023) Board of Governors of the Federal Reserve System (US), Industrial Production: Manufacturing: Durable Goods: Glass and Glass Product (NAICS = 3272) [IPG3272N], retrieved from FRED, Federal Reserve Bank of St. Louis. Available at: https://fred.stlouisfed.org/series/IPG3272N. Accessed on November 21, 2023.

IPCC (2006) *2006 IPCC Guidelines* for National Greenhouse Gas Inventories. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change. [H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (eds.)]. Hayama, Kanagawa, Japan.

RTI (2023) Expert judgment, RTI International. March 30, 2023.

RTI (2022) Expert judgment. Melissa Icenhour, RTI International. November 16, 2022.

U.S. Bureau of Mines (1991 and 1993a) Minerals Yearbook: Crushed Stone Annual Report. U.S. Department of the Interior. Washington, D.C.

U.S. Department of Energy (DOE) (2002) Glass Industry of the Future: Energy and Environmental Profile of the U.S. Glass Industry. Office of Industrial Technologies, U.S. Department of Energy. Washington, D.C.

U.S. Environmental Protection Agency (EPA) (2023) Greenhouse Gas Reporting Program (GHGRP). Aggregation of Reported Facility Level Data under Subpart N -National Glass Production for Calendar Years 2010 through 2022. Office of Air and Radiation, Office of Atmospheric Programs, U.S. Environmental Protection Agency, Washington, D.C.

U.S. EPA (2009) Technical Support Document for the Glass Manufacturing Sector: Proposed Rule for Mandatory Reporting of Greenhouse Gases. U.S. Environmental Protection Agency, Washington, D.C.

United States Geological Survey (USGS) (1995 through 2015b) *Minerals Yearbook: Soda Ash Annual Report*. U.S. Geological Survey, Reston, VA.

USGS (2023) *Mineral Industry Surveys: Soda Ash in January 2023*. U.S. Geological Survey, Reston, VA. November 2023. Available online at: https://www.usgs.gov/centers/national-minerals-information-center/soda-ash-statistics-and-information.

USGS (2022) *Mineral Industry Surveys: Soda Ash in June 2022*. U.S. Geological Survey, Reston, VA. November 2022. Available online at: Index of /minerals-information-archives/soda_ash (usgs.gov).

USGS (2021) *Mineral Industry Surveys: Soda Ash in April 2021*. U.S. Geological Survey, Reston, VA. July 2021. Available online at: Index of /minerals-information-archives/soda_ash (usgs.gov).

USGS (2020) *Mineral Industry Surveys: Soda Ash in April 2020*. U.S. Geological Survey, Reston, VA. July 2020. Available online at: Index of /minerals-information-archives/soda_ash (usgs.gov).

USGS (2019) *Mineral Industry Surveys: Soda Ash in December 2018*. U.S. Geological Survey, Reston, VA. March 2019. Available online at: Index of /minerals-information-archives/soda_ash (usgs.gov).

USGS (2018) *Mineral Industry Surveys: Soda Ash in February 2018*. U.S. Geological Survey, Reston, VA. 2018. Available online at: Index of /minerals-information-archives/soda_ash (usgs.gov).

USGS (2017) *Minerals Industry Surveys: Soda Ash in January 2017*. U.S. Geological Survey, Reston, VA. March 2017. Available online at: Index of /minerals-information-archives/soda_ash (usgs.gov).

Other Process Uses of Carbonates

AISI (2018 through 2021) *Annual Statistical Report.* American Iron and Steel Institute.

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change. [H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (eds.)]. Hayama, Kanagawa, Japan.

Kostick, D. S. (2012) Personal communication. Dennis S. Kostick, U.S. Geological Survey, Soda Ash Commodity Specialist and Gopi Manne and Bryan Lange of Eastern Research Group, Inc. October 2012.

McNeece (2023) Personal communication, Steve McNeece, Nevada Department of Environmental Quality and Amanda Chiu, U.S. Environmental Protection Agency. November 28, 2023.

RTI (2023) Expert judgment, RTI International. March 30, 2023.

Simmons (2024) Personal communication, Kristi Simmons, U.S. Geological Survey and Amanda Chiu, U.S. Environmental Protection Agency. February 9, 2024.

U.S. Bureau of Mines (1991 and 1993a) *Minerals Yearbook: Crushed Stone Annual Report*. U.S. Department of the Interior. Washington, D.C.

U.S. Environmental Protection Agency (EPA) (2023). Greenhouse Gas Reporting Program (GHGRP). Dataset as of August 18, 2023. Available online at: https://ghgdata.epa.gov/ghgp/

United States Geological Survey (USGS) (2023a) *Mineral Industry Surveys: Soda Ash in September 2023*. U.S. Geological Survey, Reston, VA. November 2023.

USGS (2023b) *2021 Minerals Yearbook: Stone, Crushed [Advanced Release]*. U.S. Geological Survey, Reston, VA. June 2023.

USGS (2022a) *Mineral Industry Surveys: Soda Ash in August 2022*. U.S. Geological Survey, Reston, VA. November 2022.

USGS (2022b) *2020 Minerals Yearbook: Stone, Crushed [Advanced Release]*. U.S. Geological Survey, Reston, VA. August 2022.

USGS (2022c) *2018 Minerals Yearbook: Stone, Crushed [Advanced Release]*. U.S. Geological Survey, Reston, VA. August 2022.

USGS (2022d) *2019 Minerals Yearbook: Stone, Crushed [Advanced Release]*. U.S. Geological Survey, Reston, VA. June 2022.

USGS (2022e) *2018 Minerals Yearbook: Magnesium Compounds [Advanced Release]*. U.S. Geological Survey, Reston, VA. May 2022.

USGS (2022f) *2018 Minerals Yearbook: Clay and Shale [Advanced Release]*. U.S. Geological Survey, Reston, VA. March 2022.

USGS (2022g) *2018 Minerals Yearbook: Soda Ash [Advanced Release]*. U.S. Geological Survey, Reston, VA. January 2022.

USGS (2021a) *Minerals Yearbook 2019: Soda Ash [Advanced Data Release of the 2019 Annual Tables]*. U.S. Geological Survey, Reston, VA. August 2021.

USGS (2021b) *Mineral Industry Surveys: Soda Ash in April 2021*. U.S. Geological Survey, Reston, VA. July 2021.

USGS (2021c) 2017 *Minerals Yearbook: Stone, Crushed [Advanced Release]*. U.S. Geological Survey, Reston, VA. June 2021.

USGS (2021d) *2020 Mineral Commodity Summaries: Stone (Crushed).* U.S. Geological Survey, Reston, VA. January 2021.

USGS (2020a) *Minerals Yearbook 2017: Stone, Crushed [Advanced Data Release of the 2017 Annual Tables]*. U.S. Geological Survey, Reston, VA. August 2020.

USGS (2020b) *Mineral Industry Surveys: Soda Ash in April 2020*. U.S. Geological Survey, Reston, VA. July 2020.

USGS (2020c) 2016 *Minerals Yearbook: Stone, Crushed [Advanced Release]*. U.S. Geological Survey, Reston, VA. January 2020.

USGS (2019) *Mineral Industry Surveys: Soda Ash in April 2019*. U.S. Geological Survey, Reston, VA. July 2019.

USGS (2018) *Mineral Industry Surveys: Soda Ash in February 2018*. U.S. Geological Survey, Reston, VA. 2018.

USGS (2017) *Mineral Industry Surveys: Soda Ash in January 2017*. U.S. Geological Survey, Reston, VA. March 2017.

USGS (1995a through 2017) *Minerals Yearbook: Crushed Stone Annual Report*. U.S. Geological Survey, Reston, VA.

USGS (1994 through 2015b) *Minerals Yearbook: Soda Ash Annual Report*. U.S. Geological Survey, Reston, VA.

USGS (1990 through 2002) *Minerals Yearbook: Magnesium Compounds Annual Report*. U.S. Geological Survey, Reston, VA.

USGS (1948) *Reports: Magnesite and brucite deposits at Gabbs, Nye County, Nevada*. U.S. Geological Survey, Reston, VA

Willett (2023) Personal communication, Jason Christopher Willett, U.S. Geological Survey and Amanda Chiu, U.S. Environmental Protection Agency. November 21, 2023.

Willett (2017) Personal communication, Jason Christopher Willett, U.S. Geological Survey and Mausami Desai and John Steller, U.S. Environmental Protection Agency. March 9, 2017.

Ammonia Production

ACC (2023) Business of Chemistry (Annual Data). American Chemistry Council, Arlington, VA.

Coffeyville Resources Energy, Inc. (CVR) (2008) *CVR Energy, Inc. 2008 Annual Report.* Available online at: https://cvrenergy.gcs-web.com/annual-report-and-proxy-archive.

CVR (2022) CVR Energy, Inc. *2022 Annual Report on Form 10-K.* Available online at: https://cvrenergy.gcs-web.com/annual-report-proxy-information.

CVR (2021) CVR Energy, Inc. *2021 CVI Annual Report on Form 10-K.* Available online at: https://cvrenergy.gcs-web.com/annual-report-and-proxy-archive.

CVR (2020) CVR Energy, Inc. *2020 CVI Annual Report on Form 10-K --Final*. Available online at: https://cvrenergy.gcs-web.com/annual-report-and-proxy-archive.

CVR (2019) CVR Energy, Inc. *2019 CVI Form 10-K - Final*. Available online at https://cvrenergy.gcs-web.com/annual-report-and-proxy-archive.

CVR (2018) CVR Energy, Inc. *2018 CVI Annual Report on Form 10-K --Final*. Available online at: https://cvrenergy.gcs-web.com/annual-report-and-proxy-archive.

CVR (2017) CVR Energy, Inc. *2017 CVI Annual Report on Form 10-K (Web).* Available online at: https://cvrenergy.gcs-web.com/annual-report-and-proxy-archive.

CVR (2016) CVR Energy, Inc. *2016 CVI Annual Report on Form 10-K (Web).* Available online at: https://cvrenergy.gcs-web.com/annual-report-and-proxy-archive.

CVR (2014) CVR Energy, Inc. *2014 Annual Report.* Available online at: https://cvrenergy.gcs-web.com/annual-report-and-proxy-archive.

CVR (2015) CVR Energy, Inc. *2015 Annual Report*. Available online at: https://cvrenergy.gcs-web.com/annual-report-and-proxy-archive.

CVR (2013) CVR Energy, Inc. *2013 Annual Report.* Available online at: https://cvrenergy.gcs-web.com/annual-report-and-proxy-archive.

CVR (2012) *CVR Energy, Inc. 2012 Annual Report.* Available online at: https://cvrenergy.gcs-web.com/annual-report-and-proxy-archive.

CVR (2011) *CVR Energy, Inc. 2011 Annual Report.* Available online at: https://cvrenergy.gcs-web.com/annual-report-and-proxy-archive.

CVR (2010) *CVR Energy, Inc. 2010 Annual Report.* Available online at: https://cvrenergy.gcs-web.com/annual-report-and-proxy-archive.

CVR (2009) *CVR Energy, Inc. 2009 Annual Report.* Available online at: https://cvrenergy.gcs-web.com/annual-report-and-proxy-archive.

EFMA (2000) *Best Available Techniques for Pollution Prevention* and *Control in the European Fertilizer Industry*. Booklet No. 5 of 8: Production of Urea and Urea Ammonium Nitrate. Available online at: http://fertilizerseurope.com/site/index.php?id=390.

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change. [H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (eds.)]. Hayama, Kanagawa, Japan.

RTI (2023) Expert judgment, RTI International. March 30, 2023.

United States Census Bureau (2011) *Current Industrial Reports Fertilizer Materials and Related Products: 2010 Summary.* Available online at: http://www.census.gov/manufacturing/cir/historical_data/mq325b/index.html.

U.S. Census Bureau (2010) *Current Industrial Reports Fertilizer Materials and Related Products: 2009 Summary.* Available online at: http://www.census.gov/manufacturing/cir/historical_data/mq325b/index.html.

U.S. Census Bureau (2009) *Current Industrial Reports Fertilizer Materials and Related Products: 2008 Summary.* Available online at: http://www.census.gov/manufacturing/cir/historical_data/mq325b/index.html.

U.S. Census Bureau (2008) *Current Industrial Reports Fertilizer Materials and Related Products: 2007 Summary*. Available online at: http://www.census.gov/cir/www/325/mq325b/mq325b075.xls.

U.S. Census Bureau (2007) *Current Industrial Reports Fertilizer Materials and Related Products: 2006 Summary*. Available online at: http://www.census.gov/industry/1/mq325b065.pdf.

U.S. Census Bureau (2006) *Current Industrial Reports Fertilizer Materials and Related Products: 2005 Summary*. Available online at: http://www.census.gov/cir/www/325/mq325b.html.

U.S. Census Bureau (2004, 2005) *Current Industrial Reports Fertilizer Materials and Related Products: Fourth Quarter Report Summary*. Available online at: http://www.census.gov/cir/www/325/mq325b.html.

U.S. Census Bureau (1998 through 2003) *Current Industrial Reports Fertilizer Materials and Related Products: Annual Reports Summary*. Available online at: http://www.census.gov/cir/www/325/mq325b.html.

U.S. Census Bureau (1991 through 1994) *Current Industrial Reports Fertilizer Materials Annual Report.* Report No. MQ28B. U.S. Census Bureau, Washington, D.C.

United States EIA (2023) *Monthly Energy Review, February 2023,* Energy Information Administration, U.S. Department of Energy, Washington, DC. DOE/EIA-0035(2023/2).

United States Environmental Protection Agency (EPA) (2023) Greenhouse Gas Reporting Program. Aggregation of Reported Facility Level Data under Subpart G -Annual Urea Production from Ammonia Manufacturing for Calendar Years 2017-2022. Office of Air and Radiation, Office of Atmospheric Programs, U.S. Environmental Protection Agency, Washington, D.C.

U.S. EPA (2018) Greenhouse Gas Reporting Program. Aggregation of Reported Facility Level Data under Subpart G - Annual Urea Production from Ammonia Manufacturing for Calendar Years 2011-2016. Office of Air and Radiation, Office of Atmospheric Programs, U.S. Environmental Protection Agency, Washington, D.C

United States Geological Survey (USGS) (2023) *2023 Mineral Commodity Summaries: Nitrogen (Fixed) - Ammonia.* January 2023. Available online at: https://pubs.usgs.gov/periodicals/mcs2023/mcs2023-nitrogen.pdf.

USGS (1994-2009) *Minerals Yearbook: Nitrogen*. Available online at: http://minerals.usgs.gov/minerals/pubs/commodity/nitrogen/

Urea Consumption for Non-Agricultural Purposes

EFMA (2000) *Best Available Techniques for Pollution Prevention and Control in the European Fertilizer Industry*. Booklet No. 5 of 8: Production of Urea and Urea Ammonium Nitrate.

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change. [H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (eds.)]. Hayama, Kanagawa, Japan.

RTI (2023) Expert judgment, RTI International. March 30, 2023.

TFI (2002) *U.S. Nitrogen Imports/Exports Table.* The Fertilizer Institute. Available online at: http://www.tfi.org/statistics/usnexim.asp. August 2002.

United States Census Bureau (2001 through 2011) *Current Industrial Reports Fertilizer Materials and Related Products: Annual Summary.* Available online at: http://www.census.gov/manufacturing/cir/historical_data/index.html.

United States Department of Agriculture (2012) Economic Research Service Data Sets, Data Sets, U.S. Fertilizer Imports/Exports: Standard Tables. Available online at: http://www.ers.usda.gov/data-products/fertilizer-importsexports/standard-tables.aspx.

U.S. EPA (2023a) Greenhouse Gas Reporting Program. Aggregation of Reported Facility Level Data under Subpart G -Annual Urea Production from Ammonia Manufacturing for Calendar Years 2017-2022. Office of Air and Radiation, Office of Atmospheric Programs, U.S. Environmental Protection Agency, Washington, D.C.

U.S. EPA (2023b). Greenhouse Gas Reporting Program. Dataset as of August 18, 2023. Available online at: https://ghgdata.epa.gov/ghgp/.

U.S. EPA (2018) Greenhouse Gas Reporting Program. Aggregation of Reported Facility Level Data under Subpart G - Annual Urea Production from Ammonia Manufacturing for Calendar Years 2011-2016. Office of Air and Radiation, Office of Atmospheric Programs, U.S. Environmental Protection Agency, Washington, D.C.

United States International Trade Commission (ITC) (2002) *United States International Trade Commission Interactive Tariff and Trade DataWeb, Version 2.5.0*. Available online at: http://dataweb.usitc.gov/. August 2002.

United States Geological Survey (USGS) (1994 through 2023a) *Minerals Yearbook: Nitrogen*. Available online at: http://minerals.usgs.gov/minerals/pubs/commodity/nitrogen/.

USGS (2023b) *Minerals Commodity Summaries: Nitrogen (Fixed) – Ammonia*. January 2023. Available online at: https://pubs.usgs.gov/periodicals/mcs2023/mcs2023-nitrogen.pdf.

Nitric Acid Production

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change. [H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (eds.)]. Hayama, Kanagawa, Japan.

Icenhour (2020) Personal communication, Melissa Icenhour, RTI International and Amanda Chiu, U.S. Environmental Protection Agency. December 3, 2020.

RTI (2023) Expert judgment, RTI International. March 30, 2023.

United States Census Bureau (2010a) *Current Industrial Reports. Fertilizers and Related Chemicals: 2009.* "Table 1: Summary of Production of Principle Fertilizers and Related Chemicals: 2009 and 2008." June, 2010. MQ325B(08)-5. Available online at: http://www.census.gov/manufacturing/cir/historical_data/mq325b/index.html.

U.S. Census Bureau (2010b) Personal communication between Hilda Ward (of U.S. Census Bureau) and Caroline Cochran (of ICF International). October 26, 2010 and November 5, 2010.

U.S. Census Bureau (2009) *Current Industrial Reports. Fertilizers and Related Chemicals: 2008.* "Table 1: Shipments and Production of Principal Fertilizers and Related Chemicals: 2004 to 2008." June, 2009. MQ325B(08)-5. Available online at: http://www.census.gov/manufacturing/cir/historical_data/mq325b/index.html.

U.S. Census Bureau (2008) *Current Industrial Reports. Fertilizers and Related Chemicals: 2007.* "Table 1: Shipments and Production of Principal Fertilizers and Related Chemicals: 2003 to 2007." June, 2008. MQ325B(07)-5. Available online at: http://www.census.gov/manufacturing/cir/historical_data/mq325b/index.html.

U.S. EPA (2023) Greenhouse Gas Reporting Program. Aggregation of Reported Facility Level Data under Subpart V - National Nitric Acid Production for Calendar Years 2017 through 2022. Office of Air and Radiation, Office of Atmospheric Programs, U.S. Environmental Protection Agency, Washington, D.C.

U.S. EPA (2018) Greenhouse Gas Reporting Program. Aggregation of Reported Facility Level Data under Subpart V - National Nitric Acid Production for Calendar Years 2010 through 2016. Office of Air and Radiation, Office of Atmospheric Programs, U.S. Environmental Protection Agency, Washington, D.C.

U.S. EPA (2015) *Greenhouse Gas Reporting Program Report Verification*. Available online at https://www.epa.gov/sites/production/files/2015-07/documents/ghgrp_verification_factsheet.pdf.

U.S. EPA (2010) *Available and Emerging Technologies for Reducing Greenhouse Gas Emissions from the Nitric Acid Production Industry.* Office of Air Quality Planning and Standards, U.S. Environmental Protection Agency. Research Triangle Park, NC. December 2010. Available online at: http://www.epa.gov/nsr/ghgdocs/nitricacid.pdf.

U.S. EPA (1998) *Compilation of Air Pollutant Emission Factors, AP-42.* Office of Air Quality Planning and Standards, U.S. Environmental Protection Agency. Research Triangle Park, NC. February 1998.

Adipic Acid Production

ACC (2023) Business of Chemistry (Annual Data). American Chemistry Council, Arlington, VA.

Ard (2024) Personal communication, Howard Ard, Florida Department of Environmental Protection and Amanda Chiu, U.S. Environmental Protection Agency. February 6, 2024.

Ascend (2023) "Ascend reaches GHG abatement milestone." Available online at https://www.ascendmaterials.com/news/ascend-reaches-ghg-abatement-milestone. December 1, 2023.

C&EN (1995) "Production of Top 50 Chemicals Increased Substantially in 1994." *Chemical & Engineering News*, 73(15):17. April 10, 1995.

C&EN (1994) "Top 50 Chemicals Production Rose Modestly Last Year." *Chemical & Engineering News*, 72(15):13. April 11, 1994.

C&EN (1993) "Top 50 Chemicals Production Recovered Last Year." *Chemical & Engineering News*, 71(15):11. April 12, 1993.

C&EN (1992) "Production of Top 50 Chemicals Stagnates in 1991." *Chemical & Engineering News*, 70(15): 17. April 13, 1992.

CMR (2001) "Chemical Profile: Adipic Acid." *Chemical Market Reporter*. July 16, 2001.

CMR (1998) "Chemical Profile: Adipic Acid." *Chemical Market Reporter*. June 15, 1998.

CW (2005) "Product Focus: Adipic Acid." *Chemical Week*. May 4, 2005.

CW (1999) "Product Focus: Adipic Acid/Adiponitrile." *Chemical Week*, p. 31. March 10, 1999.

Desai (2010, 2011) Personal communication. Mausami Desai, U.S. Environmental Protection Agency and Adipic Acid Plant Engineers. 2010 and 2011.

ICIS (2007) "Adipic Acid." *ICIS Chemical Business Americas*. July 9, 2007.

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change. [H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (eds.)]. Hayama, Kanagawa, Japan.

Reimer, R.A., Slaten, C.S., Seapan, M., Koch, T.A. and Triner, V.G. (1999) "Implementation of Technologies for Abatement of N_2O Emissions Associated with Adipic Acid Manufacture." Proceedings of the 2nd Symposium on Non-CO_2 Greenhouse Gases (NCGG-2), Noordwijkerhout, The Netherlands, 8-10 Sept. 1999, Ed. J. van Ham et al., Kluwer Academic Publishers, Dordrecht, pp. 347-358.

RTI (2023) Expert judgment, RTI International. March 30, 2023.

Thiemens, M.H., and W.C. Trogler (1991) "Nylon production; an unknown source of atmospheric nitrous oxide." *Science* 251:932-934.

United States Environmental Protection Agency (EPA) (2021 through 2023) Greenhouse Gas Reporting Program. Subpart E Data. Office of Air and Radiation, Office of Atmospheric Programs, U.S. Environmental Protection Agency, Washington, D.C. Available online at: https://www.epa.gov/ghgreporting/ghg-reporting-program-data-sets.

U.S. EPA (2019, 2020) Greenhouse Gas Reporting Program. Subpart E, S-CEMS, BB, CC, LL Data Set (XLSX) (Adipic Acid Tab). Office of Air and Radiation, Office of Atmospheric Programs, U.S. Environmental Protection Agency, Washington, D.C. Available online at: https://www.epa.gov/ghgreporting/ghg-reporting-program-data-sets.

U.S. EPA (2015) *Greenhouse Gas Reporting Program Report Verification*. Available online at https://www.epa.gov/sites/production/files/2015-07/documents/ghgrp_verification_factsheet.pdf.

U.S. EPA (2014 through 2018) Greenhouse Gas Reporting Program. Subpart E, S-CEMS, BB, CC, LL Data Set (XLSX) (Adipic Acid Tab). Office of Air and Radiation, Office of Atmospheric Programs, U.S. Environmental Protection Agency, Washington, D.C. Available online at: http://www2.epa.gov/ghgreporting/ghg-reporting-program-data-sets.

U.S. EPA (2010 through 2013) Analysis of Greenhouse Gas Reporting Program data – Subpart E (Adipic Acid), Office of Air and Radiation, Office of Atmospheric Programs, U.S. Environmental Protection Agency, Washington, D.C.

Caprolactam, Glyoxal and Glyoxylic Acid Production

American Chemistry Council (ACC) (2023) Business of Chemistry (Annual Data). American Chemistry Council, Arlington, VA.

AdvanSix (2023) AdvanSix's Hopewell Facility Fact Sheet. Retrieved from: https://www.advansix.com/hopewell/about-us/ on September 13, 2023.

BASF (2023) Welcome to BASF in Freeport Texas. Retrieved from https://www.basf.com/us/en/who-we-are/organization/locations/featured-sites/Freeport.html on September 13, 2023.

ChemView (2021). Compilation of data submitted under TSCA in 2012 and 2016. Accessed April 2021. Available at https://chemview.epa.gov/chemview.

Cline, D. (2019) Firm to Clean Up and Market Former Fibrant Site. *The Augusta Chronicle*. September 9, 2019. Retrieved from https://www.augustachronicle.com.

Ecofys, et al. (2009). *Methodology for the free allocation of emission allowances in the EU ETS post 2012: Sector Report for the Chemical Industry*. Prepared by Ecofys, Fraunhofer Institute for Systems and Innovation Research, and Oko-Institut for the European Commission. November 2009. Available at https://ec.europa.eu/clima/system/files/2016-11/bm_study-chemicals_en.pdf.

ICIS (2006) Chemical Profile – Caprolactam. October 15, 2006. Available online at: https://www.icis.com/explore/resources/news/2006/10/18/2016832/chemical-profile-caprolactam/.

ICIS (2004) Chemical Profile – Caprolactam. January 5, 2004. Available online at: https://www.icis.com/explore/resources/news/2005/12/02/547244/chemical-profile-caprolactam/.

IPCC (2013) *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change.* [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1535 pp.

IPCC (2007) *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change.* [S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds.)]. Cambridge University Press. Cambridge, United Kingdom 996 pp.

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change. [H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (eds.)]. Hayama, Kanagawa, Japan.

RTI (2023) Expert judgment, RTI International. March 30, 2023.

Shaw Industries Group, Inc. (Shaw) (2015) "Shaw Carpet Recycling Facility Successfully Processes Nylon and Polyester". July 13, 2015. Available online at: https://shawinc.com/Newsroom/Press-Releases/Shaw-Carpet-Recycling-Facility-Successfully-Proces/.

Textile World (2000) "Evergreen Makes Nylon Live Forever". Textile World. October 1, 2000. Available online at: https://www.textileworld.com/textile-world/textile-news/2000/10/evergreen-makes-nylon-live-forever/.

Carbide Production and Consumption

IPCC (2013) *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change.* [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1535 pp.

IPCC (2007) *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change.* [S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds.)]. Cambridge University Press. Cambridge, United Kingdom 996 pp.

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change. [H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (eds.)]. Hayama, Kanagawa, Japan.

Biscay, Nicolas & Henry, Lucile & Adschiri, Tadafumi & Yoshimura, Masahiro & Aymonier, Cyril. (2021). Behavior of Silicon Carbide Materials under Dry to Hydrothermal Conditions. Nanomaterials. 11. 1351. doi: 10.3390/nano11051351.

Environment and Climate Change Canada (ECCC) (2022), Personal Communication between Genevieve Leblanc-Power, Environment and Climate Change Canada and Mausami Desai and Amanda Chiu, U.S. Environmental Protection Agency. April 12, 2022.

RTI (2023) Expert judgment, RTI International. March 30, 2023.

United States Census Bureau (1990 through 2022) *USITC Trade DataWeb.* Available online at: http://dataweb.usitc.gov/.

USGS (1991a through 2021) *Minerals Yearbook: Manufactured Abrasives Annual Report.* U.S. Geological Survey, Reston, VA. Available online at: https://www.usgs.gov/centers/national-minerals-information-center/manufactured-abrasives-statistics-and-information.

USGS (1991b through 2021) *Minerals Yearbook: Silicon Annual Report.* U.S. Geological Survey, Reston, VA. Available online at: http://minerals.usgs.gov/minerals/pubs/commodity/silicon/.

USGS (2023a) 2022 *Minerals Yearbook: Manufactured Abrasives (2022 advanced-release tables),* September 27, 2023. U.S. Geological Survey, Reston, VA. Available online at: https://www.usgs.gov/centers/national-minerals-information-center/manufactured-abrasives-statistics-and-information

USGS (2023b) *Mineral Commodity Summaries: Abrasives (Manufactured)*. U.S. Geological Survey, Reston, Va. January 2023.

USGS (2023c) *2022 Minerals Yearbook: Silicon (2022 advanced-release tables*), November 27, 2023. U.S. Geological Survey, Reston, VA. Available online at: https://www.usgs.gov/centers/national-minerals-information-center/silicon-statistics-and-information

USGS (2021a) *Mineral Commodity Summaries: Abrasives (Manufactured)*. U.S. Geological Survey, Reston, Va. January 2021. Available online at: https://pubs.usgs.gov/periodicals/mcs2021/mcs2021-abrasives.pdf.

Washington Mills (2023), North Grafton, MA. Available online at: https://www.washingtonmills.com/silicon-carbide/sic-industries. Accessed on April 4, 2023.

Titanium Dioxide Production

Gambogi, J. (2002) Telephone communication. Joseph Gambogi, Commodity Specialist, U.S. Geological Survey and Philip Groth, ICF International. November 2002.

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, Intergovernmental Panel on Climate Change. [H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (eds.)]. Hayama, Kanagawa, Japan.

RTI (2023) Expert judgment, RTI International. March 30, 2023.

United States Geological Survey (USGS) (2023a) 2020 *Minerals Yearbook: Titanium*, 2020 tables-only release, Table 1. U.S. Geological Survey, Reston, Va. March 2023.

USGS (2023b) *Mineral Commodity Summaries: Titanium and Titanium Dioxide*. U.S. Geological Survey, Reston, Va. January 2023.

USGS (1991 through 2022) *Minerals Yearbook: Titanium.* U.S. Geological Survey, Reston, VA.

Soda Ash Production

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change. [H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (eds.)]. Hayama, Kanagawa, Japan.

RTI (2023) Expert judgment, RTI International. March 30, 2023.

United States Geological Survey (USGS) (2023a) *Mineral Commodity Summary: Soda Ash*. U.S. Geological Survey, Reston, VA. January 2023.

USGS (2023b) *Mineral Industry Surveys: Soda Ash in June 2023*. U.S. Geological Survey, Reston, VA. August 2023.

United States Geological Survey (USGS) (2022a) *Mineral Commodity Summary: Soda Ash*. U.S. Geological Survey, Reston, VA. January 2022.

USGS (2022b) *Mineral Industry Surveys: Soda Ash in June 2022*. U.S. Geological Survey, Reston, VA. August 2022.

USGS (2021) *Mineral Industry Surveys: Soda Ash in April 2021*. U.S. Geological Survey, Reston, VA. July 2021.

USGS (2020) *Mineral Industry Surveys: Soda Ash in April 2020*. U.S. Geological Survey, Reston, VA. July 2020.

USGS (2019) *Mineral Industry Surveys: Soda Ash in April 2019*. U.S. Geological Survey, Reston, VA. July 2019.

USGS (2018a) *Mineral Industry Surveys: Soda Ash in February 2018*. U.S. Geological Survey, Reston, VA. Accessed September 2018.

USGS (2017) *Mineral Industry Surveys: Soda Ash in January 2017*. U.S. Geological Survey, Reston, VA. March 2017.

USGS (2016) *Mineral Industry Surveys: Soda Ash in November 2016*. U.S. Geological Survey, Reston, VA. January 2017.

USGS (2015a) *Mineral Industry Surveys: Soda Ash in July 2015*. U.S. Geological Survey, Reston, VA. September 2015.

USGS (1994 through 2015b, 2018b) *Minerals Yearbook: Soda Ash Annual Report*. U.S. Geological Survey, Reston, VA.

USGS (1995c) *Trona Resources in the Green River Basin, Southwest Wyoming.* U.S. Department of the Interior, U.S. Geological Survey. Open-File Report 95-476. Wiig, Stephen, Grundy, W.D., Dyni, John R.

Petrochemical Production

ACC (2023) Business of Chemistry (Annual Data). American Chemistry Council, Arlington, VA.

AN (2014) *About Acrylonitrile: Production*. AN Group, Washington, D.C.

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change. [H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (eds.)]. Hayama, Kanagawa, Japan.

Johnson, G. L. (2005 through 2010) Personal communication. Greg Johnson of Liskow & Lewis, on behalf of the International Carbon Black Association (ICBA) and Caroline Cochran, ICF International. September 2010.

Johnson, G. L. (2003) Personal communication. Greg Johnson of Liskow & Lewis, on behalf of the International Carbon Black Association (ICBA) and Caren Mintz, ICF International. November 2003.

United States Environmental Protection Agency (EPA) (2023) Greenhouse Gas Reporting Program. Aggregation of Reported Facility Level Data under Subpart X -National Petrochemical Production for Calendar Years 2010 through 2022. Office of Air and Radiation, Office of Atmospheric Programs, U.S. Environmental Protection Agency, Washington, D.C.

U.S. EPA (2015) *Greenhouse Gas Reporting Program Report Verification*. Available online at https://www.epa.gov/sites/production/files/2015-07/documents/ghgrp_verification_factsheet.pdf.

U.S. EPA (2008) *Technical Support Document for the Petrochemical Production Sector: Proposed Rule for Mandatory Reporting of Greenhouse Gases.* U.S. Environmental Protection Agency. September 2008.

U.S. EPA (2000) *Economic Impact Analysis for the Proposed Carbon Black Manufacturing NESHAP,* U.S. Environmental Protection Agency. Research Triangle Park, NC. EPA-452/D-00-003. May 2000.

HCFC-22 Production

ARAP (2010) Electronic mail communication from Dave Stirpe, Executive Director, Alliance for Responsible Atmospheric Policy to Deborah Ottinger of the U.S. Environmental Protection Agency. September 10, 2010.

ARAP (2009) Electronic mail communication from Dave Stirpe, Executive Director, Alliance for Responsible Atmospheric Policy to Deborah Ottinger of the U.S. Environmental Protection Agency. September 21, 2009.

ARAP (2008) Electronic mail communication from Dave Stirpe, Executive Director, Alliance for Responsible Atmospheric Policy to Deborah Ottinger of the U.S. Environmental Protection Agency. October 17, 2008.

ARAP (2007) Electronic mail communication from Dave Stirpe, Executive Director, Alliance for Responsible Atmospheric Policy to Deborah Ottinger of the U.S. Environmental Protection Agency. October 2, 2007.

ARAP (2006) Electronic mail communication from Dave Stirpe, Executive Director, Alliance for Responsible Atmospheric Policy to Sally Rand of the U.S. Environmental Protection Agency. July 11, 2006.

ARAP (2005) Electronic mail communication from Dave Stirpe, Executive Director, Alliance for Responsible Atmospheric Policy to Deborah Ottinger of the U.S. Environmental Protection Agency. August 9, 2005.

ARAP (2004) Electronic mail communication from Dave Stirpe, Executive Director, Alliance for Responsible Atmospheric Policy to Deborah Ottinger of the U.S. Environmental Protection Agency. June 3, 2004.

ARAP (2003) Electronic mail communication from Dave Stirpe, Executive Director, Alliance for Responsible Atmospheric Policy to Sally Rand of the U.S. Environmental Protection Agency. August 18, 2003.

ARAP (2002) Electronic mail communication from Dave Stirpe, Executive Director, Alliance for Responsible Atmospheric Policy to Deborah Ottinger of the U.S. Environmental Protection Agency. August 7, 2002.

ARAP (2001) Electronic mail communication from Dave Stirpe, Executive Director, Alliance for Responsible Atmospheric Policy to Deborah Ottinger of the U.S. Environmental Protection Agency. August 6, 2001.

ARAP (2000) Electronic mail communication from Dave Stirpe, Executive Director, Alliance for Responsible Atmospheric Policy to Sally Rand of the U.S. Environmental Protection Agency. August 13, 2000.

ARAP (1999) Facsimile from Dave Stirpe, Executive Director, Alliance for Responsible Atmospheric Policy to Deborah Ottinger Schaefer of the U.S. Environmental Protection Agency. September 23, 1999.

ARAP (1997) Letter from Dave Stirpe, Director, Alliance for Responsible Atmospheric Policy to Elizabeth Dutrow of the U.S. Environmental Protection Agency. December 23, 1997.

EPA (2015) *Greenhouse Gas Reporting Program Report Verification*. Available online at https://www.epa.gov/sites/production/files/2015-07/documents/ghgrp_verification_factsheet.pdf.

IPCC (2007) *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. [S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds.)]. Cambridge University Press. Cambridge, United Kingdom 996 pp.

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change. [H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (eds.)]. Hayama, Kanagawa, Japan.

RTI (2008) "Verification of Emission Estimates of HFC-23 from the Production of HCFC-22:Emissions from 1990 through 2006." Report prepared by RTI International for the Climate Change Division. March 2008.

RTI (1997) "Verification of Emission Estimates of HFC-23 from the Production of HCFC-22: Emissions from 1990 through 1996." Report prepared by Research Triangle Institute for the Cadmus Group. November 25, 1997; revised February 16, 1998.

UNFCCC (2014) Report of the Conference of the Parties on its nineteenth session, held in Warsaw from 11 to 23 November 2013. United Nations Framework Convention on Climate Change, Warsaw. (FCCC/CP/2013/10/Add.3). January 31, 2014. Available online at: http://unfccc.int/resource/docs/2013/cop19/eng/10a03.pdf.

Production of Fluorochemicals Other Than HCFC-22

3M (2024) *3M Global EHS Laboratory Response to EPA Data Request on Fluorochemical Emissions.* February 2024.

Daikin (2013) *Major Source Operating Permit*, Daikin America, Alabama Department of Environmental Management, August 1, 2013. http://lf.adem.alabama.gov/WebLink/DocView.aspx?id=29951882&dbid=0. (p. 11-1).

Honeywell (2012) *Part 70 Operating Permit*, Geismar Plant, Honeywell International Inc., Louisiana, Louisiana Department of Environmental Quality, Page 13, January 28, 2011. https://edms.deq.louisiana.gov/app/doc/view?doc=7812895.

Honeywell (2011) *Part 70 Operating Permit*, Baton Rouge Plant Honeywell International Inc., Louisiana Department of Environmental Quality, Page 25, October 16, 2012. https://edms.deq.louisiana.gov/app/doc/view?doc=8579001.

ICI Americas (1993) *New Permit, KLEA – 134a Plant*, ICI Americas, St. Gabriel, Louisiana, Louisiana Department of Environmental Quality, Page 44, May 28, 1993. https://edms.deq.louisiana.gov/app/doc/view?doc=1309650.

IPCC (2021) *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change.* [Masson-Delmotte, V., P. Zhai, A. Pirani, S.L.

Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 2391 pp. doi:10.1017/9781009157896. Available from www.ipcc.ch. The AR6 GWPs are listed in Table 7.SM.7, which appears on page 16 of the Supplementary Material.

IPCC (2019) *2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories*, Calvo Buendia, E., Tanabe, K., Kranjc, A., Baasansuren, J., Fukuda, M., Ngarize S., Osako, A., Pyrozhenko, Y., Shermanau, P. and Federici, S. (eds). Published: IPCC, Switzerland.

IPCC (2013) *Climate Change 2013: The Physical Science Basis.* Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1535 pp. The GWPs are listed in Table 8.A.1 of Appendix 8.A: Lifetimes, Radiative Efficiencies and Metric Values, which appears on pp. 731-737 of Chapter 8, "Anthropogenic and Natural Radiative Forcing."

IPCC (2007) *Climate Change 2007: The Physical Science Basis.* Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, Pachauri, R.K and Reisinger, A. (eds.)]. IPCC, Geneva, Switzerland, 104 pp.

McKenna (2022) *A 3M Plant in Illinois Was the Country's Worst Emitter of a Climate-Killing 'Immortal' Chemical in 2021*, Phil McKenna, Inside Climate News, December 29, 2022. [3M Cordova IL facility.] https://insideclimatenews.org/news/29122022/3m-cordova-illinois-pfas-cf4-pollution/.

Perkins (1982) Perkins, B. L., *Evaluation of Environmental Control Technologies for Commercial Nuclear Fuel Conversion (UF_6) Facilities*, LA-9397-MS, October 1982 [030000442.pdf].

Rand (2007) *2004-2006 SF_6 Data Summary*, Project Memorandum Prepared by D. Knopman and K. Smythe, RAND Corporation, for the National Electrical Manufacturers Association, June 2007.

SRI Consulting (2004) *Chemical Economics Handbook (CEH) Market Research Report: Fluorocarbons*, R. Will, A. Kishi, S. Schlag. SRI Consulting, 2004.

U.S. EPA (2008) Survey of Producers of HFCs, PFCs, SF_6 and NF_3, 2008. Office of Air and Radiation, Office of Atmospheric Programs, U.S. Environmental Protection Agency.

U.S. EPA (2023a) GHGRP Data Relevant to the AIM Act, Greenhouse Gas Reporting Program. https://www.epa.gov/ghgreporting/ghgrp-data-relevant-aim-act. Last accessed 11/16/2023.

U.S. EPA (2023b) Vintaging Model for HFCs. 2023. Office of Atmospheric Programs, U.S. Environmental Protection Agency.

U.S. EPA (2023c) Estimated layer-weighted substrate production by the semiconductor industry. Office of Atmospheric Programs, Office of Atmospheric Programs, U.S. Environmental Protection Agency.

U.S. EPA (2023d) SF_6 Consumption by Users. 2023. SF_6 consumption for 3 industries, Electric Transmission and Distribution, Semiconductor Manufacturing, and Magnesium Production. Office of Atmospheric Protection, U.S. Environmental Protection Agency.

U.S. EPA (2015) Greenhouse Gas Reporting Program Report Verification. Available online at https://www.epa.gov/sites/production/files/2015-07/documents/ghgrp_verification_factsheet.pdf.

U.S. EPA (1995) *Protocol for Equipment Leak Emission Estimates*. Office of Air and Radiation, Office of Air Quality Planning and Standards, U.S. Environmental Protection Agency. Publication No. EPA-453/R-95-017. November 1995.

Vollmer et al. (2019) Vollmer, M. K., Bernard, F., Mitrevski, B., Steele, L. P., Trudinger, C. M., Reimann, S., Langenfelds, R. L., Krummel, P. B., Fraser, P. J., Etheridge, D. M., Curran, M. A. J., and Burkholder, J. B.: Abundances, emissions, and loss processes of the long-lived and potent greenhouse gas octafluorooxolane

(octafluorotetrahydrofuran, c-C4F8O) in the atmosphere, Atmos. Chem. Phys., 19, 3481–3492, https://doi.org/10.5194/acp-19-3481-2019 , 2019..

Carbon Dioxide Consumption

ARI (1990 through 2010) *CO_2 Use in Enhanced Oil Recovery.* Deliverable to ICF International under Task Order 102, July 15, 2011.

ARI (2007) *CO_2-EOR: An Enabling Bridge for the Oil Transition*. Presented at "Modeling the Oil Transition—a DOE/EPA Workshop on the Economic and Environmental Implications of Global Energy Transitions." Washington, D.C. April 20-21, 2007.

ARI (2006) *CO_2-EOR: An Enabling Bridge for the Oil Transition*. Presented at "Modeling the Oil Transition—a DOE/EPA Workshop on the Economic and Environmental Implications of Global Energy Transitions." Washington, D.C. April 20-21, 2006.

Broadhead (2003) Personal communication. Ron Broadhead, Principal Senior Petroleum Geologist and Adjunct faculty, Earth and Environmental Sciences Department, New Mexico Bureau of Geology and Mineral Resources, and Robin Petrusak, ICF International. September 5, 2003.

COGCC (2014) Monthly CO_2 Produced by County (1999-2009). Available online at: http://cogcc.state.co.us/COGCCReports/production.aspx?id=MonthlyCO2ProdByCounty. Accessed October 2014.

Denbury Resources Inc. (2002 through 2010) Annual Report: 2001 through 2009, Form 10-K. Available online at: http://www.denbury.com/investor-relations/SEC-Filings/SEC-Filings-Details/default.aspx?FilingId=9823015. Accessed September 2014.

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change. [H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (eds.)]. Hayama, Kanagawa, Japan.

New Mexico Bureau of Geology and Mineral Resources (2006) Natural Accumulations of Carbon Dioxide in New Mexico and Adjacent Parts of Colorado and Arizona: Commercial Accumulation of CO_2. Available online at: http://geoinfo.nmt.edu/staff/broadhead/CO2.html#commercial.

RTI (2023) Expert judgment, RTI International. March 30, 2023.

U.S. Environmental Protection Agency (EPA) (2023) Greenhouse Gas Reporting Program (GHGRP). Aggregation of Reported Facility Level Data under Subpart PP -National Level CO_2 Transferred for Food & Beverage Applications for Calendar Years 2010 through 2022. Office of Air and Radiation, Office of Atmospheric Programs, U.S. Environmental Protection Agency, Washington, D.C.

U.S. EPA (2015) *Greenhouse Gas Reporting Program Report Verification*. Available online at https://www.epa.gov/sites/production/files/2015-07/documents/ghgrp_verification_factsheet.pdf.

Phosphoric Acid Production

EFMA (2000) "Production of Phosphoric Acid." *Best Available Techniques for Pollution Prevention and Control in the European Fertilizer Industry.* Booklet 4 of 8. European Fertilizer Manufacturers Association. Available online at: http://www.efma.org/Publications/BAT%202000/Bat04/section04.asp.

Florida Institute of Phosphate Research (FIPR) (2003a) "Analyses of Some Phosphate Rocks." Facsimile Gary Albarelli, Florida Institute of Phosphate Research, Bartow, Florida, to Robert Lanza, ICF International. July 29, 2003.

FIPR (2003b) Florida Institute of Phosphate Research. Personal communication between Michael Lloyd (Laboratory Manager, FIPR, Bartow, Florida) aand Robert Lanza (ICF International) on August 2003.

Golder Associates and M3 Engineering, *Bayovar 12 Phosphate Project: NI 43-101 Updated Pre-Feasibility Study*, Issued June 28, 2016. Available at: https://www.sec.gov/Archives/edgar/data/1471603/000121716016000634/focusjune2016bayovar_techrep.htm. Accessed on October 7, 2020.

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change. [H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (eds.)]. Hayama, Kanagawa, Japan.

NCDENR (2013) North Carolina Department of Environment and Natural Resources, Title V Air Permit Review for PCS Phosphate Company, Inc. – Aurora. Available online at: http://www.ncair.org/permits/permit_reviews/PCS_rev_08282012.pdf. Accessed on January 25, 2013.

United States Environmental Protection Agency (EPA) (2023) Greenhouse Gas Reporting Program. Review of Reported Facility Level Data under Subpart Z -Annual Phosphoric Acid Production from Phosphate Rock for Calendar Year 2022. Office of Air and Radiation, Office of Atmospheric Programs, U.S. Environmental Protection Agency, Washington, D.C.

United States Geological Survey (USGS) (2023) *Mineral Commodity Summaries: Phosphate Rock 2023*. January 2023. U.S. Geological Survey, Reston, VA. Available online at: https://www.usgs.gov/centers/nmic/phosphate-rock-statistics-and-information

USGS (2022) *Mineral Commodity Summaries: Phosphate Rock 2022*. January 2022. U.S. Geological Survey, Reston, VA. Available online at: https://www.usgs.gov/centers/nmic/phosphate-rock-statistics-and-information

USGS (2021a) *Mineral Commodity Summaries: Phosphate Rock 2021*. January 2021. U.S. Geological Survey, Reston, VA. Available online at: https://www.usgs.gov/centers/nmic/phosphate-rock-statistics-and-information.

USGS (2021b) Personal communication between Stephen Jasinski (USGS) and Amanda Chiu (EPA) on August 25, 2021.

USGS (2020) *Mineral Commodity Summaries: Phosphate Rock 2020*. January 2020. U.S. Geological Survey, Reston, VA. Available online at: https://www.usgs.gov/centers/nmic/phosphate-rock-statistics-and-information.

USGS (2019a) *Mineral Commodity Summaries: Phosphate Rock 2019*. February 2019. U.S. Geological Survey, Reston, VA. Available online at: https://www.usgs.gov/centers/nmic/phosphate-rock-statistics-and-information.

USGS (2019b) Communication between Stephen Jasinski (USGS) and John Steller (EPA) on November 15, 2019.

USGS (2018) *Mineral Commodity Summaries: Phosphate Rock 2018*. January 2018. U.S. Geological Survey, Reston, VA. Available online at: https://www.usgs.gov/centers/nmic/phosphate-rock-statistics-and-information.

USGS (2017) *Mineral Commodity Summaries: Phosphate Rock 2017*. January 2017. U.S. Geological Survey, Reston, VA. Available online at: https://www.usgs.gov/centers/nmic/phosphate-rock-statistics-and-information.

USGS (2016) *Mineral Commodity Summaries: Phosphate Rock 2016*. January 2016. U.S. Geological Survey, Reston, VA. Available online at: https://www.usgs.gov/centers/nmic/phosphate-rock-statistics-and-information.

USGS (1994 through 2015b) *Minerals Yearbook*. *Phosphate Rock Annual Report*. U.S. Geological Survey, Reston, VA.

USGS (2012) Personal communication between Stephen Jasinski (USGS) and Mausami Desai (EPA) on October 12, 2012.

Iron and Steel Production and Metallurgical Coke Production

American Coke and Coal Chemicals Institute (ACCCI) (2021) *U.S. Coke Plants as of November 2021,* ACCCI, Washington, D.C. November 2021.

American Iron and Steel Institute (AISI) (2004 through 2023) *Annual Statistical Report*, American Iron and Steel Institute, Washington, D.C.

Carroll (2017) Personal communication, Colin P. Carroll, Director of Environment, Health and Safety, American Iron and Steel Institute and John Steller, U.S. Environmental Protection Agency, November 2017.

Carroll (2016) Personal communication, Colin P. Carroll, Director of Environment, Health and Safety, American Iron and Steel Institute and Mausami Desai, U.S. Environmental Protection Agency, December 2016.

IPCC (2013) *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change.* [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1535 pp.

IPCC (2007) *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change.* [S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds.)]. Cambridge University Press. Cambridge, United Kingdom996 pp.IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change. [H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (eds.)]. Hayama, Kanagawa, Japan.

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change. [H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (eds.)]. Hayama, Kanagawa, Japan.

IPCC/UNEP/OECD/IEA (1995) "Volume 3: Greenhouse Gas Inventory Reference Manual. Table 2-2." *IPCC Guidelines for National Greenhouse Gas Inventories.* Intergovernmental Panel on Climate Change, United Nations Environment Programme, Organization for Economic Co-Operation and Development, International Energy Agency. IPCC WG1 Technical Support Unit, United Kingdom.

RTI (2024) Expert judgment, RTI International. April 2024.

RTI (2023) Expert judgment, RTI International. March 30, 2023.

Steiner (2008) Personal communication, Bruce Steiner, Technical Consultant with the American Iron and Steel Institute and Mausami Desai, U.S. Environmental Protection Agency, November 2008.

Tuck (2023a) Personal communication, Cris Tuck, Commodity Specialist, U.S. Geological Survey and Amanda Chiu, U.S. Environmental Protection Agency, January 24, 2023.

Tuck (2023b) Personal communication, Candice Tuck, Commodity Specialist, U.S. Geological Survey and Amanda Chiu, U.S. Environmental Protection Agency, November 30, 2023.

United States Department of Energy (DOE) (2000) *Energy and Environmental Profile of the U.S. Iron and Steel Industry*. Office of Industrial Technologies, U.S. Department of Energy. August 2000. DOE/EE-0229.EIA.

United States Energy Information Administration (EIA) (1998 through 2019) *Quarterly Coal Report: October-December*, Energy Information Administration, U.S. Department of Energy, Washington, D.C.

U.S. EIA (2021 through 2023) *Quarterly Coal Report: January – March,* Energy Information Administration, U.S. Department of Energy. Washington, D.C.

U.S. EIA (2020) *Natural Gas Annual 2019.* Energy Information Administration, U.S. Department of Energy. Washington, D.C. September 2020.

U.S. EIA (2017b) *Monthly Energy Review*, *December 2017*, Energy Information Administration, U.S. Department of Energy, Washington, D.C. DOE/EIA-0035(2015/12).

U.S. EIA (1992) Coal and lignite production. *EIA State Energy Data Report 1992*, Energy Information Administration, U.S. Department of Energy, Washington, D.C.

United States Environmental Protection Agency (EPA) (2023). Greenhouse Gas Reporting Program. Dataset as of August 18, 2023. Available online at: https://ghgdata.epa.gov/ghgp/.

EPA (2010) Carbon Content Coefficients Developed for EPA's Mandatory Reporting Rule. Office of Air and Radiation, Office of Atmospheric Programs, U.S. Environmental Protection Agency, Washington, D.C.

United States Geological Survey (USGS) (2023a) *2022 Mineral Commodities Summaries: Iron and Steel.* U.S. Geological Survey, Reston, VA. January 2023.

USGS (2023b) *2021 USGS Minerals Yearbook – Iron and Steel Scrap (tables-only release)*. U.S. Geological Survey, Reston, VA.

USGS (2022) *2020 USGS Minerals Yearbook – Iron and Steel Scrap (tables-only release)*. U.S. Geological Survey, Reston, VA.

USGS (2021a) *2021 Mineral Commodities Summaries: Iron and Steel.* U.S. Geological Survey, Reston, VA. January 2021.

USGS (2021b) *2019 USGS Minerals Yearbook – Iron and Steel Scrap (tables-only release)*. U.S. Geological Survey, Reston, VA.

USGS (2020a) *2018 USGS Minerals Yearbook – Iron and Steel Scrap (tables-only release)*. U.S. Geological Survey, Reston, VA.

USGS (2020b) *2017 USGS Minerals Yearbook – Iron and Steel*. U.S. Geological Survey, Reston, VA.

USGS (1991 through 2020) *USGS Minerals Yearbook – Iron and Steel Scrap.* U.S. Geological Survey, Reston, VA.

Ferroalloy Production

IPCC (2013) *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change.* [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1535 pp.

IPCC (2007) *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change.* [S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds.)]. Cambridge University Press. Cambridge, United Kingdom 996 pp.

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change. [H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (eds.)]. Hayama, Kanagawa, Japan.

Onder, H., and E.A. Bagdoyan (1993) Everything You've Always Wanted to Know about Petroleum Coke. Allis Mineral Systems.

RTI (2023) Expert judgment, RTI International. March 30, 2023.

United States Geological Survey (USGS) (2023a) *Mineral Industry Survey: Silicon in June 2023*. U.S. Geological Survey, Reston, VA. September 2023.

USGS (2023b) *2022 Mineral Commodity Summaries: Silicon.* U.S. Geological Survey, Reston, VA. January 2023.

USGS (2022a) *2021 Minerals Yearbook: Silicon (*tables-only release). U.S. Geological Survey, Reston, VA. September 2022.

USGS (2022b) *2020 Minerals Yearbook: Ferroalloys (tables-only release)*. U.S. Geological Survey, Reston, VA. May 2023.

USGS (2022c) *2021 Mineral Commodity Summaries*. U.S. Geological Survey, Reston, VA. January 2022.

USGS (2021) *2020 Mineral Commodity Summaries: Silicon*. U.S. Geological Survey, Reston, VA. January 2021.

USGS (2020) *2019 Mineral Commodity Summaries: Silicon*. U.S. Geological Survey, Reston, VA. January 2020.

USGS (2013a) *2013 Minerals Yearbook: Chromium*. U.S. Geological Survey, Reston, VA. March 2016.

USGS (1996 through 2022) *Minerals Yearbook: Silicon*. U.S. Geological Survey, Reston, VA.

Aluminum Production

EPA (2023) Greenhouse Gas Reporting Program (GHGRP). Envirofacts, Subpart: F Aluminum Production. Available online at: https://www.epa.gov/enviro/greenhouse-gas-subpart-f

EPA (2015) *Greenhouse Gas Reporting Program Report Verification*. Available online at https://www.epa.gov/sites/production/files/2015-07/documents/ghgrp_verification_factsheet.pdf.

IPCC (2019) *2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change. [Calvo Buendia, E., Tanabe, K., Kranjc, A., Baasansuren, J., Fukuda, M., Ngarize, S., Osako, A., Pyrozhenko, Y., Shermanau, P. and Federici, S. (eds.)]. Switzerland.

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change. [H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (eds.)]. Hayama, Kanagawa, Japan.

USGS (2023) *Minerals Yearbook: Aluminum Annual Report*. U.S. Geological Survey, Reston, VA.

USGS (2022) Mineral Commodity Summaries 2022. U.S. Geological Survey, Reston VA.

USGS (2021) *2020 Mineral Commodity Summaries: Aluminum.* U.S. Geological Survey, Reston, VA.

USGS (2021) *2019 Mineral Commodity Summaries: Aluminum.* U.S. Geological Survey, Reston, VA.

USGS (2020) *Minerals Yearbook: Aluminum Annual Report*. U.S. Geological Survey, Reston, VA.

USGS (2020) Mineral Industry Surveys: Aluminum in December 2020. U.S. Geological Survey, Reston VA. December 2020

USGS (2020) *2019 Mineral Commodity Summaries: Aluminum.* U.S. Geological Survey, Reston, VA.

USGS (2019) *Minerals Yearbook: Aluminum Annual Report*. U.S. Geological Survey, Reston, VA.

USGS (2018) *Minerals Yearbook: Aluminum Annual Report*. U.S. Geological Survey, Reston, VA.

USGS (2017) *Minerals Yearbook: Aluminum Annual Report*. U.S. Geological Survey, Reston, VA.

USGS (2016) *Minerals Yearbook: Aluminum Annual Report*. U.S. Geological Survey, Reston, VA.

USGS (2015) *Minerals Yearbook: Aluminum Annual Report*. U.S. Geological Survey, Reston, VA.

USGS (2014) *Minerals Yearbook: Aluminum Annual Report*. U.S. Geological Survey, Reston, VA.

USGS (2013) *Minerals Yearbook: Aluminum Annual Report*. U.S. Geological Survey, Reston, VA.

USGS (2012) *Minerals Yearbook: Aluminum Annual Report*. U.S. Geological Survey, Reston, VA.

USGS (2011) *Minerals Yearbook: Aluminum Annual Report*. U.S. Geological Survey, Reston, VA.

USGS (2010) *Minerals Yearbook: Aluminum Annual Report*. U.S. Geological Survey, Reston, VA.

USGS (2009) *Minerals Yearbook: Aluminum Annual Report*. U.S. Geological Survey, Reston, VA.

USGS (2008) *Minerals Yearbook: Aluminum Annual Report*. U.S. Geological Survey, Reston, VA.

USGS (2007) *Minerals Yearbook: Aluminum Annual Report*. U.S. Geological Survey, Reston, VA.

USGS (2006) *Minerals Yearbook: Aluminum Annual Report*. U.S. Geological Survey, Reston, VA.

USGS (2005) *Minerals Yearbook: Aluminum Annual Report*. U.S. Geological Survey, Reston, VA.

USGS (2004) *Minerals Yearbook: Aluminum Annual Report*. U.S. Geological Survey, Reston, VA.

USGS (2003) *Minerals Yearbook: Aluminum Annual Report*. U.S. Geological Survey, Reston, VA.

USGS (2002) *Minerals Yearbook: Aluminum Annual Report*. U.S. Geological Survey, Reston, VA.

USGS (2001) *Minerals Yearbook: Aluminum Annual Report*. U.S. Geological Survey, Reston, VA.

USGS (2000) *Minerals Yearbook: Aluminum Annual Report*. U.S. Geological Survey, Reston, VA.

USGS (1999) *Minerals Yearbook: Aluminum Annual Report*. U.S. Geological Survey, Reston, VA.

USGS (1998) *Minerals Yearbook: Aluminum Annual Report*. U.S. Geological Survey, Reston, VA.

USGS (1997) *Minerals Yearbook: Aluminum Annual Report*. U.S. Geological Survey, Reston, VA.

USGS (1996) *Minerals Yearbook: Aluminum Annual Report*. U.S. Geological Survey, Reston, VA.

USGS (1995) *Minerals Yearbook: Aluminum Annual Report*. U.S. Geological Survey, Reston, VA.

USGS (1994) *Minerals Yearbook: Aluminum Annual Report*. U.S. Geological Survey, Reston, VA.

USGS (1993) *Minerals Yearbook: Aluminum Annual Report*. U.S. Geological Survey, Reston, VA.

USGS (1992) *Minerals Yearbook: Aluminum Annual Report*. U.S. Geological Survey, Reston, VA.

USGS (1991) *Minerals Yearbook: Aluminum Annual Report*. U.S. Geological Survey, Reston, VA.

USGS (1990) *Minerals Yearbook: Aluminum Annual Report*. U.S. Geological Survey, Reston, VA.

Magnesium Production and Processing

ARB (2015) "Magnesium casters successfully retool for a cleaner future." California Air Resources Board News Release. Release # 15-07. February 5, 2015. Accessed October 2017. Available online at: https://www.arb.ca.gov/newsrel/newsrelease.php?id=704.

Bartos S., C. Laush, J. Scharfenberg, and R. Kantamaneni (2007) "Reducing greenhouse gas emissions from magnesium die casting." *Journal of Cleaner Production*, 15: 979-987, March.

EPA (2020) Envirofacts. Greenhouse Gas Reporting Program (GHGRP), Subpart T: Magnesium Production and Processing. Available online at: https://www.epa.gov/enviro/greenhouse-gas-customized-search. Accessed on October 2020.

EPA (2015) *Greenhouse Gas Reporting Program Report Verification*. Available online at https://www.epa.gov/sites/production/files/2015-07/documents/ghgrp_verification_factsheet.pdf.

Gjestland, H. and D. Magers (1996) "Practical Usage of Sulphur [Sulfur] Hexafluoride for Melt Protection in the Magnesium Die Casting Industry." #13, *1996 Annual Conference Proceedings*, International Magnesium Association. Ube City, Japan.

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change. [H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (eds.)]. Hayama, Kanagawa, Japan.

Kramer Deborah A. (2000) "Magnesium" U.S. Geological Survey *Minerals Yearbook* – 2000.

RAND (2002) RAND Environmental Science and Policy Center, "Production and Distribution of SF_6 by End-Use Applications" Katie D. Smythe. *International Conference on SF_6 and the Environment: Emission Reduction Strategies*. San Diego, CA. November 21-22, 2002.

USGS (1995 through 2023) *Minerals Yearbook: Magnesium Annual Report*. U.S. Geological Survey, Reston, VA. Available online at: http://minerals.usgs.gov/minerals/pubs/commodity/magnesium/index.html#mis.

USGS (2010b) *Mineral Commodity Summaries: Magnesium Metal*. U.S. Geological Survey, Reston, VA. Available online at: http://minerals.usgs.gov/minerals/pubs/commodity/magnesium/mcs-2010-mgmet.pdf.

USGS (2005b) Personal Communication between Deborah Kramer of the USGS and Jeremy Scharfenberg of ICF Consulting.

Lead Production

Dutrizac, J.E., V. Ramachandran, and J.A. Gonzalez (2000) *Lead-Zinc 2000*. The Minerals, Metals, and Materials Society.

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change. [H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (eds.)]. Hayama, Kanagawa, Japan.

Morris, D., F.R. Steward, and P. Evans (1983) *Energy Efficiency of a Lead Smelter.* Energy 8(5):337-349.

RTI (2023) Expert judgment, RTI International. March 30, 2023.

Sjardin, M. (2003) *CO_2 Emission Factors for Non-Energy Use in the Non-Ferrous Metal, Ferroalloys and Inorganics Industry*. Copernicus Institute. Utrecht, the Netherlands.

Ullman (1997) *Ullman's Encyclopedia of Industrial Chemistry: Fifth Edition.* Volume A5. John Wiley and Sons.

United States Geological Survey (USGS) (2023a) *2022 Mineral Commodity Summary, Lead*. U.S. Geological Survey, Reston, VA. January 2023.

USGS (2023b) *2020 Minerals Yearbook, Lead – Advance Data Release*. U.S. Geological Survey, Reston, VA. July 2023.

USGS (2023c) *2022 Mineral Industries Surveys: Lead in September 2022.* U.S. Geological Survey, Reston, VA. December 2022.

USGS (2022a) *2019 Minerals Yearbook, Lead – Advance Data Release*. U.S. Geological Survey, Reston, VA. October 2022.

USGS (2022b) *2021 Mineral Commodity Summary, Lead.* U.S. Geological Survey, Reston, VA. January 2022.

USGS (2021a) *2017 Minerals Yearbook, Lead – Advance Release*. U.S. Geological Survey, Reston, VA. July 2021.

USGS (2021b) *2020 Mineral Commodity Summary, Lead.* U.S. Geological Survey, Reston, VA. February 2021.

USGS (2020) *2019 Mineral Commodity Summary, Lead*. U.S. Geological Survey, Reston, VA. February 2020.

USGS (2019) *2018 Mineral Commodity Summary, Lead*. U.S. Geological Survey, Reston, VA. February 2019.

USGS (2018) *2017 Mineral Commodity Summary, Lead*. U.S. Geological Survey, Reston, VA. January 2018.

USGS (2017) *2016 Mineral Commodity Summary, Lead*. U.S. Geological Survey, Reston, VA. January 2017.

USGS (2016) *2015 Mineral Commodity Summary, Lead*. U.S. Geological Survey, Reston, VA. January 2016.

USGS (2015) *2014 Mineral Commodity Summary, Lead.* U.S. Geological Survey, Reston, VA. January 2015.

USGS (2014) *2013 Mineral Commodity Summary, Lead*. U.S. Geological Survey, Reston, VA. February 2014.

USGS (1994 through 2013) *Minerals Yearbook: Lead Annual Report.* U.S. Geological Survey, Reston, VA..

Zinc Production

American Zinc Recycling (AZR) (2021) Summary of Company History. Available online at https://azr.com/our-history/. Accessed on March 16, 2021.

AZR (2020) Personal communication. Erica Livingston, American Zinc Recycling and Amanda Chiu, U.S. Environmental Protection Agency. October 29, 2020.

American Zinc Products (AZP) (2021) American Zinc Products Marks First Anniversary of Zinc Production. Available online at https://americanzincproducts.com/american-zinc-products-marks-first-anniversary-of-zinc-production/. Accessed on March 1, 2022.

Befesa (2023) Personal communication. Eric Hunsberger, Befesa Zinc US Inc. and Amanda Chiu, U.S. Environmental Protection Agency. September 19, 2023.

Befesa (2022) Personal communication. Eric Hunsberger, Befesa Zinc US Inc. and Amanda Chiu, U.S. Environmental Protection Agency. November 8, 2022.

Horsehead Corp. (2016) Form 10-K, Annual Report for the Fiscal Year Ended December 31, 2015. Available online at: https://www.sec.gov/Archives/edgar/data/1385544/000119312516725704/d236839d10k.htm. Submitted on January 25, 2017.

Horsehead Corp. (2015) Form 10-K, Annual Report for the Fiscal Year Ended December 31, 2014. Available online at: http://www.sec.gov/Archives/edgar/data/1385544/000138554415000005/zinc-2014123110k.htm. Submitted on March 2, 2015.

Horsehead Corp. (2014) Form 10-K, Annual Report for the Fiscal Year Ended December 31, 2013. Available online at: http://www.sec.gov/Archives/edgar/data/1385544/000138554414000003/zinc-2013123110k.htm. Submitted on March 13, 2014.

Horsehead Corp. (2013) Form 10-K, Annual Report for the Fiscal Year Ended December 31, 2012. Available online at: http://www.sec.gov/Archives/edgar/data/1385544/000119312513110431/0001193125-13-110431-index.htm. Submitted March 18, 2013.

Horsehead Corp. (2012a) Form 10-K, Annual Report for the Fiscal Year Ended December 31, 2011. Available online at: http://www.sec.gov/Archives/edgar/data/1385544/000119312512107345/d293011d10k.htm. Submitted on March 9, 2012.

Horsehead Corp. (2012b) *Horsehead's New Zinc Plant and its Impact on the Zinc Oxide Business.* February 22, 2012. Available online at: http://www.horsehead.net/downloadAttachmentNDO.php?ID=118. Accessed on September 10, 2015.

Horsehead Corp. (2011) 10-K Annual Report for the Fiscal Year Ended December 31, 2010. Available online at: http://google.brand.edgar-online.com/default.aspx?sym=zinc. Submitted on March 16, 2011.

Horsehead Corp. (2010a) 10-K Annual Report for the Fiscal Year Ended December 31, 2009. Available online at: http://google.brand.edgar-online.com/default.aspx?sym=zinc. Submitted on March 16, 2010.

Horsehead Corp. (2010b) *Horsehead Holding Corp. Provides Update on Operations at its Monaca, PA Plant.* July 28, 2010. Available online at: http://www.horsehead.net/pressreleases.php?showall=no&news=&ID=65.

Horsehead Corp (2009) 10-K Annual Report for the Fiscal Year Ended December 31, 2008. Available online at: https://www.sec.gov/Archives/edgar/data/1385544/000095015209002674/l35087ae10vk.htm. Submitted on March 16, 2009.

Horsehead Corp (2008) 10-K Annual Report for the Fiscal Year Ended December 31, 2007. Available online at: http://google.brand.edgar-online.com/default.aspx?sym=zinc. Submitted on March 31, 2008.

Horsehead Corp (2007) Registration Statement (General Form) S-1. Available online at http://google.brand.edgar-online.com/default.aspx?sym=zinc. Submitted on April 13, 2007.

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change. [H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (eds.)]. Hayama, Kanagawa, Japan.

Nyrstar (2017) 2016 Clarksville Fact Sheet. Available online at: http://www.nyrstar.com/~/media/Files/N/Nyrstar/operations/melting/fact-sheet-clarksville-en.pdf. Accessed on September 27, 2017.

PIZO (2021) Personal communication. Thomas Rheaume, Arkansas Department of Energy and Environment and Amanda Chiu, U.S. Environmental Protection Agency. February 16, 2021.

PIZO (2012) Available online at http://pizotech.com/index.html. Accessed on October 10, 2012.

Recycling Today (2020) "AZR to restart for zinc recycling plant in North Carolina." March 6, 2020. https://www.recyclingtoday.com/article/american-zinc-recycling-restarting-north-carolina-plant-2020/. Accessed October 10, 2020.

Recycling Today (2017) "Horsehead announces corporate name change to American Zinc Recycling." May 3, 2017. https://www.recyclingtoday.com/article/horsehead-changes-name-american-zinc-recycling/. Accessed September 19, 2022.

Steel Dust Recycling (SDR) (2023) Personal communication. Jeremy Whitten, Steel Dust Recycling LLC and Amanda Chiu, U.S. Environmental Protection Agency. September 20 and 25, 2023.

SDR (2022) Personal communication. Jeremy Whitten, Steel Dust Recycling LLC and Amanda Chiu, U.S. Environmental Protection Agency. October 10, 2022.

SDR (2021) Personal communication. Jeremy Whitten, Steel Dust Recycling LLC and Amanda Chiu, U.S. Environmental Protection Agency. January 8, 2021.

SDR (2018) Personal communication. Jeremy Whitten, Steel Dust Recycling LLC and John Steller, U.S. Environmental Protection Agency. October 25, 2018.

SDR (2017) Personal communication. Jeremy Whitten, Steel Dust Recycling LLC and John Steller, U.S. Environmental Protection Agency. January 26, 2017.

SDR (2015) Personal communication. Jeremy Whitten, Steel Dust Recycling LLC and Gopi Manne, Eastern Research Group, Inc. September 22, 2015.

SDR (2014) Personal communication. Art Rowland, Steel Dust Recycling LLC and Gopi Manne, Eastern Research Group, Inc. December 9, 2014.

SDR (2013) Available online at http://steeldust.com/home.htm. Accessed on October 29, 2013.

SDR (2012) Personal communication. Art Rowland, Steel Dust Recycling LLC and Gopi Manne, Eastern Research Group, Inc. October 5, 2012.

Sjardin (2003) CO_2 *Emission Factors for Non-Energy Use in the Non-Ferrous Metal, Ferroalloys and Inorganics Industry*. Copernicus Institute. Utrecht, the Netherlands.

United States Environmental Protection Agency (EPA) (1992) "Applications Analysis Report: Horsehead Resource Development Company Inc., Flame Reactor Technology" EPA/540/A5-91/005. May 1992.

United States Geological Survey (USGS) (2023) *2023 Mineral Commodity Summary: Zinc*. U.S. Geological Survey, Reston, VA. January 2023. Available online at: https://pubs.usgs.gov/periodicals/mcs2023/mcs2023-zinc.pdf

USGS (2022) *2022 Mineral Commodity Summary: Zinc*. U.S. Geological Survey, Reston, VA. January 2022.

USGS (2021) *2021 Mineral Commodity Summary: Zinc*. U.S. Geological Survey, Reston, VA. January 2021.

USGS (2020) *2020 Mineral Commodity Summary: Zinc*. U.S. Geological Survey, Reston, VA. January 2020.

USGS (2019) *2019 Mineral Commodity Summary: Zinc*. U.S. Geological Survey, Reston, VA. January 2019.

USGS (2018) *2018 Mineral Commodity Summary: Zinc*. U.S. Geological Survey, Reston, VA. January 2018.

USGS (2017) *2017 Mineral Commodity Summary: Zinc*. U.S. Geological Survey, Reston, VA. January 2017.

USGS (2016) *2016 Mineral Commodity Summary: Zinc*. U.S. Geological Survey, Reston, VA. January 2016.

USGS (2015) *2015 Mineral Commodity Summary: Zinc*. U.S. Geological Survey, Reston, VA. January 2015.

USGS (1994 through 2014) *Minerals Yearbook: Zinc Annual Report.* U.S. Geological Survey, Reston, VA.

Viklund-White (2000) *The use of LCA for the environmental evaluation of the recycling of galvanized steel*. ISIJ International, Vol. 40. No. 3, pp 292-299.

Electronics Industry

Burton, C.S., and R. Beizaie (2001) "EPA's PFC Emissions Model (PEVM) v. 2.14: Description and Documentation" prepared for Office of Global Programs, U. S. Environmental Protection Agency, Washington, DC. November 2001.

Citigroup Smith Barney (2005) *Global Supply/Demand Model for Semiconductor*s. March 2005.

DisplaySearch (2010) DisplaySearch Q4'09 Quarterly FPD Supply/Demand and Capital Spending Report. DisplaySearch, LLC.

Doering, R. and Nishi, Y (2000) "Handbook of Semiconductor Manufacturing Technology", Marcel Dekker, New York, USA, 2000.

EPA (2023) *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2021*. U.S. Environmental Protection Agency, Washington, DC. EPA-430-R-23-002.

EPA (2010) *Technical Support Document for Process Emissions from Electronics Manufacture (e.g., Micro-Electro-Mechanical Systems, Liquid Crystal Displays, Photovoltaics, and Semiconductors)*. U.S. Environmental Protection Agency, Washington, DC.

EPA (2006) *Uses and Emissions of Liquid PFC Heat Transfer Fluids from the Electronics Sector.* U.S. Environmental Protection Agency, Washington, DC. EPA-430-R-06-901.

EPA Greenhouse Gas Reporting Program (GHGRP) Envirofacts. Subpart I: Electronics Manufacture. Available online at: https://enviro.epa.gov/facts/ghg/search.html.

IPCC (2019) *2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change. Calvo Buendia, E., Tanabe, K., Kranjc, A., Baasansuren, J., Fukuda, M., Ngarize, S., Osako, A., Pyrozhenko, Y., Shermanau, P. and Federici, S. (eds). Published: IPCC, Switzerland.

IPCC (2013) *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1535 pp.

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change. [H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (eds.)]. Hayama, Kanagawa, Japan.

ITRS (2007, 2008, 2011, 2013) *International Technology Roadmap for Semiconductors: 2006 Update*, January 2007; *International Technology Roadmap for Semiconductors: 2007 Edition,* January 2008*; International Technology Roadmap for Semiconductors: 2011, January 2012; Update, International Technology Roadmap for*

Semiconductors: 2013 Edition, Available online at: https://www.semiconductors.org/resources/2007-international-technology-roadmap-for-semiconductors-itrs/. These and earlier editions and updates are available online at: https://www.semiconductors.org/resources/?fwp_resource_types=utilization-reports&fwp_paged=2. Information about the number of interconnect layers for years 1990–2010 is contained in Burton and Beizaie, 2001. PEVM is updated using new editions and updates of the ITRS, which are published annually.

Platzer, Michaela D. (2015) *U.S. Solar Photovoltaic Manufacturing: Industry Trends, Global Competition, Federal Support*. Congressional Research Service. January 27, 2015. https://fas.org/sgp/crs/misc/R42509.pdf.

SEMI – Semiconductor Equipment and Materials Industry (2021) *World Fab Forecast, June 2021 Edition.*

SEMI - Semiconductor Equipment and Materials Industry (2018) *World Fab Forecast*, *June 2018 Edition*.

SEMI - Semiconductor Equipment and Materials Industry (2017) *World Fab Forecast*, *August 2018 Edition*.

SEMI - Semiconductor Equipment and Materials Industry (2016) *World Fab Forecast*, *May 2017 Edition*.

SEMI - Semiconductor Equipment and Materials Industry (2013) *World Fab Forecast*, *May 2013 Edition*.

SEMI - Semiconductor Equipment and Materials Industry (2012) *World Fab Forecast*, *August 2012 Edition*.

Semiconductor Industry Association (SIA) (2009-2011) STATS: SICAS Capacity and Utilization Rates Q1-Q4 2008, Q1-Q4 2009, Q1-Q4 2010. Available online at: http://www.semiconductors.org/industry_statistics/semiconductor_capacity_utilization_sicas_reports/.

United States Census Bureau (USCB) (2011, 2012, 2014, 2015, 2016, 2017, 2018, 2019, 2020, 2021, 2022) *Historical Data: Quarterly Survey of Plant Capacity Utilization*. Available online at: https://www.census.gov/programs-surveys/qpc.html.

VLSI Research, Inc. (2012) Worldwide Silicon Demand. August 2012.

Substitution of Ozone Depleting Substances

EPA (2023a) Summary of Updates to the Unitary Air-conditioning End-uses in the Vintaging Model. Prepared for U.S. EPA's Stratospheric Protection Division by ICF under EPA Contract Number 68HERH19D0029.

EPA (2023b) Summary of Updates to the Window Units End-use in the Vintaging Model. Prepared for U.S. EPA's Stratospheric Protection Division by ICF under EPA Contract Number 68HERH19D0029.

EPA (2023c) Proposed Addition of Small and Large Ductless Mini-Split and Multi-Split Air Conditioning End-uses to U.S. EPA's Vintaging Model. Prepared for U.S. EPA's Stratospheric Protection Division by ICF under EPA Contract Number 68HERH19D0029.

EPA (2023d) Proposed Updates to the Streaming Agent End-uses in U.S. EPA's Vintaging Model. Prepared for U.S. EPA's Stratospheric Protection Division by ICF under EPA Contract Number 68HERH19D0029.

EPA (2018) EPA's Vintaging Model of ODS Substitutes: A Summary of the 2017 Peer Review. Office of Air and Radiation. Document Number EPA-400-F-18-001. Available online at: https://www.epa.gov/sites/production/files/2018-09/documents/epas-vintaging-model-of-ods-substitutes-peer-review-factsheet.pdf.

IPCC (2013) *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1535 pp.

IPCC (2007) *Climate Change 2007: The Physical Science Basis*. Contribution of Working Group I to the *Fourth Assessment Report* of the Intergovernmental Panel on Climate Change. [S. Solomon, D. Qin, M. Manning, Z. Chen,

M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds.)]. Cambridge University Press. Cambridge, United Kingdom 996 pp.

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change. [H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (eds.)]. Hayama, Kanagawa, Japan.

Electrical Equipment

CARB (2023). *California Greenhouse Gas Emission Inventory – 2023 Edition.* Accessed March 2024. Available online at: https://ww2.arb.ca.gov/ghg-inventory-data.

EPA (2022) *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2020*. EPA 430-R-22-003. Available online at: https://www.epa.gov/ghgemissions/inventory-us-greenhouse-gas-emissions-and-sinks-1990-2020.

Harnisch and Eisenhauer, "Natural CF_4 and SF_6 on Earth," GEOPHYSICAL RESEARCH LETTERS, VOL. 25, NO.13, PAGES 2401-2404, JULY 1, 1998. https://agupubs.onlinelibrary.wiley.com/doi/pdf/10.1029/98GL01779.

HIFLD (2022) Federal Energy Regulatory Commission. Homeland Infrastructure Foundation-Level Data (HIFLD). 2021. Accessed September 2023. Available online at: https://hifld-geoplatform.opendata.arcgis.com/datasets/geoplatform::transmission-lines/explore?location=38.924381%2C-122.290494%2C4.78 .

HIFLD (2021) Federal Energy Regulatory Commission. Homeland Infrastructure Foundation-Level Data (HIFLD). 2021. Accessed September 2022. Available online at: https://hifld-geoplatform.opendata.arcgis.com/datasets/electric-power-transmission-lines.

HIFLD (2020) Federal Energy Regulatory Commission. Homeland Infrastructure Foundation-Level Data (HIFLD). 2020. Accessed October 2021. Available online at: https://hifld-geoplatform.opendata.arcgis.com/datasets/electric-power-transmission-lines/explore?showTable=true.

HIFLD (2019) Federal Energy Regulatory Commission. Homeland Infrastructure Foundation-Level Data (HIFLD). 2019. Accessed March 2021. Available online at: https://hifld-geoplatform.opendata.arcgis.com/datasets/electric-power-transmission-lines.

Hu, L., Ottinger, D., Bogle, S., Montzka, S., DeCola, P., Dlugokencky, E., Andrews, A., Thoning, K., Sweeney, C., Dutton, G., Aepli, L., and Crotwell, A. (2022) "Declining, seasonal-varying emissions of sulfur hexafluoride from the United States point to a new mitigation opportunity." *EGUsphere* [preprint]. Available online at: https://doi.org/10.5194/egusphere-2022-862.

IPCC (2013) *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1535 pp.

IPCC (2007) *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds.). Cambridge University Press. Cambridge, United Kingdom 996 pp.

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change. H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (eds.). Hayama, Kanagawa, Japan.

IPCC (1996) *Climate Change 1995: The Science of Climate Change*. Intergovernmental Panel on Climate Change, J.T. Houghton, L.G. Meira Filho, B.A. Callander, N. Harris, A. Kattenberg, and K. Maskell (eds.). Cambridge University Press. Cambridge, United Kingdom.

Levin et al. (2010) "The Global SF_6 Source Inferred from Long-term High Precision Atmospheric Measurements and its Comparison with Emission Inventories." *Atmospheric Chemistry and Physics*, 10: 2655–2662.

Middleton, B. (2000) *Cold Weather Applications of Gas Mixture (SF_6/N_2, SF_6/CF_4) Circuit Breakers: A User Utility's Perspective* [Conference Presentation]. The U.S. Environmental Protection Agency's Conference on SF_6 and the Environment: Emission Reduction Strategies, San Diego, CA, United States. Available online at: https://www.epa.gov/sites/default/files/2016-02/documents/conf00_middleton.pdf

O'Connell, P., F. Heil, J. Henriot, G. Mauthe, H. Morrison, L. Neimeyer, M. Pittroff, R. Probst, J.P. Tailebois (2002) *SF_6 in the Electric Industry, Status 2000,* CIGRE. February 2002.

Ottinger D, Averyt, M. & Harris, D. (2014). *Trends in emissions of fluorinated GHGs reported under the Greenhouse Gas Reporting Program: Patterns and potential causes*. Submitted to the Seventh International Symposium on Non-CO_2 Greenhouse Gases (NCGG-7), Amsterdam, Netherlands.

RAND (2004) "Trends in SF_6 Sales and End-Use Applications: 1961-2003," Katie D. Smythe. *International Conference on SF_6 and the Environment: Emission Reduction Strategies*. RAND Environmental Science and Policy Center, Scottsdale, AZ. December 1-3, 2004.

UDI (2017) *2017 UDI Directory of Electric Power Producers and Distributors, 125th Edition*, Platts.

UDI (2013) *2013 UDI Directory of Electric Power Producers and Distributors,121st Edition*, Platts.

UDI (2010) *2010 UDI Directory of Electric Power Producers and Distributors, 118th Edition*, Platts.

UDI (2007) *2007 UDI Directory of Electric Power Producers and Distributors, 115th Edition*, Platts.

UDI (2004) *2004 UDI Directory of Electric Power Producers and Distributors, 112th Edition*, Platts.

UDI (2001) *2001 UDI Directory of Electric Power Producers and Distributors, 109th Edition*, Platts.

UNFCCC (2014) Report of the Conference of the Parties on its nineteenth session, held in Warsaw from 11 to 23 November 2013. United Nations Framework Convention on Climate Change, Warsaw. (FCCC/CP/2013/10/Add.3). January 31, 2014. Available online at: http://unfccc.int/resource/docs/2013/cop19/eng/10a03.pdf.

SF_6 and PFCs from Other Product Use

IPCC (2019) *2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change. Calvo Buendia, E., Tanabe, K., Kranjc, A., Baasansuren, J., Fukuda, M., Ngarize, S., Osako, A., Pyrozhenko, Y., Shermanau, P. and Federici, S. (eds). Published: IPCC, Switzerland.

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change. [H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (eds.)]. Hayama, Kanagawa, Japan.

Workman, R.L. et al. Particle Data Group). Prog. Theor. Exp. Phys. 2022, 083C01. Available online at: https://pdg.lbl.gov/2022/reviews/rpp2022-rev-particle-detectors-accel.pdf

U.S. Department of Energy (DOE). 2022. Federal Energy Management Program (FEMP). Available online at: https://www.energy.gov/femp/federal-comprehensive-annual-energy-reporting-requirements.

Nitrous Oxide from Product Use

CGA (2003) "CGA Nitrous Oxide Abuse Hotline: CGA/NWSA Nitrous Oxide Fact Sheet." Compressed Gas Association. November 3, 2003.

CGA (2002) "CGA/NWSA Nitrous Oxide Fact Sheet." Compressed Gas Association. March 25, 2002.

Heydorn, B. (1997) "Nitrous Oxide—North America." *Chemical Economics Handbook*, SRI Consulting. May 1997.

IPCC (2013) *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change.* [Stocker, T.F., D. Qin, G.K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1535 pp.

IPCC (2007) *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. [S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds.)]. Cambridge University Press. Cambridge, United Kingdom 996 pp.

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change. [H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (eds.)]. Hayama, Kanagawa, Japan.

Ottinger (2021) Personal communication. Deborah Ottinger, U.S. Environmental Protection Agency and Amanda Chiu, U.S. Environmental Protection Agency. January 7, 2021.

RTI (2023) Expert judgment, RTI International. March 30, 2023.

Tupman, M. (2002) Personal communication. Martin Tupman, Airgas Nitrous Oxide and Laxmi Palreddy, ICF International. July 3, 2002.

Industrial Processes and Product Use Sources of Precursor Greenhouse Gases

EPA (2023a) "Criteria pollutants National Tier 1 for 1970 - 2023." National Emissions Inventory (NEI) Air Pollutant Emissions Trends Data. Office of Air Quality Planning and Standards, March 2024. Available online at: https://www.epa.gov/air-emissions-inventories/air-pollutant-emissions-trends-data.

EPA (2023b) EPA's Emissions Inventory System (EIS) to National Inventory Report (NIR) Mapping file EIS_NIR_mapping.xlsx. U.S. Environmental Protection Agency. Washington, D.C."

EPA (2023c) "2020 National Emissions Inventory Technical Support Document: Introduction." Office of Air Quality Planning and Standards, March 2023. Available online at: https://www.epa.gov/system/files/documents/2023-01/NEI2020_TSD_Section1_Introduction.pdf.

Agriculture

Enteric Fermentation

Archibeque, S. (2011) Personal Communication. Shawn Archibeque, Colorado State University, Fort Collins, Colorado and staff at ICF International.

Crutzen, P.J., I. Aselmann, and W. Seiler (1986) Methane Production by Domestic Animals, Wild Ruminants, Other Herbivores, Fauna, and Humans. Tellus, 38B:271-284.

Donovan, K. (1999) Personal Communication. Kacey Donovan, University of California at Davis and staff at ICF International.

Donovan, K. and L. Baldwin. (1999) "Results of the AAMOLLY Model Runs for the Enteric Fermentation Model"; University of California, Davis, 1999.

Doren, P.E., J. F. Baker, C. R. Long and T. C. Cartwright (1989) Estimating Parameters of Growth Curves of Bulls, J Animal Science 67:1432-1445.

Enns, M. (2008) Personal Communication. Dr. Mark Enns, Colorado State University and staff at ICF International.

EPA (2002) Quality Assurance/Quality Control and Uncertainty Management Plan for the U.S. Greenhouse Gas Inventory: Procedures Manual for Quality Assurance/Quality Control and Uncertainty Analysis, U.S. Greenhouse Gas Inventory Program, U.S. Environmental Protection Agency, Office of Atmospheric Programs, EPA 430-R-02-007B, June 2002.

ERG (2021) Updated Other Animal Population Distribution Methodology. ERG, Lexington, MA.

ERG (2016) Development of Methane Conversion Rate Scaling Factor and Diet-Related Inputs to the Cattle Enteric Fermentation Model for Dairy Cows, Dairy Heifers, and Feedlot Animals. ERG, Lexington, MA. December 2016.

Galyean and Gleghorn (2001) Summary of the 2000 Texas Tech University Consulting Nutritionist Survey. Texas Tech University. Available online at http://www.depts.ttu.edu/afs/burnett_center/progress_reports/bc12.pdf. June 2009.

Holstein Association (2010) History of the Holstein Breed (website). Available online at: http://www.holsteinusa.com/holstein_breed/breedhistory.html. Accessed September 2010.

ICF (2006) Cattle Enteric Fermentation Model: Model Documentation. Prepared by ICF International for the Environmental Protection Agency. June 2006.

ICF (2003) Uncertainty Analysis of 2001 Inventory Estimates of Methane Emissions from Livestock Enteric Fermentation in the U.S. Memorandum from ICF International to the Environmental Protection Agency. May 2003.

IPCC (2019) *2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change. [CalvoBuendia, E., Tanabe, K., Kranjc, A., Baasansuren, J., Fukuda, M., Ngarize S., Osako, A., Pyrozhenko, Y., Shermanau, P. and Federici, S. (eds)]. Switzerland.

IPCC (2013) *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1535 pp.

IPCC (2007) *Climate Change 2007: The Physical Science Basis*. Contribution of Working Group I to the *Fourth Assessment Report* of the Intergovernmental Panel on Climate Change. S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds.). Cambridge University Press. Cambridge, United Kingdom 996 pp.

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change. H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (eds.). Hayama, Kanagawa, Japan.

Johnson, D. (2002) Personal Communication. Don Johnson, Colorado State University, Fort Collins, and ICF International.

Johnson, D. (1999) Personal Communication. Don Johnson, Colorado State University, Fort Collins, and David Conneely, ICF International.

Kebreab E., K. A. Johnson, S. L. Archibeque, D. Pape, and T. Wirth (2008) Model for estimating enteric methane emissions from United States dairy and feedlot cattle. J. Anim. Sci. 86: 2738-2748.

Lippke, H., T. D. Forbes, and W. C. Ellis. (2000) Effect of supplements on growth and forage intake by stocker steers grazing wheat pasture. J. Anim. Sci. 78:1625-1635.

National Bison Association (1999) Total Bison Population—1999. Report provided during personal email communication with Dave Carter, Executive Director, National Bison Association, July 19, 2011.

Pinchak, W.E., D. R. Tolleson, M. McCloy, L. J. Hunt, R. J. Gill, R. J. Ansley, and S. J. Bevers (2004) Morbidity effects on productivity and profitability of stocker cattle grazing in the southern plains. J. Anim. Sci. 82:2773-2779.

Platter, W. J., J. D. Tatum, K. E. Belk, J. A. Scanga, and G. C. Smith (2003) Effects of repetitive use of hormonal implants on beef carcass quality, tenderness, and consumer ratings of beef palatability. J. Anim. Sci. 81:984-996.

Preston, R.L. (2010) What's The Feed Composition Value of That Cattle Feed? Beef Magazine, March 1, 2010. Available at: http://beefmagazine.com/nutrition/feed-composition-tables/feed-composition-value-cattle--0301.

Skogerboe, T. L., L. Thompson, J. M. Cunningham, A. C. Brake, V. K. Karle (2000) The effectiveness of a single dose of doramectin pour-on in the control of gastrointestinal nematodes in yearling stocker cattle. Vet. Parasitology 87:173-181.

Soliva, C.R. (2006) Report to the attention of IPCC about the data set and calculation method used to estimate methane formation from enteric fermentation of agricultural livestock population and manure management in Swiss agriculture. On behalf of the Federal Office for the Environment (FOEN), Berne, Switzerland.

U.S. Department of Agriculture (USDA) (2023) Quick Stats: Agricultural Statistics Database. National Agriculture Statistics Service, U.S. Department of Agriculture. Washington, D.C. Available online at http://quickstats.nass.usda.gov/. Accessed May-June 2023.

USDA (2022) Economic Research Service "Supply and allocation of milk fat and skim solids by product". Available online at: https://www.ers.usda.gov/data-products/dairy-data/. Accessed May 2023.

USDA (2021) Economic Research Service Dairy Data. Available online at: https://www.ers.usda.gov/data-products/dairy-data/. Accessed May 2021.

USDA (2019) *1987, 1992, 1997, 2002, 2007, 2012, and 2017 Census of Agriculture*. National Agriculture Statistics Service, U.S. Department of Agriculture. Washington, D.C. Available online at: https://www.nass.usda.gov/AgCensus/index.php. May 2019.

USDA (1996) Beef Cow/Calf Health and Productivity Audit (CHAPA): Forage Analyses from Cow/Calf Herds in 18 States. National Agriculture Statistics Service, U.S. Department of Agriculture. Washington, D.C. Available online at http://www.aphis.usda.gov/vs/ceah/cahm. March 1996.

USDA:APHIS:VS (2010) Beef 2007–08, Part V: Reference of Beef Cow-calf Management Practices in the United States, 2007–08. USDA–APHIS–VS, CEAH. Fort Collins, CO.

USDA:APHIS:VS (2002) Reference of 2002 Dairy Management Practices. USDA–APHIS–VS, CEAH. Fort Collins, CO. Available online at http://www.aphis.usda.gov/vs/ceah/cahm.

USDA:APHIS:VS (1998) Beef '97, Parts I-IV. USDA–APHIS–VS, CEAH. Fort Collins, CO. Available online at http://www.aphis.usda.gov/animal_health/nahms/beefcowcalf/index.shtml#beef97.

USDA:APHIS:VS (1996) Reference of 1996 Dairy Management Practices. USDA–APHIS–VS, CEAH. Fort Collins, CO. Available online at http://www.aphis.usda.gov/vs/ceah/cahm.

USDA:APHIS:VS (1994) Beef Cow/Calf Health and Productivity Audit. USDA–APHIS–VS, CEAH. Fort Collins, CO. Available online at http://www.aphis.usda.gov/vs/ceah/cahm.

USDA:APHIS:VS (1993) Beef Cow/Calf Health and Productivity Audit. USDA–APHIS–VS, CEAH. Fort Collins, CO. August 1993. Available online at http://www.aphis.usda.gov/vs/ceah/cahm.

Vasconcelos and Galyean (2007) Nutritional recommendations of feedlot consulting nutritionists: The 2007 Texas Tech University Study. J. Anim. Sci. 85:2772-2781.

Manure Management

ASAE (1998) ASAE Standards 1998, 45th Edition. American Society of Agricultural Engineers. St. Joseph, MI.

Bryant, M.P., V.H. Varel, R.A. Frobish, and H.R. Isaacson (1976) In H.G. Schlegel (ed.)]; Seminar on Microbial Energy Conversion. E. Goltz KG. Göttingen, Germany.

Bush, E. (1998) Personal communication with Eric Bush, Centers for Epidemiology and Animal Health, U.S. Department of Agriculture regarding National Animal Health Monitoring System's (NAHMS) Swine '95 Study.

EPA (2023) AgSTAR Anaerobic Digester Database. Available online at: https://www.epa.gov/agstar/livestock-anaerobic-digester-database. Accessed August 2023.

EPA (2008) Climate Leaders Greenhouse Gas Inventory Protocol Offset Project Methodology for Project Type Managing Manure with Biogas Recovery Systems.

EPA (2005) National Emission Inventory—Ammonia Emissions from Animal Agricultural Operations, Revised Draft Report. U.S. Environmental Protection Agency. Washington, D.C. April 22, 2005.

EPA (2002a) Development Document for the Final Revisions to the National Pollutant Discharge Elimination System (NPDES) Regulation and the Effluent Guidelines for Concentrated Animal Feeding Operations (CAFOS). U.S. Environmental Protection Agency. EPA-821-R-03-001. December 2002.

EPA (2002b) Cost Methodology for the Final Revisions to the National Pollutant Discharge Elimination System Regulation and the Effluent Guidelines for Concentrated Animal Feeding Operations. U.S. Environmental Protection Agency. EPA-821-R-03-004. December 2002.

EPA (1992) Global Methane Emissions from Livestock and Poultry Manure, Office of Air and Radiation, U.S. Environmental Protection Agency. February 1992.

ERG (2023) Summary of Data Processing and Proposed Integration of 2018 Beef Feedlot and Poultry Waste Management System Data into the Manure Management Greenhouse Gas Inventory. Memorandum to EPA from ERG, December 2023.

ERG (2021) Updated Other Animal Population Distribution Methodology. Memorandum to EPA from ERG.

ERG (2019) "Incorporation of USDA 2016 ARMS Dairy Data into the Manure Management Greenhouse Gas Inventory." Memorandum to USDA OCE and EPA from ERG, December 2019.

ERG (2018) "Incorporation of USDA 2009 ARMS Swine Data into the Manure Management Greenhouse Gas Inventory." Memorandum to USDA OCE and EPA from ERG, November 2018.

ERG (2010a) "Typical Animal Mass Values for Inventory Swine Categories." Memorandum to EPA from ERG. July 19, 2010.

ERG (2010b) Telecon with William Boyd of USDA NRCS and Cortney Itle of ERG Concerning Updated VS and Nex Rates. August 8, 2010.

ERG (2010c) "Updating Current Inventory Manure Characteristics new USDA Agricultural Waste Management Field Handbook Values." Memorandum to EPA from ERG. August 13, 2010.

ERG (2008) "Methodology for Improving Methane Emissions Estimates and Emission Reductions from Anaerobic Digestion System for the 1990-2007 Greenhouse Gas Inventory for Manure Management." Memorandum to EPA from ERG. August 18, 2008.

ERG (2003a) "Methodology for Estimating Uncertainty for Manure Management Greenhouse Gas Inventory." Contract No. GS-10F-0036, Task Order 005. Memorandum to EPA from ERG, Lexington, MA. September 26, 2003.

ERG (2003b) "Changes to Beef Calves and Beef Cows Typical Animal Mass in the Manure Management Greenhouse Gas Inventory." Memorandum to EPA from ERG, October 7, 2003.

ERG (2001) Summary of development of MDP Factor for methane conversion factor calculations. ERG, Lexington, MA. September 2001.

ERG (2000a) Calculations: Percent Distribution of Manure for Waste Management Systems. ERG, Lexington, MA. August 2000.

ERG (2000b) Discussion of Methodology for Estimating Animal Waste Characteristics (Summary of Bo Literature Review). ERG, Lexington, MA. June 2000.

Groffman, P.M., R. Brumme, K. Butterbach-Bahl, K.E. Dobbie, A.R. Mosier, D. Ojima, H. Papen, W.J. Parton, K.A. Smith, and C. Wagner-Riddle (2000) "Evaluating annual nitrous oxide fluxes at the ecosystem scale." Global Biogeochemical Cycles, 14(4):1061-1070.

Hashimoto, A.G. (1984) "Methane from Swine Manure: Effect of Temperature and Influent Substrate Composition on Kinetic Parameter (k)." Agricultural Wastes, 9:299-308.

Hashimoto, A.G., V.H. Varel, and Y.R. Chen (1981) "Ultimate Methane Yield from Beef Cattle Manure; Effect of Temperature, Ration Constituents, Antibiotics and Manure Age." Agricultural Wastes, 3:241-256.

Hill, D.T. (1984) "Methane Productivity of the Major Animal Types." Transactions of the ASAE, 27(2):530-540.

Hill, D.T. (1982) "Design of Digestion Systems for Maximum Methane Production." Transactions of the ASAE, 25(1):226-230.

IPCC (2019) *2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change. [CalvoBuendia, E., Tanabe, K., Kranjc, A., Baasansuren, J., Fukuda, M., Ngarize S., Osako, A., Pyrozhenko, Y., Shermanau, P. and Federici, S. (eds)]. Switzerland.

IPCC (2013) *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1535 pp.IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change. [H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (eds.)]. Hayama, Kanagawa, Japan.

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change. H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (eds.). Hayama, Kanagawa, Japan.

Morris, G.R. (1976) Anaerobic Fermentation of Animal Wastes: A Kinetic and Empirical Design Fermentation. M.S. Thesis. Cornell University.

National Bison Association (1999) Total Bison Population—1999. Report provided during personal email communication with Dave Carter, Executive Director, National Bison Association July 19, 2011.

Ott, S.L. (2000) Dairy '96 Study. Stephen L. Ott, Animal and Plant Health Inspection Service, U.S. Department of Agriculture. June 19, 2000.

Robertson, G. P. and P. M. Groffman (2015) Nitrogen transformations. Soil Microbiology, Ecology, and Biochemistry, pages 421-446. Academic Press, Burlington, Massachusetts, USA.

Safley, L.M., Jr. (2000) Personal Communication. Deb Bartram, ERG and L.M. Safley, President, Agri-Waste Technology. June and October 2000.

Sweeten, J. (2000) Personal Communication. John Sweeten, Texas A&M University and Indra Mitra, ERG. June 2000.

UEP (1999) Voluntary Survey Results—Estimated Percentage Participation/Activity. Caged Layer Environmental Management Practices, Industry data submissions for EPA profile development, United Egg Producers and National Chicken Council. Received from John Thorne, Capitolink. June 2000.

USDA (2023a) Quick Stats: Agricultural Statistics Database. National Agriculture Statistics Service, U.S. Department of Agriculture. Washington, D.C. Available online at: http://quickstats.nass.usda.gov/.

USDA (2023b) Chicken and Eggs 2022 Summary. National Agriculture Statistics Service, U.S. Department of Agriculture. Washington, D.C. February 2023. Available online at: https://www.nass.usda.gov/Publications/.

USDA (2023c) Poultry - Production and Value 2022 Summary. National Agriculture Statistics Service, U.S. Department of Agriculture. Washington, D.C. April 2023. Available online at: https://www.nass.usda.gov/Publications/.

USDA (2021a) Chicken and Eggs 2020 Summary. National Agriculture Statistics Service, U.S. Department of Agriculture. Washington, D.C. February 2021. Available online at: http://www.nass.usda.gov/Publications/index.asp.

USDA (2021b) Poultry - Production and Value 2020 Summary. National Agriculture Statistics Service, U.S. Department of Agriculture. Washington, D.C. April 2021. Available online at: http://www.nass.usda.gov/Publications/index.asp.

USDA (2019a) Chicken and Eggs 2018 Summary. National Agriculture Statistics Service, U.S. Department of Agriculture. Washington, D.C. February 2019. Available online at: http://www.nass.usda.gov/Publications/index.php.

USDA (2019b) Poultry - Production and Value 2018 Summary. National Agriculture Statistics Service, U.S. Department of Agriculture. Washington, D.C. April 2019. Available online at: http://www.nass.usda.gov/Publications/index.php.

USDA (2019c) Chicken and Eggs 2013-2017 Summary. National Agriculture Statistics Service, U.S. Department of Agriculture. Washington, D.C. June 2019. Available online at: http://www.nass.usda.gov/Publications/index.php.

USDA (2019d) 1987, 1992, 1997, 2002, 2007, 2012, and 2017 Census of Agriculture. National Agriculture Statistics Service, U.S. Department of Agriculture. Washington, D.C. Available online at: https://www.nass.usda.gov/AgCensus/index.php. May 2019.

USDA (2018) Poultry - Production and Value 2017 Summary. National Agriculture Statistics Service, U.S. Department of Agriculture. Washington, D.C. April 2018. Available online at: http://www.nass.usda.gov/Publications/index.php.

USDA (2017) Poultry - Production and Value 2016 Summary. National Agriculture Statistics Service, U.S. Department of Agriculture. Washington, D.C. April 2017. Available online at: http://www.nass.usda.gov/Publications/index.php.

USDA (2016) Poultry - Production and Value 2015 Summary. National Agriculture Statistics Service, U.S. Department of Agriculture. Washington, D.C. April 2016. Available online at: http://www.nass.usda.gov/Publications/index.php.

USDA (2015) Poultry - Production and Value 2014 Summary. National Agriculture Statistics Service, U.S. Department of Agriculture. Washington, D.C. April 2015. Available online at: http://www.nass.usda.gov/Publications/index.php.

USDA (2014) Poultry - Production and Value 2013 Summary. National Agriculture Statistics Service, U.S. Department of Agriculture. Washington, D.C. April 2014. Available online at: http://www.nass.usda.gov/Publications/index.php.

USDA (2013a) Chicken and Eggs 2012 Summary. National Agriculture Statistics Service, U.S. Department of Agriculture. Washington, D.C. February 2013. Available online at: http://www.nass.usda.gov/Publications/index.php.

USDA (2013b) Poultry - Production and Value 2012 Summary. National Agriculture Statistics Service, U.S. Department of Agriculture. Washington, D.C. April 2013. Available online at: http://www.nass.usda.gov/Publications/index.php.

USDA (2012a) Chicken and Eggs 2011 Summary. National Agriculture Statistics Service, U.S. Department of Agriculture. Washington, D.C. February 2012. Available online at: http://www.nass.usda.gov/Publications/index.php.

USDA (2012b) Poultry - Production and Value 2011 Summary. National Agriculture Statistics Service, U.S. Department of Agriculture. Washington, D.C. April 2012. Available online at: http://www.nass.usda.gov/Publications/index.php.

USDA (2011a) Chicken and Eggs 2010 Summary. National Agriculture Statistics Service, U.S. Department of Agriculture. Washington, D.C. February 2011. Available online at: http://www.nass.usda.gov/Publications/index.php.

USDA (2011b) Poultry - Production and Value 2010 Summary. National Agriculture Statistics Service, U.S. Department of Agriculture. Washington, D.C. April 2011. Available online at: http://www.nass.usda.gov/Publications/index.php.

USDA (2010a) Chicken and Eggs 2009 Summary. National Agriculture Statistics Service, U.S. Department of Agriculture. Washington, D.C. February 2010. Available online at: http://www.nass.usda.gov/Publications/index.php.

USDA (2010b) Poultry - Production and Value 2009 Summary. National Agriculture Statistics Service, U.S. Department of Agriculture. Washington, D.C. April 2010. Available online at: http://www.nass.usda.gov/Publications/index.php.

USDA (2009a) Chicken and Eggs 2008 Summary. National Agriculture Statistics Service, U.S. Department of Agriculture. Washington, D.C. February 2009. Available online at: http://www.nass.usda.gov/Publications/index.php.

USDA (2009b) Poultry - Production and Value 2008 Summary. National Agriculture Statistics Service, U.S. Department of Agriculture. Washington, D.C. April 2009. Available online at: http://www.nass.usda.gov/Publications/index.php.

USDA (2009c) Chicken and Eggs – Final Estimates 2003-2007. National Agriculture Statistics Service, U.S. Department of Agriculture. Washington, D.C. March 2009. Available online at: https://www.nass.usda.gov/Publications/index.php.

USDA (2009d) Poultry Production and Value—Final Estimates 2003-2007. National Agriculture Statistics Service, U.S. Department of Agriculture. Washington, D.C. May 2009. Available online at: https://www.nass.usda.gov/Publications/index.php.

USDA (2008) Agricultural Waste Management Field Handbook, National Engineering Handbook (NEH), Part 651. Natural Resources Conservation Service, U.S. Department of Agriculture.

USDA (2004a) Chicken and Eggs—Final Estimates 1998-2003. National Agriculture Statistics Service, U.S. Department of Agriculture. Washington, D.C. April 2004. Available online at: https://www.nass.usda.gov/Publications/index.php.

USDA (2004b) Poultry Production and Value—Final Estimates 1998-2002. National Agriculture Statistics Service, U.S. Department of Agriculture. Washington, D.C. April 2004. Available online at: https://www.nass.usda.gov/Publications/index.php.

USDA (1999) Poultry Production and Value—Final Estimates 1994-97. National Agriculture Statistics Service, U.S. Department of Agriculture. Washington, D.C. March 1999. Available online at: https://www.nass.usda.gov/Publications/index.php.

USDA (1998) Chicken and Eggs—Final Estimates 1994-97. National Agriculture Statistics Service, U.S. Department of Agriculture. Washington, D.C. December 1998. Available online at: https://www.nass.usda.gov/Publications/index.php.

USDA (1996) Agricultural Waste Management Field Handbook, National Engineering Handbook (NEH), Part 651. Natural Resources Conservation Service, U.S. Department of Agriculture. July 1996.

USDA (1995a) Poultry Production and Value—Final Estimates 1988-1993. National Agriculture Statistics Service, U.S. Department of Agriculture. Washington, D.C. March 1995. Available online at: https://www.nass.usda.gov/Publications/index.php.

USDA (1995b) Chicken and Eggs—Final Estimates 1988-1993. National Agriculture Statistics Service, U.S. Department of Agriculture. Washington, D.C. December 1995. Available online at: https://www.nass.usda.gov/Publications/index.php.

USDA (1994) Sheep and Goats—Final Estimates 1989-1993. National Agriculture Statistics Service, U.S. Department of Agriculture. Washington, D.C. January 31, 1994. Available online at: https://www.nass.usda.gov/Publications/index.php.

USDA APHIS (2003) Sheep 2001, Part I: Reference of Sheep Management in the United States, 2001 and Part IV: Baseline Reference of 2001 Sheep Feedlot Health and Management. USDA-APHIS-VS. Fort Collins, CO. #N356.0702. Available online at http://www.aphis.usda.gov/animal_health/nahms/sheep/index.shtml#sheep2001.

USDA APHIS (2000) Layers '99—Part II: References of 1999 Table Egg Layer Management in the U.S. USDA-APHIS-VS. Fort Collins, CO. Available online at http://www.aphis.usda.gov/animal_health/nahms/poultry/downloads/layers99/Layers99_dr_PartII.pdf.

USDA APHIS (1996) Swine '95: Grower/Finisher Part II: Reference of 1995 U.S. Grower/Finisher Health & Management Practices. USDA-APHIS-VS. Fort Collins, CO. Available online at: http://www.aphis.usda.gov/animal_health/nahms/swine/downloads/swine95/Swine95_dr_PartII.pdf.

Rice Cultivation

Baicich, P. (2013) The Birds and Rice Connection. *Bird Watcher's Digest*. Available online at: http://www.usarice.com/doclib/194/6867.pdf.

Brockwell, P.J., and R.A. Davis (2016) Introduction to time series and forecasting. Springer.

Cantens, G. (2004 through 2005) Personal Communication. Janet Lewis, Assistant to Gaston Cantens, Vice President of Corporate Relations, Florida Crystals Company and ICF International.

Cheng, K., S.M. Ogle, W.J. Parton, G. Pan. (2014) "Simulating greenhouse gas mitigation potentials for Chinese croplands using the DAYCENT ecosystem model." *Global Change Biology* 20:948-962.

Cheng, K., S.M. Ogle, W.J. Parton and G. Pan. (2013) "Predicting methanogenesis from rice paddies using the DAYCENT ecosystem model." *Ecological Modelling* 261-262:19-31.

Del Grosso, S.J., S.M. Ogle, W.J. Parton, and F.J. Breidt (2010) "Estimating Uncertainty in N_2O Emissions from U.S. Cropland Soils." Global Biogeochemical Cycles, 24, GB1009, doi:10.1029/2009GB003544.

Deren, C. (2002) Personal Communication and Dr. Chris Deren, Everglades Research and Education Centre at the University of Florida and Caren Mintz, ICF International. August 15, 2002.

Fitzgerald, G.J., K. M. Scow & J. E. Hill (2000) "Fallow Season Straw and Rice Management Effects on Methane Emissions in California Rice." Global biogeochemical cycles, 14 (3), 767-776.

Fleskes, J.P., Perry, W.M., Petrik, K.L., Spell, R., and Reid, F. (2005) Change in area of winter-flood and dry rice in the northern Central Valley of California determined by satellite imagery. California Fish and Game, 91: 207-215.

Gonzalez, R. (2007 through 2014) Email correspondence. Rene Gonzalez, Plant Manager, Sem-Chi Rice Company and ICF International.

Hardke, J.T. (2015) Trends in Arkansas rice production, 2014. B.R. Wells Arkansas Rice Research Studies 2014. Norman, R.J. and Moldenhauer, K.A.K. (Eds.). Research Series 626, Arkansas Agricultural Experiment Station, University of Arkansas.

Hardke, J. (2014) Personal Communication. Dr. Jarrod Hardke, Rice Extension Agronomist at the University of Arkansas Rice Research and Extension Center and Kirsten Jaglo, ICF International. September 11, 2014.

Hardke, J. (2013) Email correspondence. Dr. Jarrod Hardke, Rice Extension Agronomist at the University of Arkansas Rice Research and Extension Center and Cassandra Snow, ICF International. July 15, 2013.

Hardke, J.T., and Wilson, C.E. Jr., (2014) Trends in Arkansas rice production, 2013. B.R. Wells Arkansas Rice Research Studies 2013. Norman, R.J., and Moldenhauer, K.A.K., (Eds.). Research Series 617, Arkansas Agricultural Experiment Station, University of Arkansas.

Hardke, J.T., and Wilson, C.E. Jr., (2013) Trends in Arkansas rice production. B.R. Wells Arkansas Rice Research Studies 2012. Norman, R.J., and Moldenhauer, K.A.K., (Eds.). Research Series 609, Arkansas Agricultural Experiment Station, University of Arkansas.

Hollier, C. A. (ed), (1999) Louisiana rice production handbook. Louisiana State University Agricultural Center. LCES Publication Number 2321. 116 pp.

Holzapfel-Pschorn, A., R. Conrad, and W. Seiler (1985) "Production, Oxidation, and Emissions of Methane in Rice Paddies." *FEMS Microbiology Ecology,* 31:343-351.

IPCC (2013) *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1535 pp.

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change. [H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (eds.)]. Hayama, Kanagawa, Japan.

Johnson, D.M., and R. Mueller (2010) The 2009 Cropland Data Layer. Photogrammetric engineering and remote sensing 76:1201-1205.

Kirstein, A. (2003 through 2004, 2006) Personal Communication. Arthur Kirstein, Coordinator, Agricultural Economic Development Program, Palm Beach County Cooperative Extension Service, FL and ICF International.

Klosterboer, A. (1997, 1999 through 2003) Personal Communication. Arlen Klosterboer, retired Extension Agronomist, Texas A&M University and ICF International. July 7, 2003.

Lindau, C.W. and P.K. Bollich (1993) "Methane Emissions from Louisiana First and Ratoon Crop Rice." *Soil Science,* 156:42-48.

Linquist, B.A., M.A. Adviento-Borbe, C.M. Pittelkow, C.v. Kessel, et al. (2012) Fertilizer management practices and greenhouse gas emissions from rice systems: A quantitative review and analysis. *Field Crops Research*, 135:10-21.

Linscombe, S. (1999, 2001 through 2014) Email correspondence. Steve Linscombe, Professor with the Rice Research Station at Louisiana State University Agriculture Center and ICF International.

LSU, (2015) Louisiana ratoon crop and conservation: Ratoon & Conservation Tillage Estimates. Louisiana State University, College of Agriculture AgCenter. Online at: www.lsuagcenter.com.

Miller, M.R., Garr, J.D., and Coates, P.S., (2010) Changes in the status of harvested rice fields in the Sacramento Valley, California: Implications for wintering waterfowl. Wetlands, 30: 939-947.

Nelson, Mark D.; Riitters, Kurt H.; Coulston, John W.; Domke, Grant M.; Greenfield, Eric J.; Langner, Linda L.; Nowak, David J.; O'Dea, Claire B.; Oswalt, Sonja N.; Reeves, Matthew C.; Wear, David N. 2020. Defining the United States land base: a technical document supporting the USDA Forest Service 2020 RPA assessment. Gen. Tech. Rep. NRS-191. Madison, WI: U.S. Department of Agriculture, Forest Service, Northern Research Station. 70 p. https://doi.org/10.2737/NRS-GTR-191.

Neue, H.U., R. Wassmann, H.K. Kludze, W. Bujun, and R.S. Lantin (1997) "Factors and processes controlling methane emissions from rice fields." *Nutrient Cycling in Agroecosystems* 49: 111-117.

Ogle, S.M., F.J. Breidt, M. Easter, S. Williams and K. Paustian. (2007) "An empirically based approach for estimating uncertainty associated with modeling carbon sequestration in soils." *Ecological Modelling* 205:453-463.

Ogle, S.M., F.J. Breidt, M. Easter, S. Williams, K. Killian, and K. Paustian (2010) "Scale and uncertainty in modeled soil organic carbon stock changes for U.S. croplands using a process-based model." Global Change Biology 16:810-822.

Ogle, S.M., S. Spencer, M. Hartman, L. Buendia, L. Stevens, D. du Toit, J. Witi (2016) "Developing national baseline GHG emissions and analyzing mitigation potentials for agriculture and forestry using an advanced national GHG inventory software system." In Advances in Agricultural Systems Modeling 6, *Synthesis and Modeling of Greenhouse Gas Emissions and Carbon Storage in Agricultural and Forestry Systems to Guide Mitigation and Adaptation*, S. Del Grosso, L.R. Ahuja and W.J. Parton (eds.), American Society of Agriculture, Crop Society of America and Soil Science Society of America, pp. 129-148.

Parton, W.J., M.D. Hartman, D.S. Ojima, and D.S. Schimel (1998) "DAYCENT: Its Land Surface Submodel: Description and Testing". Glob. Planet. Chang. 19: 35-48.

Parton, W.J., D.S. Schimel, C.V. Cole, D.S. Ojima (1987) "Analysis of factors controlling soil organic matter levels in Great Plains grasslands." Soil Science Society of America Journal 51:1173-1179.

Särndal C-E, Swensson B, Wretman, J (1992) Model Assisted Survey Sampling. Springer, New York.

Sass, R. L. (2001) CH_4 Emissions from Rice Agriculture. Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories. 399-417. Available online at: http://www.ipcc-nggip.iges.or.jp/public/gp/bgp/4_7_CH4_Rice_Agriculture.pdf.

Sass, R.L., F.M. Fisher, P.A. Harcombe, and F.T. Turner (1990) "Methane Production and Emissions in a Texas Rice Field." *Global Biogeochemical Cycles,* 4:47-68.

Sass, R.L., F.M. Fisher, S.T. Lewis, M.F. Jund, and F.T. Turner. (1994) "Methane emissions from rice fields: effect of soil texture." *Global Biogeochemical Cycles* 8:135-140.

Schueneman, T. (1997, 1999 through 2001) Personal Communication. Tom Schueneman, Agricultural Extension Agent, Palm Beach County, FL and ICF International.

Slaton, N. (1999 through 2001) Personal Communication. Nathan Slaton, Extension Agronomist—Rice, University of Arkansas Division of Agriculture Cooperative Extension Service and ICF International.

Stansel, J. (2004 through 2005) Email correspondence. Dr. Jim Stansel, Resident Director and Professor Emeritus, Texas A&M University Agricultural Research and Extension Center and ICF International.

TAMU (2015) Texas Rice Crop Survey. Texas A&M AgriLIFE Research Center at Beaumont. Online at: https://beaumont.tamu.edu/.

Texas Agricultural Experiment Station (2007 through 2014) *Texas Rice Acreage by Variety*. Agricultural Research and Extension Center, Texas Agricultural Experiment Station, Texas A&M University System. Available online at: http://beaumont.tamu.edu/CropSurvey/CropSurveyReport.aspx.

Texas Agricultural Experiment Station (2006) *2005 - Texas Rice Crop Statistics Report*. Agricultural Research and Extension Center, Texas Agricultural Experiment Station, Texas A&M University System, p. 8. Available online at: http://beaumont.tamu.edu/eLibrary/TRRFReport_default.htm.

University of California Cooperative Extension (UCCE) (2015) Rice Production Manual. Revised (2015) UCCE, Davis, in collaboration with the California Rice Research Board.

USDA (2005 through 2015) *Crop Production Summary*. National Agricultural Statistics Service, Agricultural Statistics Board, U.S. Department of Agriculture, Washington, D.C. Available online at: http://usda.mannlib.cornell.edu.

USDA (2012) *Summary of USDA-ARS Research on the Interrelationship of Genetic and Cultural Management Factors That Impact Grain Arsenic Accumulation in Rice*. News and Events. Agricultural Research Service, U.S. Department of Agriculture, Washington, D.C. Available online at: http://www.ars.usda.gov/is/pr/2012/120919.htm. September 2013.

USDA (2003) *Field Crops, Final Estimates 1997-2002*. Statistical Bulletin No. 982. National Agricultural Statistics Service, Agricultural Statistics Board, U.S. Department of Agriculture, Washington, D.C. Available online at: http://usda.mannlib.cornell.edu/usda/reports/general/sb/. September 2005.

USDA (1998) *Field Crops Final Estimates 1992-1997*. Statistical Bulletin Number 947 a. National Agricultural Statistics Service, Agricultural Statistics Board, U.S. Department of Agriculture, Washington, D.C. Available online at: http://usda.mannlib.cornell.edu/. July 2001.

USDA (1994) *Field Crops Final Estimates 1987-1992*. Statistical Bulletin Number 896. National Agricultural Statistics Service, Agricultural Statistics Board, U.S. Department of Agriculture, Washington, D.C. Available online at: http://usda.mannlib.cornell.edu/. July 2001.

USDA-NASS (2021) Published crop data layer. Available at https://nassgeodata.gmu.edu/CropScape/, Accessed July 2021, USDA-NASS, Washington, DC.

USDA-NRCS (2020) Summary Report: 2017 National Resources Inventory. Natural Resources Conservation Service, Washington, DC, and Center for Survey Statistics and Methodology, Iowa State University, Ames, Iowa. https://www.nrcs.usda.gov/wps/portal/nrcs/main/national/technical/nra/nri/results/.

van Bodegom, P.M., R. Wassmann, T.M. Metra-Corton (2001) "A process based model for methane emission predictions from flooded rice paddies." *Global Biogeochemical Cycles* 15: 247-263.

Wang, J.J., S.K. Dodla, S. Viator, M. Kongchum, S. Harrison, S. D. Mudi, S. Liu, Z. Tian (2013) Agriculture Field Management Practices and Greenhouse Gas Emissions from Louisiana Soils. *Louisiana Agriculture*, Spring 2013: 8-9. Available online at: http://www.lsuagcenter.com/NR/rdonlyres/78D8B61A-96A8-49E1-B2EF-BA1D4CE4E698/93016/v56no2Spring2013.pdf.

Wassmann, R. H.U. Neue, R.S. Lantin, K. Makarim, N. Chareonsil5, L.V. Buendia, and H. Rennenberg (2000a) Characterization of methane emissions from rice fields in Asia II. Differences among irrigated, rainfed, and deepwater rice." *Nutrient Cycling in Agroecosystems*, 58(1):13-22.

Wassmann, R., R.S. Lantin, H.U. Neue, L.V. Buendia, et al. (2000b) "Characterization of Methane Emissions from Rice Fields in Asia. III. Mitigation Options and Future Research Needs." *Nutrient Cycling in Agroecosystems*, 58(1):23-36.

Way, M.O., McCauley, G.M., Zhou, X.G., Wilson, L.T., and Morace, B. (Eds.), (2014) 2014 Texas Rice Production Guidelines. Texas A&M AgriLIFE Research Center at Beaumont.

Wilson, C. (2002 through 2007, 2009 through 2012) Personal Communication. Dr. Chuck Wilson, Rice Specialist at the University of Arkansas Cooperative Extension Service and ICF International.

Wilson, C.E. Jr., and Branson, J.W., (2006) Trends in Arkansas rice production. B.R. Wells Arkansas Rice Research Studies 2005. Norman, R.J., Meullenet, J.-F., and Moldenhauer, K.A.K., (Eds.). Research Series 540, Arkansas Agricultural Experiment Station, University of Arkansas.

Wilson, C.E. Jr., and Branson, J.W., (2005) Trends in Arkansas rice production. B.R. Wells Arkansas Rice Research Studies 2004. Norman, R.J., Meullenet, J.-F., and Moldenhauer, K.A.K., (Eds.). Research Series 529, Arkansas Agricultural Experiment Station, University of Arkansas.

Wilson, C.E. Jr., Runsick, S.K., and Mazzanti, R., (2010) Trends in Arkansas rice production. B.R. Wells Arkansas Rice Research Studies 2009. Norman, R.J., and Moldenhauer, K.A.K., (Eds.). Research Series 581, Arkansas Agricultural Experiment Station, University of Arkansas.

Wilson, C.E. Jr., Runsick, S.K., Mazzanti, R., (2009) Trends in Arkansas rice production. B.R. Wells Arkansas Rice Research Studies (2008) Norman, R.J., Meullenet, J.-F., and Moldenhauer, K.A.K., (Eds.). Research Series 571, Arkansas Agricultural Experiment Station, University of Arkansas.

Wilson, C.E. Jr., and Runsick, S.K., (2008) Trends in Arkansas rice production. B.R. Wells Arkansas Rice Research Studies 2007. Norman, R.J., Meullenet, J.-F., and Moldenhauer, K.A.K., (Eds.). Research Series 560, Arkansas Agricultural Experiment Station, University of Arkansas.

Wilson, C.E. Jr., and Runsick, S.K., (2007) Trends in Arkansas rice production. B.R. Wells Arkansas Rice Research Studies 2006. Norman, R.J., Meullenet, J.-F., and Moldenhauer, K.A.K., (Eds.). Research Series 550, Arkansas Agricultural Experiment Station, University of Arkansas.

Yan, X., H. Akiyana, K. Yagi, and H. Akimoto (2009) “Global estimations of the inventory and mitigation potential of methane emissions from rice cultivation conducted using the 2006 Intergovernmental Panel on Climate Change Guidelines.” *Global Biogeochemical Cycles*, 23, DOI: 0.1029/2008GB003299.

Yang, L., et al. (2018). "A new generation of the United States National Land Cover Database: Requirements, research priorities, design, and implementation strategies.” ISPRS Journal of Photogrammetry and Remote Sensing 146: 108-123.

Young, M. (2013) Rice and Ducks. Ducks Unlimited, Memphis, TN. Available online at: http://www.ducks.org/conservation/farm-bill/rice-and-ducks---by-matt-young.

Agricultural Soil Management

AAPFCO (2008 through 2022) Commercial Fertilizers: 2008-2017. Association of American Plant Food Control Officials. University of Missouri. Columbia, MO.

AAPFCO (1995 through 2000a, 2002 through 2007) Commercial Fertilizers: 1995-2007. Association of American Plant Food Control Officials. University of Kentucky. Lexington, KY.

Brockwell, Peter J., and Richard A. Davis (2016) Introduction to time series and forecasting. Springer.

Cibrowski, P. (1996) Personal Communication. Peter Cibrowski, Minnesota Pollution Control Agency and Heike Mainhardt, ICF Incorporated. July 29, 1996.

Cheng, B., and D.M. Titterington (1994) "Neural networks: A review from a statistical perspective." Statistical science 9: 2-30.

Claassen, R., M. Bowman, J. McFadden, D. Smith, and S. Wallander (2018) Tillage intensity and conservation cropping in the United States, EIB 197. United States Department of Agriculture, Economic Research Service, Washington, D.C.

CTIC (2004) 2004 Crop Residue Management Survey. Conservation Technology Information Center. Available at http://www.ctic.purdue.edu/CRM/.

Del Grosso, S. J., S. M. Ogle, C. Nevison, R. Gurung, W. J. Parton, C. Wagner-Riddle, W. Smith, W. Winiwarter, B. Grant, M. Tenuta, E. Marx, S. Spencer, and S. Williams. 2022. A gap in nitrous oxide emission reporting complicates long-term climate mitigation. Proceedings of the National Academy of Sciences 119:e2200354119.

Del Grosso, S.J., A.R. Mosier, W.J. Parton, and D.S. Ojima (2005) "DAYCENT Model Analysis of Past and Contemporary Soil N_2O and Net Greenhouse Gas Flux for Major Crops in the USA." *Soil Tillage and Research*, 83: 9-24. doi: 10.1016/j.still.2005.02.007.

Del Grosso, S.J., S.M. Ogle, W.J. Parton, and F.J. Breidt (2010) "Estimating Uncertainty in N_2O Emissions from U.S. Cropland Soils." *Global Biogeochemical Cycles*, 24, GB1009, doi:10.1029/2009GB003544.

Del Grosso, S.J., T. Wirth, S.M. Ogle, W.J. Parton (2008) Estimating agricultural nitrous oxide emissions. EOS 89, 529-530.

Del Grosso, S.J., W.J. Parton, A.R. Mosier, M.D. Hartman, J. Brenner, D.S. Ojima, and D.S. Schimel (2001) "Simulated Interaction of Carbon Dynamics and Nitrogen Trace Gas Fluxes Using the DAYCENT Model." In Schaffer, M., L. Ma, S. Hansen, (eds.). Modeling Carbon and Nitrogen Dynamics for Soil Management. CRC Press. Boca Raton, Florida. 303-332.

Del Grosso, S.J., W.J. Parton, C.A. Keough, and M. Reyes-Fox. (2011) Special features of the DAYCENT modeling package and additional procedures for parameterization, calibration, validation, and applications, in Methods of Introducing System Models into Agricultural Research, L.R. Ahuja and Liwang Ma, editors, p. 155-176, American Society of Agronomy, Crop Science Society of America, Soil Science Society of America, Madison, WI. USA.

Delgado, J.A., S.J. Del Grosso, and S.M. Ogle (2009) "15N isotopic crop residue cycling studies and modeling suggest that IPCC methodologies to assess residue contributions to N_2O-N emissions should be reevaluated." *Nutrient Cycling in Agroecosystems*, DOI 10.1007/s10705-009-9300-9.

Edmonds, L., N. Gollehon, R.L. Kellogg, B. Kintzer, L. Knight, C. Lander, J. Lemunyon, D. Meyer, D.C. Moffitt, and J. Schaeffer (2003) "Costs Associated with Development and Implementation of Comprehensive Nutrient Management Plans." Part 1. Nutrient Management, Land Treatment, Manure and Wastewater Handling and Storage, and Recordkeeping. Natural Resource Conservation Service, U.S. Department of Agriculture.

EPA (2003) Clean Watersheds Needs Survey 2000—Report to Congress, U.S. Environmental Protection Agency. Washington, D.C. Available online at: http://www.epa.gov/owm/mtb/cwns/2000rtc/toc.htm.

EPA (1999) Biosolids Generation, Use and Disposal in the United States. Office of Solid Waste, U.S. Environmental Protection Agency. Available online at: http://biosolids.policy.net/relatives/18941.PDF.

EPA (1993) Federal Register. Part II. Standards for the Use and Disposal of Sewage Sludge; Final Rules. U.S. Environmental Protection Agency, 40 CFR Parts 257, 403, and 503.

Firestone, M. K., and E.A. Davidson, Ed. (1989) Microbiological basis of NO and N_2O production and consumption in soil. Exchange of trace gases between terrestrial ecosystems and the atmosphere. New York, John Wiley & Sons.

Friedman, J.H. (2001) "Greedy function approximation: A gradient boosting machine." Ann. Statist. 29 (5) 1189 – 1232.

Hagen, S. C., G. Delgado, P. Ingraham, I. Cooke, R. Emery, J. P. Fisk, L. Melendy, T. Olson, S. Patti, N. Rubin, B. Ziniti, H. Chen, W. Salas, P. Elias, and D. Gustafson. 2020. Mapping Conservation Management Practices and Outcomes in the Corn Belt Using the Operational Tillage Information System (OpTIS) and the Denitrification–Decomposition (DNDC) Model. Land **9**:408.

ILENR (1993) Illinois Inventory of Greenhouse Gas Emissions and Sinks: 1990. Office of Research and Planning, Illinois Department of Energy and Natural Resources. Springfield, IL.

IPCC (2014) *2013 Supplement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories: Wetlands*. The Intergovernmental Panel on Climate Change. [T, Hiraishi, T. Krug, K. Tanabe, N. Srivastava, B. Jamsranjav, M. Fukuda and T. Troxler (eds.)]. Hayama, Kanagawa, Japan.

IPCC (2013) *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Stocker, T.F., D. Qin, G.-K. Plattner, M.

Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1535 pp.

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change. [H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (eds.)]. Hayama, Kanagawa, Japan.

Johnson, D.M., and R. Mueller (2010) The 2009 Cropland Data Layer. Photogrammetric engineering and remote sensing 76:1201-1205.

Little, R. (1988) "Missing-data adjustments in large surveys." *Journal of Business and Economic Statistics* 6: 287–296.

McFarland, M.J. (2001) Biosolids Engineering, New York: McGraw-Hill, p. 2.12.

McGill, W.B., and C.V. Cole (1981) Comparative aspects of cycling of organic C, N, S and P through soil organic matter. *Geoderma* 26:267-286.

Metherell, A.K., L.A. Harding, C.V. Cole, and W.J. Parton (1993) "CENTURY Soil Organic Matter Model Environment." Agroecosystem version 4.0. Technical documentation, GPSR Tech. Report No. 4, USDA/ARS, Ft. Collins, CO.

Mosier A., C. Kroeze, C. Nevison, O. Oenema, S. Seitzinger, and O. van Cleemput (1998) Closing the global atmospheric N_2O budget: Nitrous oxide emissions through the agricultural nitrogen cycle, Nutrient Cycling in Agroecosystems, 52, 225-248.

NEBRA (2007) A National Biosolids Regulation, Quality, End Use & Disposal Survey. North East Biosolids and Residuals Association, July 21, 2007.

Nelson, Mark D.; Riitters, Kurt H.; Coulston, John W.; Domke, Grant M.; Greenfield, Eric J.; Langner, Linda L.; Nowak, David J.; O'Dea, Claire B.; Oswalt, Sonja N.; Reeves, Matthew C.; Wear, David N. 2020. Defining the United States land base: a technical document supporting the USDA Forest Service 2020 RPA assessment. Gen. Tech. Rep. NRS-191. Madison, WI: U.S. Department of Agriculture, Forest Service, Northern Research Station. 70 p. https://doi.org/10.2737/NRS-GTR-191.

Noller, J. (1996) Personal Communication. John Noller, Missouri Department of Natural Resources and Heike Mainhardt, ICF Incorporated. July 30, 1996.

Ogle, S.M., F.J. Breidt, M. Easter, S. Williams, K. Killian, and K. Paustian (2010) "Scale and uncertainty in modeled soil organic carbon stock changes for U.S. croplands using a process-based model." Global Change Biology 16:810-822.

Ogle, S.M., F.J. Breidt, M. Easter, S. Williams and K. Paustian (2007) "Empirically-Based Uncertainty Associated with Modeling Carbon Sequestration Rates in Soils." *Ecological Modeling* 205:453-463.

Oregon Department of Energy (1995) Report on Reducing Oregon's Greenhouse Gas Emissions: Appendix D Inventory and Technical Discussion. Oregon Department of Energy. Salem, OR.

Parton, W.J., M.D. Hartman, D.S. Ojima, and D.S. Schimel (1998) "DAYCENT: Its Land Surface Submodel: Description and Testing." *Glob. Planet. Chang*. 19: 35-48.

Potter, C., S. Klooster, A. Huete, and V. Genovese (2007) Terrestrial carbon sinks for the United States predicted from MODIS satellite data and ecosystem modeling. *Earth Interactions* 11, Article No. 13, DOI 10.1175/EI228.1.

Potter, C. S., J.T. Randerson, C.B. Fields, P.A. Matson, P.M. Vitousek, H.A. Mooney, and S.A. Klooster (1993) "Terrestrial ecosystem production: a process model based on global satellite and surface data." *Global Biogeochemical Cycles* 7:811-841.

PRISM Climate Group (2022) PRISM Climate Data, Oregon State University, http://prism.oregonstate.edu, downloaded January 2022.

Pukelsheim, F. (1994) “The 3-Sigma-Rule.” American Statistician 48:88-91.

Ruddy B.C., D.L. Lorenz, and D.K. Mueller (2006) County-level estimates of nutrient inputs to the land surface of the conterminous United States, 1982-2001. Scientific Investigations Report 2006-5012. U.S Department of the Interior.

Särndal C-E, Swensson B, Wretman, J (1992) Model Assisted Survey Sampling. Springer, New York.

Scheer, C., S.J. Del Grosso, W.J. Parton, D.W. Rowlings, P.R. Grace (2013) Modeling Nitrous Oxide Emissions from Irrigated Agriculture: Testing DAYCENT with High Frequency Measurements, Ecological Applications, in press. Available online at: http://dx.doi.org/10.1890/13-0570.1.

Soil Survey Staff (2020) Gridded Soil Survey Geographic (gSSURGO) Database for the Conterminous United States. United States Department of Agriculture, Natural Resources Conservation Service, Accessed February 2020 (FY2020 official release), Available online at https://gdg.sc.egov.usda.gov/.

Towery, D. (2001) Personal Communication. Dan Towery regarding adjustments to the CTIC (1998) tillage data to reflect long-term trends, Conservation Technology Information Center, West Lafayette, IN, and Marlen Eve, National Resource Ecology Laboratory, Fort Collins, CO. February 2001.

TVA (1991 through 1992a, 1993 through 1994) Commercial Fertilizers. Tennessee Valley Authority, Muscle Shoals, AL.

USDA-ERS (2020) Agricultural Resource Management Survey (ARMS) Farm Financial and Crop Production Practices: Tailored Reports. Available online at: https://www.ers.usda.gov/data-products/arms-farm-financial-and-crop-production-practices/.

USDA-ERS (1997) Cropping Practices Survey Data—1995. Economic Research Service, United States Department of Agriculture. Available online at: http://www.ers.usda.gov/data/archive/93018/.

USDA-NASS (2023) Quick Stats. National Agricultural Statistics Service, United States Department of Agriculture, Washington, D.C., Accessed August 2023, http://quickstats.nass.usda.gov/.

USDA-NASS (2021) Published crop data layer. Available at https://nassgeodata.gmu.edu/CropScape/, Accessed July 2021, USDA-NASS, Washington, DC.

USDA-NASS (2017) 2017 Census of Agriculture. USDA National Agricultural Statistics Service, Complete data available at http://www.nass.usda.gov/AgCensus.

USDA-NASS (2012) 2012 Census of Agriculture. USDA National Agricultural Statistics Service, Complete data available at http://www.nass.usda.gov/AgCensus.

USDA-NASS (2004) Agricultural Chemical Usage: 2003 Field Crops Summary. Report AgCh1(04)a. National Agricultural Statistics Service, U.S. Department of Agriculture, Washington, D.C. Available online at: http://usda.mannlib.cornell.edu/reports/nassr/other/pcu-bb/agcs0504.pdfH.

USDA-NASS (1999) Agricultural Chemical Usage: 1998 Field Crops Summary. Report AgCH1(99). National Agricultural Statistics Service, U.S. Department of Agriculture, Washington, DC. Available online at: http://usda.mannlib.cornell.edu/reports/nassr/other/pcu-bb/agch0599.pdf.

USDA-NASS (1992) Agricultural Chemical Usage: 1991 Field Crops Summary. Report AgCh1(92). National Agricultural Statistics Service, U.S. Department of Agriculture, Washington, D.C. Available online at: http://usda.mannlib.cornell.edu/reports/nassr/other/pcu-bb/agch0392.txtH.

USDA-NRCS (2022) Conversation practice on cultivated croplands: A comparison of CEAP I and CEAP II survey data and modeling. United States Department of Agriculture, Natural Resources Conservation Service, https://www.nrcs.usda.gov/sites/default/files/2022-09/CEAP-Croplands-ConservationPracticesonCultivatedCroplands-Report-March2022.pdf.

USDA-NRCS (2020) Summary Report: 2017 National Resources Inventory. Natural Resources Conservation Service, Washington, DC, and Center for Survey Statistics and Methodology, Iowa State University, Ames, Iowa. https://www.nrcs.usda.gov/wps/portal/nrcs/main/national/technical/nra/nri/results/.

USDA-NRCS (2018) CEAP Cropland Farmer Surveys. USDA Natural Resources Conservation Service. https://www.nrcs.usda.gov/wps/portal/nrcs/detail/national/technical/nra/ceap/na/?cid=nrcs143_014163.

USDA-NRCS (2012) Assessment of the Effects of Conservation Practices on Cultivated Cropland in the Upper Mississippi River Basin. U.S. Department of Agriculture, Natural Resources Conservation Service, https://www.nrcs.usda.gov/Internet/FSE_DOCUMENTS/stelprdb1042093.pdf.

USFS (2019) Forest Inventory and Analysis Program. United States Department of Agriculture, U.S. Forest Service, https://www.fia.fs.fed.us/tools-data/default.asp.

Van Buuren, S. (2012) "Flexible imputation of missing data." Chapman & Hall/CRC, Boca Raton, FL.

Wagner-Riddle, C., Congreves, K. A., Abalos, D., Berg, A. A., Brown, S. E., Ambadan, J. T., Gao, X. & Tenuta, M. (2017) "Globally important nitrous oxide emissions from croplands induced by freeze-thaw cycles." *Nature Geosciences* 10(4): 279-283.

Wisconsin Department of Natural Resources (1993) Wisconsin Greenhouse Gas Emissions: Estimates for 1990. Bureau of Air Management, Wisconsin Department of Natural Resources, Madison, WI.

Yang, L., Jin, S., Danielson, P., Homer, C., Gass, L., Bender, S. M., Case, A., Costello, C., Dewitz, J., Fry, J., Funk, M., Granneman, B., Liknes, G. C., Rigge, M. & Xian, G. (2018) "A new generation of the United States National Land Cover Database: Requirements, research priorities, design, and implementation strategies." *ISPRS Journal of Photogrammetry and Remote Sensing* 146: 108-123.

Liming

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change. [H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (eds.)]. Hayama, Kanagawa, Japan.

Tepordei, V.V. (1994 through 2015) "Crushed Stone," In Minerals Yearbook. U.S. Department of the Interior/U.S. Geological Survey. Washington, D.C. Available online at: http://minerals.usgs.gov/minerals/.

Tepordei, V.V. (2003b) Personal communication. Valentin Tepordei, U.S. Geological Survey and ICF Consulting, August 18, 2003.

USGS (2023) Mineral Industry Surveys: Crushed Stone and Sand and Gravel in the First Quarter of 2023, U.S. Geological Survey, Reston, VA. Available online at: http://minerals.usgs.gov/minerals/pubs/commodity/stone_crushed/index.html#mis.

USGS (2022) Mineral Industry Surveys: Crushed Stone and Sand and Gravel in the First Quarter of 2022, U.S. Geological Survey, Reston, VA. Available online at: http://minerals.usgs.gov/minerals/pubs/commodity/stone_crushed/index.html#mis.

USGS (2021) Mineral Industry Surveys: Crushed Stone and Sand and Gravel in the Fourth Quarter of 2021, U.S. Geological Survey, Reston, VA. Available online at: http://minerals.usgs.gov/minerals/pubs/commodity/stone_crushed/index.html#mis.

USGS (2020) Mineral Industry Surveys: Crushed Stone and Sand and Gravel in the Fourth Quarter of 2020, U.S. Geological Survey, Reston, VA. Available online at: http://minerals.usgs.gov/minerals/pubs/commodity/stone_crushed/index.html#mis.

West, T.O., and A.C. McBride (2005) "The contribution of agricultural lime to carbon dioxide emissions in the United States: dissolution, transport, and net emissions," Agricultural Ecosystems & Environment 108:145-154.

West, T.O. (2008) Email correspondence. Tristram West, Environmental Sciences Division, Oak Ridge National Laboratory, U.S. Department of Energy and Nikhil Nadkarni, ICF International on suitability of liming emission factor for the entire United States. June 9, 2008.

Willett, J.C. (2023a) "Crushed Stone," In Minerals Yearbook 2021. U.S. Department of the Interior/U.S. Geological Survey, Washington, D.C. Available online at: https://www.usgs.gov/centers/national-minerals-information-center/crushed-stone-statistics-and-information. Accessed November 2023

Willett, J.C. (2023b) Personal communication. Jason Willett. Preliminary data tables from "Crushed Stone," In 2022 Minerals Yearbook. U.S. Department of the Interior/U.S. Geological Survey. Washington, D.C. November, 2023.

Willett, J.C. (2022a) "Crushed Stone," In Minerals Yearbook 2018. U.S. Department of the Interior/U.S. Geological Survey, Washington, D.C. Available online at: https://www.usgs.gov/centers/national-minerals-information-center/crushed-stone-statistics-and-information. Accessed October 2022.

Willett, J.C. (2022b) "Crushed Stone," In Minerals Yearbook 2019. U.S. Department of the Interior/U.S. Geological Survey, Washington, D.C. Available online at: https://www.usgs.gov/centers/national-minerals-information-center/crushed-stone-statistics-and-information. Accessed October 2022

Willett, J.C. (2022c) "Crushed Stone," In Minerals Yearbook 2020. U.S. Department of the Interior/U.S. Geological Survey, Washington, D.C. Available online at: https://www.usgs.gov/centers/national-minerals-information-center/crushed-stone-statistics-and-information. Accessed October 2022

Willett, J.C. (2022d) Personal communication. Jason Willett. Preliminary data tables from "Crushed Stone," In 2021 Minerals Yearbook. U.S. Department of the Interior/U.S. Geological Survey. Washington, D.C. October, 2022.

Willett, J.C. (2020a) "Crushed Stone," In Minerals Yearbook 2016. U.S. Department of the Interior/U.S. Geological Survey, Washington, D.C. Available online at: http://minerals.usgs.gov/minerals/pubs/commodity/stone_crushed/index.html#mis. Accessed November 2020.

Urea Fertilization

AAPFCO (2008 through 2022) Commercial Fertilizers. Association of American Plant Food Control Officials. University of Missouri. Columbia, MO.

AAPFCO (1995 through 2000a, 2002 through 2007) Commercial Fertilizers. Association of American Plant Food Control Officials. University of Kentucky. Lexington, KY.

AAPFCO (2000b) 1999-2000 Commercial Fertilizers Data, ASCII files. Available from David Terry, Secretary, AAPFCO.

EPA (2000) Preliminary Data Summary: Airport Deicing Operations (Revised). EPA-821-R-00-016. August 2000.

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change. [H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (eds.)]. Hayama, Kanagawa, Japan.

Itle, C. (2009) Email correspondence. Cortney Itle, ERG and Tom Wirth, U.S. Environmental Protection Agency on the amount of urea used in aircraft deicing. January 7, 2009.

TVA (1991 through 1994) Commercial Fertilizers. Tennessee Valley Authority, Muscle Shoals, AL.

TVA (1992b) Fertilizer Summary Data 1992. Tennessee Valley Authority, Muscle Shoals, AL.

Field Burning of Agricultural Residues

Akintoye, H.A., Agbeyi, E.O., and Olaniyan, A.B. (2005) “The effects of live mulches on tomato (Lycopersicon esculentum) yield under tropical conditions.” *Journal of Sustainable Agriculture* 26: 27-37.

Bange, M.P., Milroy, S.P., and Thongbai, P. (2004) “Growth and yield of cotton in response to waterlogging.” *Field Crops Research* 88: 129-142.

Beyaert, R.P. (1996) *The effect of cropping and tillage management on the dynamics of soil organic matter*. PhD Thesis. University of Guelph.

Bouquet, D.J., and Breitenbeck, G.A. (2000) “Nitrogen rate effect on partitioning of nitrogen and dry matter by cotton.” *Crop Science* 40: 1685-1693.

Brockwell, Peter J., and Richard A. Davis (2016) Introduction to time series and forecasting. Springer. Cantens, G. (2004 through 2005) Personal Communication. Janet Lewis, Assistant to Gaston Cantens, Vice President of Corporate Relations, Florida Crystals Company and ICF International.

Brouder, S.M., and Cassman, K.G (1990) “Root development of two cotton cultivars in relation to potassium uptake and plant growth in a vermiculitic soil.” *Field Crops Res.* 23: 187-203.

Costa, L.D., and Gianquinto, G. (2002) “Water stress and watertable depth influence yield, water use efficiency, and nitrogen recovery in bell pepper: lysimeter studies.” *Aust. J. Agric. Res.* 53: 201–210.

Crafts-Brandner, S.J., Collins, M., Sutton, T.G., and Burton, H.R. (1994) “Effect of leaf maleic hydrazide concentration on yield and dry matter partitioning in burley tobacco (Nicotiana tabacum L.).” *Field Crops Research* 37: 121-128.

De Pinheiro Henriques, A.R., and Marcelis, L.F.M. (2000) “Regulation of growth at steady-state nitrogen nutrition in lettuce (Lactuca sativa L.): Interactive effects of nitrogen and irradiance.” *Annals of Botany* 86: 1073-1080.0.

Díaz-Pérez, J.C., Silvoy, J., Phatak,S.C., Ruberson, J., and Morse, R. (2008) Effect of winter cover crops and co-till on the yield of organically-grown bell pepper (Capsicum annum L.). *Acta Hort*. 767:243-247.

Dua, K.L., and Sharma, V.K. (1976) “Dry matter production and energy contents of ten varieties of sugarcane at Muzaffarnagar (Western Uttar Pradesh).” *Tropical Ecology* 17: 45-49.

Fritschi, F.B., Roberts, B.A., Travis, R.L., Rains, D.W., and Hutmacher, R.B. (2003) “Seasonal nitrogen concentration, uptake, and partitioning pattern of irrigated Acala and Pima cotton as influenced by nitrogen fertility level.” *Crop Science* 44:516–527.

Gerik, T.J., K.L. Faver, P.M. Thaxton, and K.M. El-Zik. (1996) “Late season water stress in cotton: I. Plant growth, water use, and yield.” *Crop Science* 36: 914–921.

Gibberd, M.R., McKay, A.G., Calder, T.C., and Turner, N.C. (2003) “Limitations to carrot (Daucus carota L.) productivity when grown with reduced rates of frequent irrigation on a free-draining, sandy soil.” *Australian Journal of Agricultural Research* 54: 499-506.

Giglio, L., I. Csiszar, and C.O. Justice (2006) “Global distribution and seasonality of active fires as observed with the Terra and Aqua Moderate Resolution Imaging Spectroradiometer (MODIS) sensors” J. Geophys. Res. 111, G02016, doi:10.1029/2005JG000142.

Giglio, L., Justice, C., Boschetti, L., Roy, D. (2015) “*MCD64A1 MODIS/Terra+Aqua Burned Area Monthly L3 Global 500m SIN Grid V006* [Data set]”. NASA EOSDIS Land Processes Distributed Active Archive Center. Accessed 2023-12-05 from https://doi.org/10.5067/MODIS/MCD64A1.006.

Halevy, J. (1976) “Growth rate and nutrient uptake of two cotton cultivars grown under irrigation.” *Agronomy Journal* 68: 701-705.

Halvorson, A.D., Follett, R.F., Bartolo, M.E., and Schweissing, F.C. (2002) “Nitrogen fertilizer use efficiency of furrow-irrigated onion and corn.” *Agronomy Journal* 94: 442-449.

Heitholt, J.J., Pettigrew, W.T., and Meredith, W.R. (1992) “Light interception and lint yield of narrow-row cotton.” *Crop Science* 32: 728-733.

Hollifield, C.D., Silvertooth, J.C., and Moser, H. (2000) "Comparison of obsolete and modern cotton cultivars for irrigated production in Arizona." *2000 Arizona Cotton Report*, University of Arizona College of Agriculture, http://ag.arizona.edu/pubs/crops/az1170/.

Hopkinson, J.M. (1967) "Effects of night temperature on the growth of Nicotiana tabacum." *Australian Journal of Experimental Agriculture and Animal Husbandry* 7: 78–82.

Huett, D.O., and Dettman, E.B. (1991) Effect of nitrogen on growth, quality and nutrient uptake of cabbages grown in sand culture. *Australian Journal of Experimental Agriculture* 29: 875-81.

Huett, D.O., and Dettman, B. (1989) "Nitrogen response surface models of zucchini squash, head lettuce and potato." *Plant and Soil* 134: 243-254.

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change. [H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (eds.)]. Hayama, Kanagawa, Japan.

IPCC/UNEP/OECD/IEA (1997) *Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories.* Intergovernmental Panel on Climate Change, United Nations Environment Programme, Organization for Economic Co-Operation and Development, International Energy Agency, Paris, France.

Jacobs, J.L., Ward, G.N., and Kearney, G. (2004) "Effects of irrigation strategies and nitrogen fertilizer on turnip dry matter yield, water use efficiency, nutritive characteristics and mineral content in western Victoria." *Australian Journal of Experimental Agriculture* 44: 13-26.

Jacobs, J.L., Ward, G.N., McDowell, A.M., and Kearney, G. (2002) "Effect of seedbed cultivation techniques, variety, soil type and sowing time, on brassica dry matter yields, water use efficiency and crop nutritive characteristics in western Victoria." *Australian Journal of Experimental Agriculture* 42: 945-952.

Jacobs, J.L., Ward, G.N., McDowell, A.M., and Kearney, G.A. (2001) "A survey on the effect of establishment techniques, crop management, moisture availability and soil type on turnip dry matter yields and nutritive characteristics in western Victoria." *Australian Journal of Experimental Agriculture* 41: 743–751.

Kage, H., Alt, C., and Stűtzel, H. (2003) "Aspects of nitrogen use efficiency of cauliflower II. Productivity and nitrogen partitioning as influenced by N supply." *Journal of Agricultural Science* 141: 17–29.

Kumar, A., Singh, D.P., and Singh, P. (1994) "Influence of water stress on photosynthesis, transpiration, water-use efficiency and yield of Brassica juncea L." *Field Crops Research* 37: 95-101.

LANDFIRE (2008) Existing Vegetation Type Layer, LANDFIRE 1.1.0, U.S. Department of the Interior, Geological Survey. Accessed 28 October 2010 at http://landfire.cr.usgs.gov/viewer/.

MacLeod, L.B., Gupta, U.C., and Cutcliffe, J.A. (1971) "Effect of N, P, and K on root yield and nutrient levels in the leaves and roots of rutabagas grown in a greenhouse." *Plant and Soil* 35: 281-288.

Mahrani, A., and Aharonov, B. (1964) "Rate of nitrogen absorption and dry matter production by upland cotton grown under irrigation." *Israel J. Agric. Res.* 14: 3-9.

Marcussi, F.F.N., Bôas, R.L.V., de Godoy, L.J.G., and Goto, R. (2004) "Macronutrient accumulation and partitioning in fertigated sweet pepper plants." *Sci. Agric. (Piracicaba, Braz.)* 61: 62-68.

McCarty, J.L. (2011) "Remote Sensing-Based Estimates of Annual and Seasonal Emissions from Crop Residue Burning in the Contiguous United States." *Journal of the Air & Waste Management Association*, 61:1, 22-34, DOI: 10.3155/1047-3289.61.1.22.

McCarty, J.L. (2010) Agricultural Residue Burning in the Contiguous United States by Crop Type and State. Geographic Information Systems (GIS) Data provided to the EPA Climate Change Division by George Pouliot, Atmospheric Modeling and Analysis Division, EPA. Dr. McCarty's research was supported by the NRI Air Quality Program of the Cooperative State Research, Education, and Extension Service, USDA, under Agreement No. 20063511216669 and the NASA Earth System Science Fellowship.

McCarty, J.L. (2009) *Seasonal and Interannual Variability of Emissions from Crop Residue Burning in the Contiguous United States*. Dissertation. University of Maryland, College Park.

McPharlin, I.R., Aylmore, P.M., and Jeffery, R.C. (1992) "Response of carrots (Daucus carota L.) to applied phosphorus and phosphorus leaching on a Karrakatta sand, under two irrigation regimes." *Australian Journal of Experimental Agriculture* 32:225-232.

Mondino, M.H., Peterlin, O.A., and Garay, F. (2004) "Response of late-planted cotton to the application of growth regulator (chlorocholine chloride, CYCOCEL 75)." *Expl Agric.* 40: 381–387.

Moustakas, N.K., and Ntzanis, H. (2005) "Dry matter accumulation and nutrient uptake in flue-cured tobacco (Nicotiana tabacum L.)." *Field Crops Research* 94: 1-13.

Peach, L., Benjamin, L.R., and Mead, A. (2000) "Effects on the growth of carrots (Daucus carota L.), cabbage (Brassica oleracea var. capitata L.) and onion (Allium cepa L.) of restricting the ability of the plants to intercept resources." *Journal of Experimental Botany* 51: 605-615.

Pettigrew, W.T., and Meredith, W.R., Jr. (1997) "Dry matter production, nutrient uptake, and growth of cotton as affected by potassium fertilization." *J. Plant Nutr.* 20:531–548.

Pettigrew, W.T., Meredith, W.R., Jr., and Young, L.D. (2005) "Potassium fertilization effects on cotton lint yield, yield components, and reniform nematode populations." *Agronomy Journal* 97: 1245-1251.

PRISM Climate Group (2015) PRISM Climate Data. Oregon State University. July 24, 2015. Available online at: http://prism.oregonstate.edu.

Reid, J.B., and English, J.M. (2000) "Potential yield in carrots (Daucus carota L.): Theory, test, and an application." *Annals of Botany* 85: 593-605.

Sadras, V.O., and Wilson, L.J. (1997) "Growth analysis of cotton crops infested with spider mites: II. Partitioning of dry matter." *Crop Science* 37: 492-497.

Scholberg, J., McNeal, B.L., Jones, J.W., Boote, K.J., Stanley, C.D., and Obreza, T.A. (2000a) "Growth and canopy characteristics of field-grown tomato." *Agronomy Journal* 92: 152-159.

Scholberg, J., McNeal, B.L., Boote, K.J., Jones, J.W., Locasio, S.J., and Olson, S.M. (2000b) "Nitrogen stress effects on growth and nitrogen accumulation by field-grown tomato." *Agronomy Journal* 92:159-167.

Singels, A. and Bezuidenhout, C.N. (2002) "A new method of simulating dry matter partitioning in the Canegro sugarcane model." *Field Crops Research* 78: 151 - 164.

Sitompul, S.M., Hairiah, K., Cadisch, G., and Van Noordwuk, M. (2000) "Dynamics of density fractions of macro-organic matter after forest conversion to sugarcane and woodlots, accounted for in a modified Century model." *Netherlands Journal of Agricultural Science* 48: 61-73.

Stirling, G.R., Blair, B.L., Whittle, P.J.L., and Garside, A.L. (1999) "Lesion nematode (Pratylenchus zeae) is a component of the yield decline complex of sugarcane." In: Magarey, R.C. (Ed.), *Proceedings of the First Australasian Soilborne Disease Symposium*. Bureau of Sugar Experiment Stations, Brisbane, pp. 15–16.

Tan, D.K.Y., Wearing, A.H., Rickert, K.G., and Birch, C.J. (1999) "Broccoli yield and quality can be determined by cultivar and temperature but not photoperiod in south-east Queensland." *Australian Journal of Experimental Agriculture* 39: 901–909.

Tadesse, T., Nichols, M.A., and Fisher, K.J. (1999) Nutrient conductivity effects on sweet pepper plants grown using a nutrient film technique. 1. Yield and fruit quality. New Zealand Journal of Crop and Horticultural Science, 27: 229-237.

Torbert, H.A., and Reeves, D.W. (1994) "Fertilizer nitrogen requirements for cotton production as affected by tillage and traffic." Soil Sci. Soc. Am. J. 58:1416-1423.

USDA-NASS (2021) Published crop data layer. Available at https://nassgeodata.gmu.edu/CropScape/, Accessed July 2021, USDA-NASS, Washington, DC.

USDA-NASS (2019) Quick Stats: U.S. & All States Data; Crops; Production and Area Harvested; 1990 - 2018. National Agricultural Statistics Service, U.S. Department of Agriculture. Washington, D.C. U.S. Department of Agriculture, National Agricultural Statistics Service. Washington, D.C., Available online at: http://quickstats.nass.usda.gov/.

USDA-NRCS (2020) Summary Report: 2017 National Resources Inventory. Natural Resources Conservation Service, Washington, DC, and Center for Survey Statistics and Methodology, Iowa State University, Ames, Iowa. https://www.nrcs.usda.gov/wps/portal/nrcs/main/national/technical/nra/nri/results/.

USDA-NRCS (2018) *Summary Report: 2015 National Resources Inventory*, Natural Resources Conservation Service, Washington, D.C., and Center for Survey Statistics and Methodology, Iowa State University, Ames, Iowa. https://www.nrcs.usda.gov/Internet/FSE_DOCUMENTS/nrcseprd1422028.pdf.

Valantin, M., Gary, C., Vaissiére, B.E., and Frossard, J.S. (1999) "Effect of fruit load on partitioning of dry matter and energy in cantaloupe (Cucumis melo L.)." *Annals of Botany* 84: 173-181.

Wallach, D., Marani, A., and Kletter, E. (1978) "The relation of cotton crop growth and development to final yield." *Field Crops Research* 1: 283-294.

Wells, R., and Meredith, W.R., Jr. (1984) "Comparative growth of obsolete and modern cultivars. I. Vegetative dry matter partitioning." *Crop Science* 24: 858-872.4.

Wiedenfels, R.P. (2000) "Effects of irrigation and N fertilizer application on sugarcane yield and quality." *Field Crops Research* 43: 101-108.

Land Use, Land-Use Change, and Forestry

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change. [H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (eds.)]. Hayama, Kanagawa, Japan.

UNFCCC (2014) Report of the Conference of the Parties on its nineteenth session, held in Warsaw from 11 to 23 November 2013. United Nations Framework Convention on Climate Change, Warsaw. (FCCC/CP/2013/10/Add.3). January 31, 2014. Available online at: http://unfccc.int/resource/docs/2013/cop19/eng/10a03.pdf.

Representation of the U.S. Land Base

Alaska Department of Natural Resources (2006) Alaska Infrastructure 1:63,360. Available online at: http://dnr.alaska.gov/SpatialUtility/SUC?cmd=extract&layerid=75.

Alaska Interagency Fire Management Council (1998) Alaska Interagency Wildland Fire Management Plan. Available online at: http://agdc.usgs.gov/data/blm/fire/index.html.

Alaska Oil and Gas Conservation Commission (2009) Oil and Gas Information System. Available online at: http://doa.alaska.gov/ogc/publicdb.html.

Dewitz, J., 2023, National Land Cover Database (NLCD) 2021 Products: U.S. Geological Survey data release, https://doi.org/10.5066/P9JZ7AO3.

EIA (2011) Coal Production and Preparation Report Shapefile. Available online at: http://www.eia.gov/state/notes-sources.cfm#maps.

ESRI (2008) ESRI Data & Maps. Redlands, CA: Environmental Systems Research Institute. [CD-ROM].

Fry, J., Xian, G., Jin, S., Dewitz, J., Homer, C., Yang, L., Barnes, C., Herold, N., and J. Wickham. (2011) Completion of the 2006 National Land Cover Database for the Conterminous United States, PE&RS, Vol. 77(9):858-864.

Homer, C., J. Dewitz, J. Fry, M. Coan, N. Hossain, C. Larson, N. Herold, A. McKerrow, J.N. VanDriel and J. Wickham. (2007) Completion of the 2001 National Land Cover Database for the Conterminous United States, Photogrammetric Engineering and Remote Sensing, Vol. 73, No. 4, pp 337-341.

Homer, C.G., Dewitz, J.A., Yang, L., Jin, S., Danielson, P., Xian, G., Coulston, J., Herold, N.D., Wickham, J.D., and Megown, K. (2015) Completion of the 2011 National Land Cover Database for the conterminous United States-Representing a decade of land cover change information. Photogrammetric Engineering and Remote Sensing, v. 81, no. 5, p. 345-354.

IPCC (2019) *2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories*, Calvo Buendia, E., Tanabe, K., Kranjc, A., Baasansuren, J., Fukuda, M., Ngarize S., Osako, A., Pyrozhenko, Y., Shermanau, P. and Federici, S. (eds). Published: IPCC, Switzerland.

IPCC (2014) *2013 Supplement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories: Wetlands*. Hiraishi, T., Krug, T., Tanabe, K., Srivastava, N., Baasansuren, J., Fukuda, M. and Troxler, T.G. (eds.). Published: IPCC, Switzerland.

IPCC (2010) Revisiting the use of managed land as a proxy for estimating national anthropogenic emissions and removals. [Eggleston HS, Srivastava N, Tanabe K, Baasansuren J, (eds.)]. Institute for Global Environmental Studies, Intergovernmental Panel on Climate Change, Hayama, Kanagawa, Japan.

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories.* The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change. [H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (eds.)]. Hayama, Kanagawa, Japan.

Jin, S., L. Yang, P. Danielson, C. Homer, J. Fry, and G. Xian. (2013) A comprehensive change detection method for updating the National Land Cover Database to circa 2011. Remote Sensing of Environment, 132: 159-175.

Nelson, M.D., Riitters, K.H., Coulston, J.W., Domke, G.M., Greenfield, E.J., Langner, L.L., Nowak, D.J., O'Dea, C.B., Oswalt, S.N., Reeves, M.C. and Wear, D.N. (2020) Defining the United States land base: a technical document supporting the USDA Forest Service 2020 RPA assessment. Gen. Tech. Rep. NRS-191., 191, pp.1-70.

NOAA Coastal Change Analysis Program (C-CAP) Regional Land Cover Database. Data collected 1995-present Charleston, SC: National Oceanic and Atmospheric Administration (NOAA) Coastal Services Center. Data accessed at: www.csc.noaa.gov/landcover.

Nusser, S.M. and J.J. Goebel (1997) "The national resources inventory: a long-term multi-resource monitoring programme." Environmental and Ecological Statistics 4:181-204.

Ogle, S.M., G. Domke, W.A. Kurz, M.T. Rocha, T. Huffman, A. Swan, J.E. Smith, C. Woodall, T. Krug (2018) Delineating managed land for reporting greenhouse gas emissions and removals to the United Nations Framework Convention on Climate Change. Carbon Balance and Management 13:9.

U.S. Census Bureau (2010) Topologically Integrated Geographic Encoding and Referencing (TIGER) system shapefiles. U.S. Census Bureau, Washington, D.C. Available online at: http://www.census.gov/geo/www/tiger.

U.S. Department of Agriculture (2015) County Data - Livestock, 1990-2014. U.S. Department of Agriculture, National Agriculture Statistics Service, Washington, D.C.

U.S. Department of Agriculture, Forest Service. (2023) Timber Product Output (TPO) Reports. https://www.fia.fs.usda.gov/program-features/tpo/

U.S. Department of Interior (2005) Federal Lands of the United States. National Atlas of the United States, U.S. Department of the Interior, Washington D.C. Available online at: http://nationalatlas.gov/atlasftp.html?openChapters=chpbound#chpbound.

United States Geological Survey (USGS), Gap Analysis Program (2012) Protected Areas Database of the United States (PADUS), version 1.3 Combined Feature Class. November 2012.

USGS (2012) Alaska Resource Data File. Available online at: http://ardf.wr.usgs.gov/.

USGS (2005) Active Mines and Mineral Processing Plants in the United States in 2003. U.S. Geological Survey, Reston, VA.

Yang, L., Jin, S., Danielson, P., Homer, C., Gass, L., Bender, S. M., Case, A., Costello, C., Dewitz, J., Fry, J., Funk, M., Granneman, B., Liknes, G. C., Rigge, M. & Xian, G. (2018) A new generation of the United States National Land Cover Database: Requirements, research priorities, design, and implementation strategies. ISPRS Journal of Photogrammetry and Remote Sensing 146: 108-123.

Forest Land Remaining Forest Land: Changes in Forest Carbon Stocks

AF&PA (2006a and earlier) Statistical roundup. (Monthly). Washington, D.C. American Forest & Paper Association.

AF&PA (2006b and earlier) Statistics of paper, paperboard and wood pulp. Washington, D.C. American Forest & Paper Association.

AF&PA (2021) 2020 Statistics – Paper Industry – Annual Summary Data Through 2020. Washington, D.C.: American Forest and Paper Association, 54 p.

AF&PA (2023) Capacity & Fiber Consumption Survey – Paper Industry – 63rd Annual 2022-2023. Washington, D.C.: American Forest and Paper Association, 44 p.

Amichev, B.Y. and J.M. Galbraith (2004) "A Revised Methodology for Estimation of Forest Soil Carbon from Spatial Soils and Forest Inventory Data Sets." Environmental Management 33(Suppl. 1):S74-S86.

Bechtold, W.A.; Patterson, P.L. (2005) The enhanced forest inventory and analysis program—national sampling design and estimation procedures. Gen. Tech. Rep. SRS-80. Asheville, NC: U.S. Department of Agriculture Forest Service, Southern Research Station. 85 p.

Birdsey, R. (1996) "Carbon Storage for Major Forest Types and Regions in the Conterminous United States." In R.N. Sampson and D. Hair, (eds.). Forest and Global Change, Volume 2: Forest Management Opportunities for Mitigating Carbon Emissions. American Forests. Washington, D.C., 1-26 and 261-379 (appendices 262 and 263).

Coulston, J.W., Wear, D.N., and Vose, J.M. (2015) Complex forest dynamics indicate potential for slowing carbon accumulation in the southeastern United States. Scientific Reports. 5: 8002.

Deenik J, McClellan AT (2007) Soils of Hawai'i. Soil and Crop Management, SCM-20. College of Tropical Agriculture and Human Resources, University of Hawai'i at Manoa, Honolulu.

Domke, G.M., Perry, C.H., Walters, B.F., Woodall, C.W., and Smith, J.E. (2016) A framework for estimating litter carbon stocks in forests of the United States. Science of the Total Environment 557–558: 469–478.

Domke, G.M., Perry, C.H., Walters, B.F., Woodall, C.W., Nave, L., Swanston, C. (2017) Toward inventory-based estimates of soil organic carbon in forests of the United States. Ecological Applications. 27(4), 1223-1235.

Domke, G.M., Walters, B.F., Smith, J.E., Woodall, C.W. (2022) Chapter 6: FIA Carbon Attributes. In Sampling and estimation documentation for the Enhanced Forest Inventory and Analysis Program: 2022. Westfall, J.A., Coulston, J.W., Moisen, G.G., Andersen, H.-E., eds. Gen. Tech. Rep. NRS-GTR-207, Madison, WI: U.S. Department of Agriculture, Forest Service, Northern Research Station. 129 p. https://doi.org/10.2737/NRS-GTR-207.

Domke, G.M., Woodall, C.W., Smith, J.E., Westfall, J.A., McRoberts, R.E. (2012) Consequences of alternative tree-level biomass estimation procedures on U.S. forest carbon stock estimates. Forest Ecology and Management. 270: 108-116.

Domke, G.M., Woodall, C.W., Walters, B.F., Smith, J.E. (2013) From models to measurements: comparing down dead wood carbon stock estimates in the U.S. forest inventory. PLoS ONE 8(3): e59949.

EPA (2006) Municipal solid waste in the United States: 2005 Facts and figures. Office of Solid Waste, U.S. Environmental Protection Agency. Washington, D.C. (5306P) EPA530-R-06-011. Available online at: http://www.epa.gov/msw/msw99.htm.

FAO. Forestry Production and Trade. License: CC BY-NC-SA 3.0 IGO. Extracted from: https://www.fao.org/faostat/en/#data/FO. Data of Access: 13-09-2023.

Frayer, W.E., and G.M. Furnival (1999) "Forest Survey Sampling Designs: A History." Journal of Forestry 97(12): 4-10.

Freed, R. (2004) Open-dump and Landfill timeline spreadsheet (unpublished). ICF International. Washington, D.C.

Hair, D. (1958) "Historical forestry statistics of the United States." Statistical Bull. 228. U.S. Department of Agriculture Forest Service, Washington, D.C.

Hair. D. and A.H. Ulrich (1963) The Demand and price situation for forest products – 1963. U.S. Department of Agriculture Forest Service, Misc Publication No. 953. Washington, D.C.

Harmon, M.E., C.W. Woodall, B. Fasth, J. Sexton, M. Yatkov. (2011) Differences between standing and downed dead tree wood density reduction factors: A comparison across decay classes and tree species. Res. Paper. NRS-15. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northern Research Station. 40 p.

Howard, J. L. and Liang, S. (2019) U.S. timber production, trade, consumption, and price statistics 1965 to 2017. Res. Pap. FPL-RP-701. Madison, WI: USDA, Forest Service, Forest Products Laboratory.

Howard, J. L. and Jones, K.C. (2016) U.S. timber production, trade, consumption, and price statistics 1965 to 2013. Res. Pap. FPL-RP-679. Madison, WI: USDA, Forest Service, Forest Products Laboratory.

Howard, J. L. (2007) U.S. timber production, trade, consumption, and price statistics 1965 to 2005. Res. Pap. FPL-RP-637. Madison, WI: USDA, Forest Service, Forest Products Laboratory.

Howard, J. L. (2003) U.S. timber production, trade, consumption, and price statistics 1965 to 2002. Res. Pap. FPL-RP-615. Madison, WI: USDA, Forest Service, Forest Products Laboratory. Available online at: http://www.fpl.fs.fed.us/documnts/fplrp/fplrp615/fplrp615.pdf.

IPCC (2014) *2013 Supplement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories: Wetlands*. [Hiraishi, T., Krug, T., Tanabe, K., Srivastava, N., Baasansuren, J., Fukuda, M., and Troxler, T.G. (eds.)]. Switzerland.

IPCC (2007) *Climate Change 2007: The Physical Science Basis*. Contribution of Working Group I to the *Fourth Assessment Report* of the Intergovernmental Panel on Climate Change [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 996 pp.

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change. [H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (eds.)]. Hayama, Kanagawa, Japan.

Jandl, R., Rodeghiero, M., Martinez, C., Cotrufo, M. F., Bampa, F., van Wesemael, B., Harrison, R.B., Guerrini, I.A., deB Richter Jr., D., Rustad, L., Lorenz, K., Chabbi, A., Miglietta, F. (2014) Current status, uncertainty and future needs in soil organic carbon monitoring. Science of the Total Environment, 468, 376-383.

Jenkins, J.C., D.C. Chojnacky, L.S. Heath, and R.A. Birdsey (2003) "National-scale biomass estimators for United States tree species." Forest Science 49(1):12-35.

Johnson, K. Domke, G.M., Russell, M.B., Walters, B.F., Hom, J., Peduzzi, A., Birdsey, R., Dolan, K., Huang, W. (2017) Estimating aboveground live understory vegetation carbon in the United States. Environmental Research Letters.

Johnson, M.G. and Kern, J.S., (2002.) Quantifying the organic carbon held in forested soils of the United States and Puerto Rico. The potential of US forest soils to sequester and mitigate the greenhouse effect, Lewis, Boca Raton, pp.47-72.

Nelson, M.D., Riitters, K.H., Coulston, J.W., Domke, G.M., Greenfield, E.J., Langner, L.L., Nowak, D.J., O'Dea, C.B., Oswalt, S.N., Reeves, M.C. and Wear, D.N. (2020) Defining the United States land base: a technical document supporting the USDA Forest Service 2020 RPA assessment. Gen. Tech. Rep. NRS-191., 191, pp.1-70.

Ogle, S. M., G. M. Domke, W. A. Kurz, M. T. Rocha, T. Huffman, A. Swan, J. E. Smith, C. W. Woodall, and T. Krug. (2018) Delineating managed land for reporting national greenhouse gas emissions and removals to the United Nations framework convention on climate change. Carbon Balance and Management 13:9.

O'Neill, K.P., Amacher, M.C., Perry, C.H. (2005) Soils as an indicator of forest health: a guide to the collection, analysis, and interpretation of soil indicator data in the Forest Inventory and Analysis program. Gen. Tech. Rep. NC-258. St. Paul, MN: U.S. Department of Agriculture, Forest Service, North Central Research Station. 53 p.

Oswalt, S.N., Brandeis, T.J. and Woodall, C.W., (2008). Contribution of dead wood to biomass and carbon stocks in the Caribbean: St. John, US Virgin Islands. Biotropica, 40(1), pp.20-27.

Oswalt, S.N., Smith, W.B., Miles, P.D. and Pugh, S.A. (2019) Forest resources of the United States, 2017: A technical document supporting the Forest Service 2020 RPA Assessment. Gen. Tech. Rep. WO-97. Washington, DC: U.S. Department of Agriculture, Forest Service, Washington Office., 97.

Perry, C.H., C.W. Woodall, and M. Schoeneberger (2005) Inventorying trees in agricultural landscapes: towards an accounting of "working trees". In: "Moving Agroforestry into the Mainstream." Proc. 9th N. Am. Agroforestry Conf., Brooks, K.N. and Folliott, P.F. (eds.). 12-15 June 2005, Rochester, MN [CD-ROM]. Dept. of Forest Resources, Univ. Minnesota, St. Paul, MN, 12 p. Available online at: http://cinram.umn.edu/afta2005/. (verified 23 Sept 2006).

Russell, M.B.; D'Amato, A.W.; Schulz, B.K.; Woodall, C.W.; Domke, G.M.; Bradford, J.B. (2014) Quantifying understory vegetation in the U.S. Lake States: a proposed framework to inform regional forest carbon stocks. Forestry. 87: 629-638.

Russell, M.B.; Domke, G.M.; Woodall, C.W.; D'Amato, A.W. (2015) Comparisons of allometric and climate-derived estimates of tree coarse root carbon in forests of the United States. Carbon Balance and Management. 10: 20.

Selmants, P.C., Giardina, C.P., Jacobi, J.D., and Zhu, Zhiliang, eds. (2017) Baseline and projected future carbon storage and carbon fluxes in ecosystems of Hawai'i: U.S. Geological Survey Professional Paper 1834, 134 p., https://doi.org/10.3133/pp1834.

Skog, K.E. (2008) Sequestration of carbon in harvested wood products for the United States. Forest Products Journal 58:56-72.

Smith, J.E., Domke, G.M. and Woodall, C.W. (2022) Predicting downed woody material carbon stocks in forests of the conterminous United States. Science of the Total Environment, 803, p.150061.

Smith, J.E., L.S. Heath, and M.C. Nichols (2010) U.S. Forest Carbon Calculation Tool User's Guide: Forestland Carbon Stocks and Net Annual Stock Change. General Technical Report NRS-13 revised, U.S. Department of Agriculture Forest Service, Northern Research Station, 34 p.

Smith, J.E.; Heath, L.S.; Skog, K.E.; Birdsey, R.A. (2006) Methods for calculating forest ecosystem and harvested carbon with standard estimates for forest types of the United States. Gen. Tech. Rep. NE-343. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northeastern Research Station. 216 p.

Smith, W. B., P. D. Miles, C. H. Perry, and S. A. Pugh (2009) Forest Resources of the United States, 2007. General Technical Report WO-78, U.S. Department of Agriculture Forest Service, Washington Office.

Soil Survey Staff (2020a) Gridded National Soil Survey Geographic (gNATSGO) Database for the Conterminous United States. United States Department of Agriculture, Natural Resources Conservation Service. Available online at https://nrcs.app.box.com/v/soils.

Soil Survey Staff (2020b) Gridded National Soil Survey Geographic (gNATSGO) Database for Alaska. United States Department of Agriculture, Natural Resources Conservation Service. Available online at https://nrcs.app.box.com/v/soils.

Steer, Henry B. (1948) Lumber production in the United States. Misc. Pub. 669, U.S. Department of Agriculture Forest Service. Washington, D.C.

Ulrich, Alice (1985) U.S. Timber Production, Trade, Consumption, and Price Statistics 1950-1985. Misc. Pub. 1453, U.S. Department of Agriculture Forest Service. Washington, D.C.

Ulrich, Alice (1989) U.S. Timber Production, Trade, Consumption, and Price Statistics, 1950-1987. USDA Miscellaneous Publication No. 1471, U.S. Department of Agriculture Forest Service. Washington, D.C., 77.

United Nations Framework Convention on Climate Change (UNFCC) (2013) Report on the individual review of the inventory submission of the United States of America submitted in 2012. FCCC/ARR/2012/USA. 42 p.

USDA Forest Service (2022a) PNW-FIA Hawai'i Inventory Database. Last accessed: 28 September 2023. https://www.fs.usda.gov/research/pnw/products/dataandtools/tools/pnw-fia-hawaii-inventory-database

USDA Forest Service (2022b) PNW-FIA Pacific Islands Inventory Database. Last accessed: 28 September 2023. https://www.fs.usda.gov/research/pnw/products/dataandtools/tools/pnw-fia-pacific-islands-database https://www.fs.usda.gov/research/pnw/products/dataandtools/tools/pnw-fia-hawaii-inventory-database

USDA Forest Service (2023a) Forest Inventory and Analysis National Program: Program Features. U.S. Department of Agriculture Forest Service. Washington, D.C. Available online at: https://www.fia.fs.usda.gov/program-features/index.php. Accessed 28 September 2023.

USDA Forest Service. (2023b) Forest Inventory and Analysis National Program: FIA Data Mart. U.S. Department of Agriculture Forest Service. Washington, D.C. Available online at: https://apps.fs.usda.gov/fia/datamart/datamart.html. Accessed on 28 September 2023.

USDA Forest Service. (2023c) Forest Inventory and Analysis National Program, FIA library: Field Guides, Methods and Procedures. U.S. Department of Agriculture Forest Service. Washington, D.C. Available online at: https://www.fia.fs.usda.gov/library/field-guides-methods-proc/index.php. Accessed on 28 September 2023.

USDA Forest Service (2023d) Forest Inventory and Analysis National Program, FIA library: Database Documentation. U.S. Department of Agriculture, Forest Service, Washington Office. Available online at: https://www.fia.fs.usda.gov/library/database-documentation/index.php. Accessed on 28 September 2023.

U.S. Census Bureau (1976) Historical Statistics of the United States, Colonial Times to 1970, Vol. 1. Washington, D.C.

Wear, D.N., Coulston, J.W. (2015) From sink to source: Regional variation in U.S. forest carbon futures. Scientific Reports. 5: 16518.

Westfall, J.A., Coulston, J.W., Gray, A.N., Shaw, J.D., Radtke, P.J., Walker, D.M., Weiskittel, A.R., MacFarlane, D.W., Affleck, D.L.R., Zhao, D., Temesgen, H., Poudel, K.P., Frank, J.M., Prisley, S.P., Wang, Y., Sánchez Meador, A.J., Auty, D., and Domke, G.M. In press . A national-scale tree volume, biomass, and carbon modeling system for the United States. Gen. Tech. Rep. WO-104. Washington, DC: U.S. Department of Agriculture, Forest Service. 60 p. https//doi.org/10.2737/WO-GTR-104.

Westfall, J.A., Woodall, C.W., Hatfield, M.A. (2013) A statistical power analysis of woody carbon flux from forest inventory data. Climatic Change. 118: 919-931.

Woodall, C.W., Amacher, M.C., Bechtold, W.A., Coulston, J.W., Jovan, S., Perry, C.H., Randolph, K.C., Schulz, B.K., Smith, G.C., Tkacz, B., Will-Wolf, S. (2011b) "Status and future of the forest health indicators program of the United States." Environmental Monitoring and Assessment. 177: 419-436.

Woodall, C.W., and V.J. Monleon (2008) Sampling protocol, estimation, and analysis procedures for the down woody materials indicator of the FIA program. Gen. Tech. Rep. NRS-22. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northern Research Station. 68 p.

Woodall, C.W., Coulston, J.W., Domke, G.M., Walters, B.F., Wear, D.N., Smith, J.E., Anderson, H.-E., Clough, B.J., Cohen, W.B., Griffith, D.M., Hagan, S.C., Hanou, I.S.; Nichols, M.C., Perry, C.H., Russell, M.B., Westfall, J.A., Wilson, B.T. (2015a) The U.S. Forest Carbon Accounting Framework: Stocks and Stock change 1990-2016. Gen. Tech. Rep. NRS-154. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northern Research Station. 49 pp.

Woodall, C.W., L.S. Heath, G.M. Domke, and M.C. Nichols (2011a) Methods and equations for estimating aboveground volume, biomass, and carbon for trees in the U.S. forest inventory, 2010. Gen. Tech. Rep. NRS-88. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northern Research Station. 30 p.

Woodall, C.W., Walters, B.F., Coulston, J.W., D'Amato, A.W., Domke, G.M., Russell, M.B., Sowers, P.A. (2015b) Monitoring network confirms land use change is a substantial component of the forest carbon sink in the eastern United States. Scientific Reports. 5: 17028.

Woodall, C.W., Walters, B.F., Oswalt, S.N., Domke, G.M., Toney, C., Gray, A.N. (2013) Biomass and carbon attributes of downed woody materials in forests of the United States. Forest Ecology and Management 305: 48-59.

Zhu, Zhiliang, and McGuire, A.D., eds. (2016) Baseline and projected future carbon storage and greenhouse-gas fluxes in ecosystems of Alaska: U.S. Geological Survey Professional Paper 1826, 196 p., Available online at: http://dx.doi.org/10.3133/pp1826.

Forest Land Remaining Forest Land: Non-CO_2 Emissions from Forest Fires

Eidenshink, J., Schwind, B., Brewer, K., Zhu, Z.L., Quayle, B. and Howard, S. (2007) A project for monitoring trends in burn severity. Fire ecology, 3(1), pp.3-21.

French, N.H.F., W.J. de Groot, L.K. Jenkins, B.M. Rogers, E.C. Alvarado, B. Amiro, B. de Jong, S. Goetz, E. Hoy, E. Hyer, R. Keane, D. McKenzie, S.G. McNulty, B.E Law, R. Ottmar, D.R. Perez-Salicrup, J. Randerson, K.M. Robertson, and M. Turetsky (2011) "Model comparisons for estimating carbon emissions from North American wildland fire." Journal of Geophysical Research 116. 10.1029/2010JG001469

French, N.H.F., D. McKenzie, T. Erickson, B. Koziol, M. Billmire, K.A. Endsley, N.K.Y. Scheinerman, L. Jenkins, M.E. Miller, R. Ottmar, and S. Prichard (2014) "Modeling regional-scale fire emissions with the Wildland Fire Emissions Information System." Earth Interactions 18, no. 16

Giglio, L., Boschetti, L., Roy, D. P., Humber, M. L., and Justice, C. O. (2018) The Collection 6 MODIS burned area mapping algorithm and product. Remote Sensing of Environment, 217, 72-85.

IPCC (2019) Chapter 2: Generic Methodologies Applicable to Multiple Land-Use Categories. Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories, Calvo Buendia, E., Tanabe, K., Kranjc, A., Baasansuren, J., Fukuda, M., Ngarize, S., Osako, A., Pyrozhenko, Y., Shermanau, P. and Federici, S. (eds). Published: IPCC, Switzerland.

IPCC (2013) *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1535 pp.

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change. [H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (eds.)]. Hayama, Kanagawa, Japan.

Larkin, N. K., S. Raffuse, and T. T. Strand (2014) Wildland fire emissions, carbon, and climate: U.S. emissions inventories. For. Ecol. Manage. 317:61–69. doi:10.1016/j.foreco.2013.09.012.

MTBS Data Access: Fire Level Geospatial Data (August 2023) MTBS Project (USDA Forest Service/U.S. Geological Survey). Available online at: http://mtbs.gov/direct-download. Accessed on 15 August 2023.

Ogle, S. M., G. M. Domke, W. A. Kurz, M. T. Rocha, T. Huffman, A. Swan, J. E. Smith, C. W. Woodall, and T. Krug. (2018) Delineating managed land for reporting national greenhouse gas emissions and removals to the United Nations framework convention on climate change. Carbon Balance and Management 13:9.

WFEIS (2023) Wildland Fire Emissions Inventory System, home page. https://wfeis.mtri.org/.

WFIGS (2023) WFIGS, The Wildland Fire Interagency Geospatial Service Interagency Fire Perimeters. National Interagency Fire Center. https://data-nifc.opendata.arcgis.com/datasets/nifc::wfigs-interagency-fire-perimeters/explore?location=0.000000%2C0.000000%2C1.82.

Forest Land Remaining Forest Land: N_2O Emissions from Soils

Albaugh, T.J., Allen, H.L., Fox, T.R. (2007) Historical Patterns of Forest Fertilization in the Southeastern United States from 1969 to 2004. Southern Journal of Applied Forestry, 31, 129-137(9).

Binkley, D. (2004) Email correspondence regarding the 95 percent confidence interval for area estimates of southern pine plantations receiving N fertilizer (±20%) and the rate applied for areas receiving N fertilizer (100 to 200 pounds/acre). Dan Binkley, Department of Forest, Rangeland, and Watershed Stewardship, Colorado State University and Stephen Del Grosso, Natural Resource Ecology Laboratory, Colorado State University. September 19, 2004.

Binkley, D., R. Carter, and H.L. Allen (1995) Nitrogen Fertilization Practices in Forestry. In: Nitrogen Fertilization in the Environment, P.E. Bacon (ed.), Marcel Decker, Inc., New York.

Briggs, D. (2007) Management Practices on Pacific Northwest West-Side Industrial Forest Lands, 1991-2005: With Projections to 2010. Stand Management Cooperative, SMC Working Paper Number 6, College of Forest Resources, University of Washington, Seattle.

Fox, T.R., H. L. Allen, T.J. Albaugh, R. Rubilar, and C.A. Carlson (2007) Tree Nutrition and Forest Fertilization of Pine Plantations in the Southern United States. Southern Journal of Applied Forestry, 31, 5-11.

IPCC (2006) 2006 IPCC Guidelines for National Greenhouse Gas Inventories. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change. [H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (eds.)]. Hayama, Kanagawa, Japan.

USDA Forest Service (2001) U.S. Forest Facts and Historical Trends. FS-696. U.S. Department of Agriculture Forest Service, Washington, D.C. Available online at: http://www.fia.fs.fed.us/library/ForestFactsMetric.pdf.

Forest Land Remaining Forest Land: Drained Organic Soils

IPCC (2014) *2013 Supplement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories: Wetlands*, Hiraishi, T., Krug, T., Tanabe, K., Srivastava, N., Baasansuren, J., Fukuda, M. and Troxler, T.G. (eds.). Published: IPCC, Switzerland.

IPCC (2013) *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1535 pp.

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change, H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (eds.). Hayama, Kanagawa, Japan.

STATSGO2 (2016) Soil Survey Staff, Natural Resources Conservation Service, United States Department of Agriculture. U.S. General Soil Map (STATSGO2). Available online at https://sdmdataaccess.sc.egov.usda.gov. Accessed 10 November 2016.

USDA Forest Service (2023) Forest Inventory and Analysis National Program: FIA Data Mart. U.S. Department of Agriculture Forest Service. Washington, DC; 2015. Available online at https://apps.fs.usda.gov/fia/datamart/datamart.html. Accessed 30 March 2022.

USDA Forest Service (2022) Forest Inventory and Analysis National Program: FIA Data Mart. U.S. Department of Agriculture Forest Service. Washington, DC; 2015. Available online at https://apps.fs.usda.gov/fia/datamart/datamart.html. Accessed 30 March 2022.

Land Converted to Forest Land

Birdsey, R. (1996) "Carbon Storage for Major Forest Types and Regions in the Conterminous United States." In R.N. Sampson and D. Hair, (eds.). Forest and Global Change, Volume 2: Forest Management Opportunities for Mitigating Carbon Emissions. American Forests. Washington, D.C., 1-26 and 261-379 (appendices 262 and 263).

Brockwell, Peter J., and Richard A. Davis (2016) Introduction to time series and forecasting. Springer.

Domke, G.M., Perry, C.H., Walters, B.F., Woodall, C.W., and Smith, J.E. (2016) A framework for estimating litter carbon stocks in forests of the United States. Science of the Total Environment 557–558: 469–478.

Domke, G.M., Woodall, C.W., Walters, B.F., Smith, J.E. (2013) From models to measurements: comparing down dead wood carbon stock estimates in the U.S. forest inventory. PLoS ONE 8(3): e59949.

Harmon, M.E., C.W. Woodall, B. Fasth, J. Sexton, M. Yatkov. (2011) Differences between standing and downed dead tree wood density reduction factors: A comparison across decay classes and tree species. Res. Paper. NRS-15. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northern Research Station. 40 p.

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change. [H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (eds.)]. Hayama, Kanagawa, Japan.

Jenkins, J.C., D.C. Chojnacky, L.S. Heath, and R.A. Birdsey (2003) "National-scale biomass estimators for United States tree species." Forest Science 49(1):12-35.Ogle, S.M., M.D. Eve, F.J. Breidt, and K. Paustian (2003) "Uncertainty in estimating land use and management impacts on soil organic carbon storage for U.S. agroecosystems between 1982 and 1997." Global Change Biology 9:1521-1542.

Ogle, S.M., F.J. Breidt, and K. Paustian. (2006) "Bias and variance in model results due to spatial scaling of measurements for parameterization in regional assessments." Global Change Biology 12:516-523.

Smith, J.E.; Heath, L.S.; Skog, K.E.; Birdsey, R.A. (2006) Methods for calculating forest ecosystem and harvested carbon with standard estimates for forest types of the United States. Gen. Tech. Rep. NE-343. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northeastern Research Station. 216 p.

USDA Forest Service (2023a) Forest Inventory and Analysis National Program: FIA Data Mart. U.S. Department of Agriculture Forest Service. Washington, D.C. Available online at: https://apps.fs.usda.gov/fia/datamart/datamart.html. Accessed on 29 September 2023.

USDA Forest Service (2023b) Forest Inventory and Analysis National Program, FIA library: Field Guides, Methods and Procedures. U.S. Department of Agriculture Forest Service. Washington, D.C. Available online at: https://www.fia.fs.usda.gov/library/field-guides-methods-proc/index.php. Accessed on 29 September 2023.

USDA-NRCS (2018) Summary Report: 2015 National Resources Inventory, Natural Resources Conservation Service, Washington, D.C., and Center for Survey Statistics and Methodology, Iowa State University, Ames, Iowa. https://www.nrcs.usda.gov/Internet/FSE_DOCUMENTS/nrcseprd1422028.pdf.

USDA-NRCS (1997) "National Soil Survey Laboratory Characterization Data," Digital Data, Natural Resources Conservation Service, U.S. Department of Agriculture. Lincoln, NE.

Westfall, J.A., Coulston, J.W., Gray, A.N., Shaw, J.D., Radtke, P.J., Walker, D.M., Weiskittel, A.R., MacFarlane, D.W., Affleck, D.L.R., Zhao, D., Temesgen, H., Poudel, K.P., Frank, J.M., Prisley, S.P., Wang, Y., Sánchez Meador, A.J., Auty, D., and Domke, G.M. 2023. A national-scale tree volume, biomass, and carbon modeling system for the United States. Gen. Tech. Rep. WO-104.

Woodall, C.W., L.S. Heath, G.M. Domke, and M.C. Nichols (2011a) Methods and equations for estimating aboveground volume, biomass, and carbon for trees in the U.S. forest inventory, 2010. Gen. Tech. Rep. NRS-88. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northern Research Station. 30 p.

Woodall, C.W., and V.J. Monleon (2008) Sampling protocol, estimation, and analysis procedures for the down woody materials indicator of the FIA program. Gen. Tech. Rep. NRS-22. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northern Research Station. 68 p.

Woodall, C.W., Walters, B.F., Coulston, J.W., D'Amato, A.W., Domke, G.M., Russell, M.B., Sowers, P.A. (2015b) Monitoring network confirms land use change is a substantial component of the forest carbon sink in the eastern United States. Scientific Reports. 5: 17028.

Woodall, C.W., Walters, B.F., Oswalt, S.N., Domke, G.M., Toney, C., Gray, A.N. (2013) Biomass and carbon attributes of downed woody materials in forests of the United States. Forest Ecology and Management 305: 48-59.

Yang, L., Jin, S., Danielson, P., Homer, C., Gass, L., Bender, S. M., Case, A., Costello, C., Dewitz, J., Fry, J., Funk, M., Granneman, B., Liknes, G. C., Rigge, M. & Xian, G. (2018) A new generation of the United States National Land Cover Database: Requirements, research priorities, design, and implementation strategies. ISPRS Journal of Photogrammetry and Remote Sensing 146: 108-123.

Land Converted to Forest Land

Birdsey, R. (1996) "Carbon Storage for Major Forest Types and Regions in the Conterminous United States." In R.N. Sampson and D. Hair, (eds.). Forest and Global Change, Volume 2: Forest Management Opportunities for Mitigating Carbon Emissions. American Forests. Washington, D.C., 1-26 and 261-379 (appendices 262 and 263).

Brockwell, Peter J., and Richard A. Davis (2016) Introduction to time series and forecasting. Springer.

Domke, G.M., Perry, C.H., Walters, B.F., Woodall, C.W., and Smith, J.E. (2016) A framework for estimating litter carbon stocks in forests of the United States. Science of the Total Environment 557–558: 469–478.

Domke, G.M., Woodall, C.W., Walters, B.F., Smith, J.E. (2013) From models to measurements: comparing down dead wood carbon stock estimates in the U.S. forest inventory. PLoS ONE 8(3): e59949.

Harmon, M.E., C.W. Woodall, B. Fasth, J. Sexton, M. Yatkov. (2011) Differences between standing and downed dead tree wood density reduction factors: A comparison across decay classes and tree species. Res. Paper. NRS-15. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northern Research Station. 40 p.

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change. [H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (eds.)]. Hayama, Kanagawa, Japan.

Jenkins, J.C., D.C. Chojnacky, L.S. Heath, and R.A. Birdsey (2003) "National-scale biomass estimators for United States tree species." Forest Science 49(1):12-35.Ogle, S.M., M.D. Eve, F.J. Breidt, and K. Paustian (2003) "Uncertainty in estimating land use and management impacts on soil organic carbon storage for U.S. agroecosystems between 1982 and 1997." Global Change Biology 9:1521-1542.

Ogle, S.M., F.J. Breidt, and K. Paustian. (2006) "Bias and variance in model results due to spatial scaling of measurements for parameterization in regional assessments." Global Change Biology 12:516-523.

Smith, J.E.; Heath, L.S.; Skog, K.E.; Birdsey, R.A. (2006) Methods for calculating forest ecosystem and harvested carbon with standard estimates for forest types of the United States. Gen. Tech. Rep. NE-343. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northeastern Research Station. 216 p.

USDA Forest Service (2023b) Forest Inventory and Analysis National Program: FIA Data Mart. U.S. Department of Agriculture Forest Service. Washington, D.C. Available online at: https://apps.fs.usda.gov/fia/datamart/datamart.html. Accessed on 29 September 2023.

USDA Forest Service (2023c) Forest Inventory and Analysis National Program, FIA library: Field Guides, Methods and Procedures. U.S. Department of Agriculture Forest Service. Washington, D.C. Available online at: https://www.fia.fs.usda.gov/library/field-guides-methods-proc/index.php. Accessed on 29 September 2023.

USDA-NRCS (2020) Summary Report: 2017 National Resources Inventory. Natural Resources Conservation Service, Washington, DC, and Center for Survey Statistics and Methodology, Iowa State University, Ames, Iowa. https://www.nrcs.usda.gov/wps/portal/nrcs/main/national/technical/nra/nri/results/.

USDA-NRCS (2018) Summary Report: 2015 National Resources Inventory, Natural Resources Conservation Service, Washington, D.C., and Center for Survey Statistics and Methodology, Iowa State University, Ames, Iowa. https://www.nrcs.usda.gov/Internet/FSE_DOCUMENTS/nrcseprd1422028.pdf.

USDA-NRCS (1997) "National Soil Survey Laboratory Characterization Data," Digital Data, Natural Resources Conservation Service, U.S. Department of Agriculture. Lincoln, NE.

Westfall, J.A., Coulston, J.W., Gray, A.N., Shaw, J.D., Radtke, P.J., Walker, D.M., Weiskittel, A.R., MacFarlane, D.W., Affleck, D.L.R., Zhao, D., Temesgen, H., Poudel, K.P., Frank, J.M., Prisley, S.P., Wang, Y., Sánchez Meador, A.J., Auty, D., and Domke, G.M. 2023. A national-scale tree volume, biomass, and carbon modeling system for the United States. Gen. Tech. Rep. WO-104.

Woodall, C.W., L.S. Heath, G.M. Domke, and M.C. Nichols (2011a) Methods and equations for estimating aboveground volume, biomass, and carbon for trees in the U.S. forest inventory, 2010. Gen. Tech. Rep. NRS-88. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northern Research Station. 30 p.

Woodall, C.W., and V.J. Monleon (2008) Sampling protocol, estimation, and analysis procedures for the down woody materials indicator of the FIA program. Gen. Tech. Rep. NRS-22. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northern Research Station. 68 p.

Woodall, C.W., Walters, B.F., Coulston, J.W., D'Amato, A.W., Domke, G.M., Russell, M.B., Sowers, P.A. (2015b) Monitoring network confirms land use change is a substantial component of the forest carbon sink in the eastern United States. Scientific Reports. 5: 17028.

Woodall, C.W., Walters, B.F., Oswalt, S.N., Domke, G.M., Toney, C., Gray, A.N. (2013) Biomass and carbon attributes of downed woody materials in forests of the United States. Forest Ecology and Management 305: 48-59.

Yang, L., Jin, S., Danielson, P., Homer, C., Gass, L., Bender, S. M., Case, A., Costello, C., Dewitz, J., Fry, J., Funk, M., Granneman, B., Liknes, G. C., Rigge, M. & Xian, G. (2018) A new generation of the United States National Land Cover Database: Requirements, research priorities, design, and implementation strategies. ISPRS Journal of Photogrammetry and Remote Sensing 146: 108-123.

Cropland Remaining Cropland

Armentano, T. V., and E.S. Menges (1986) Patterns of change in the carbon balance of organic soil-wetlands of the temperate zone. *Journal of Ecology* 74: 755-774.

Brady, N.C. and R.R. Weil (1999) The Nature and Properties of Soils. Prentice Hall. Upper Saddle River, NJ, 881.

Brockwell, Peter J., and Richard A. Davis (2016) Introduction to time series and forecasting. Springer.

Conant, R. T., K. Paustian, and E.T. Elliott (2001) "Grassland management and conversion into grassland: effects on soil carbon." *Ecological Applications* 11: 343-355.

CTIC (2004) National Crop Residue Management Survey: 1989-2004. Conservation Technology Information Center, Purdue University, Available online at: http://www.ctic.purdue.edu/CRM/.

Daly, C., R.P. Neilson, and D.L. Phillips (1994) "A Statistical-Topographic Model for Mapping Climatological Precipitation Over Mountainous Terrain." *Journal of Applied Meteorology* 33:140-158.

Del Grosso, S.J., W.J. Parton, A.R. Mosier, M.D. Hartman, J. Brenner, D.S. Ojima, and D.S. Schimel (2001) "Simulated Interaction of Carbon Dynamics and Nitrogen Trace Gas Fluxes Using the DAYCENT Model." In Modeling Carbon and Nitrogen Dynamics for Soil Management, Schaffer, M., L. Ma, S. Hansen, (eds.). CRC Press, Boca Raton, Florida, pp. 303-332.

Del Grosso, S.J., S.M. Ogle, W.J. Parton (2011) Soil organic matter cycling and greenhouse gas accounting methodologies, Chapter 1, pp 3-13 DOI: 10.1021/bk-2011-1072.ch001. In: Understanding Greenhouse Gas Emissions from Agricultural Management, L. Guo, A. Gunasekara, L. McConnell (eds.). American Chemical Society, Washington, D.C.

Edmonds, L., R. L. Kellogg, B. Kintzer, L. Knight, C. Lander, J. Lemunyon, D. Meyer, D.C. Moffitt, and J. Schaefer (2003) "Costs associated with development and implementation of Comprehensive Nutrient Management Plans." Part I—Nutrient management, land treatment, manure and wastewater handling and storage, and recordkeeping. Natural Resources Conservation Service, U.S. Department of Agriculture. Available online at: http://www.nrcs.usda.gov/technical/land/pubs/cnmp1.html.

Euliss, N., and R. Gleason (2002) Personal communication regarding wetland restoration factor estimates and restoration activity data. Ned Euliss and Robert Gleason of the U.S. Geological Survey, Jamestown, ND, to Stephen Ogle of the National Resource Ecology Laboratory, Fort Collins, CO. August 2002.

Friedman, J.H. (2001) "Greedy function approximation: A gradient boosting machine." Ann. Statist. 29 (5) 1189 – 1232.

Fry, J., Xian, G., Jin, S., Dewitz, J., Homer, C., Yang, L., Barnes, C., Herold, N., and Wickham, J. (2011) Completion of the 2006 National Land Cover Database for the Conterminous United States, PE&RS, Vol. 77(9):858-864.

Griscom, B. W., Adams, J., Ellis, P. W., Houghton, R. A., Lomax, G., Miteva, D. A., Schlesinger, W. H., Shoch, D., Siikamäki, J. V., Smith, P., Woodbury, P., Zganjar, C., Blackman, A., Campari, J., Conant, R. T., Delgado, C., Elias, P., Gopalakrishna, T., Hamsik, M. R., Herrero, M., Kiesecker, J., Landis, E., Laestadius, L., Leavitt, S. M., Minnemeyer, S., Polasky, S., Potapov, P., Putz, F. E., Sanderman, J., Silvius, M., Wollenberg, E. & Fargione, J. (2017) "Natural climate solutions." Proceedings of the National Academy of Sciences of the United States of America 114(44): 11645-11650.

Hagen, S. C., G. Delgado, P. Ingraham, I. Cooke, R. Emery, J. P. Fisk, L. Melendy, T. Olson, S. Patti, N. Rubin, B. Ziniti, H. Chen, W. Salas, P. Elias, and D. Gustafson. 2020. Mapping Conservation Management Practices and Outcomes in the Corn Belt Using the Operational Tillage Information System (OpTIS) and the Denitrification–Decomposition (DNDC) Model. Land **9**:408

Homer, C., Dewitz, J., Fry, J., Coan, M., Hossain, N., Larson, C., Herold, N., McKerrow, A., VanDriel, J.N., and Wickham, J. (2007) Completion of the 2001 National Land Cover Database for the Conterminous United States. Photogrammetric Engineering and Remote Sensing, Vol. 73, No. 4, pp 337-341.

Homer, C.G., Dewitz, J.A., Yang, L., Jin, S., Danielson, P., Xian, G., Coulston, J., Herold, N.D., Wickham, J.D., and Megown, K. (2015) Completion of the 2011 National Land Cover Database for the conterminous United States-Representing a decade of land cover change information. Photogrammetric Engineering and Remote Sensing, v. 81, no. 5, p. 345-354.

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change. [H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (eds.)]. Hayama, Kanagawa, Japan.

IPCC (2003) *Good Practice Guidance for Land Use, Land-Use Change, and Forestry*. The Intergovernmental Panel on Climate Change, National Greenhouse Gas Inventories Programme, J. Penman, et al., eds. August 13, 2004. Available online at: http://www.ipcc-nggip.iges.or.jp/public/gpglulucf/gpglulucf.htm.

Lal, R., Kimble, J. M., Follett, R. F. & Cole, C. V. (1998) *The potential of U.S. cropland to sequester carbon and mitigate the greenhouse effect.* Chelsea, MI: Sleeping Bear Press, Inc.

Little, R. (1988) "Missing-data adjustments in large surveys." *Journal of Business and Economic Statistics* 6: 287–296.

McGill, W.B., and C.V. Cole (1981) Comparative aspects of cycling of organic C, N, S and P through soil organic matter. *Geoderma* 26:267-286.

Metherell, A.K., L.A. Harding, C.V. Cole, and W.J. Parton (1993) "CENTURY Soil Organic Matter Model Environment." Agroecosystem version 4.0. Technical documentation, GPSR Tech. Report No. 4, USDA/ARS, Ft. Collins, CO.

Mesinger, F., G. DiMego, E. Kalnay, K. Mitchell, P. C. Shafran, W. Ebisuzaki, D. Jovic, J. Woollen, E. Rogers, E. H. Berbery, M. B. Ek, Y. Fan, R. Grumbine, W. Higgins, H. Li, Y. Lin, G. Manikin, D. Parrish, and W. Shi (2006) North American regional reanalysis. Bulletin of the American Meteorological Society 87:343-360.

Nelson, Mark D.; Riitters, Kurt H.; Coulston, John W.; Domke, Grant M.; Greenfield, Eric J.; Langner, Linda L.; Nowak, David J.; O'Dea, Claire B.; Oswalt, Sonja N.; Reeves, Matthew C.; Wear, David N. 2020. Defining the United States land base: a technical document supporting the USDA Forest Service 2020 RPA assessment. Gen. Tech. Rep. NRS-191. Madison, WI: U.S. Department of Agriculture, Forest Service, Northern Research Station. 70 p. https://doi.org/10.2737/NRS-GTR-191.

NRCS (1999) Soil Taxonomy: A basic system of soil classification for making and interpreting soil surveys, 2nd Edition. Agricultural Handbook Number 436, Natural Resources Conservation Service, U.S. Department of Agriculture, Washington, D.C.

NRCS (1997) "National Soil Survey Laboratory Characterization Data," Digital Data, Natural Resources Conservation Service, U.S. Department of Agriculture. Lincoln, NE.

NRCS (1981) Land Resource Regions and Major Land Resource Areas of the United States, USDA Agriculture Handbook 296, United States Department of Agriculture, Natural Resources Conservation Service, National Soil Survey Cente., Lincoln, NE, pp. 156.

Ogle, S.M., Breidt, F.J., Del Grosso, S., Gurung, R., Marx, E., Spencer, S., Williams, S., Manning, D. (2023) "Counterfactual scenarios reveal historical impact of cropland management on soil organic carbon stocks in the United States." Scientific Reports 13(1):14564.

Ogle, S. M., Alsaker, C., Baldock, J., Bernoux, M., Breidt, F. J., McConkey, B., Regina, K. & Vazquez-Amabile, G. G. (2019) "Climate and Soil Characteristics Determine Where No-Till Management Can Store Carbon in Soils and Mitigate Greenhouse Gas Emissions." Scientific Reports 9(1): 11665.

Ogle, S.M., F.J. Breidt, M. Easter, S. Williams, K. Killian, and K. Paustian (2010) "Scale and uncertainty in modeled soil organic carbon stock changes for U.S. croplands using a process-based model." *Global Change Biology* 16:810-820.

Ogle, S.M., F.J. Breidt, M. Easter, S. Williams and K. Paustian (2007) "Empirically-Based Uncertainty Associated with Modeling Carbon Sequestration Rates in Soils." *Ecological Modeling* 205:453-463.

Ogle, S.M., F.J. Breidt, and K. Paustian (2006) "Bias and variance in model results due to spatial scaling of measurements for parameterization in regional assessments." *Global Change Biology* 12:516-523.

Ogle, S. M., et al. (2005) "Agricultural management impacts on soil organic carbon storage under moist and dry climatic conditions of temperate and tropical regions." *Biogeochemistry* 72: 87-121.

Ogle, S.M., M.D. Eve, F.J. Breidt, and K. Paustian (2003) "Uncertainty in estimating land use and management impacts on soil organic carbon storage for U.S. agroecosystems between 1982 and 1997." *Global Change Biology* 9:1521-1542.

Parton, W.J., M.D. Hartman, D.S. Ojima, and D.S. Schimel (1998) "DAYCENT: Its Land Surface Submodel: Description and Testing". *Glob. Planet. Chang*. 19: 35-48.

Parton, W.J., D.S. Ojima, C.V. Cole, and D.S. Schimel (1994) "A General Model for Soil Organic Matter Dynamics: Sensitivity to litter chemistry, texture and management," in Quantitative Modeling of Soil Forming Processes. Special Publication 39, *Soil Science Society of America*, Madison, WI, 147-167.

Parton, W.J., D.S. Schimel, C.V. Cole, D.S. Ojima (1987) "Analysis of factors controlling soil organic matter levels in Great Plains grasslands." *Soil Science Society of America Journal* 51:1173-1179.

Parton, W.J., J.W.B. Stewart, C.V. Cole. (1988) "Dynamics of C, N, P, and S in grassland soils: a model." *Biogeochemistry* 5:109-131.

Paustian, K., et al. (1997a) "Agricultural soils as a sink to mitigate CO_2 emissions." *Soil Use and Management* 13: 230-244.

Paustian, K., et al. (1997b) Management controls on soil carbon. In Soil organic matter in temperate agroecosystems: long-term experiments in North America (Paul E.A., K. Paustian, and C.V. Cole, eds.). Boca Raton, CRC Press, pp. 15-49.

Potter, C. S., J.T. Randerson, C.B. Fields, P.A. Matson, P.M. Vitousek, H.A. Mooney, and S.A. Klooster (1993) "Terrestrial ecosystem production: a process model based on global satellite and surface data." *Global Biogeochemical Cycles* 7:811-841.

Potter, C., S. Klooster, A. Huete, and V. Genovese (2007) Terrestrial carbon sinks for the United States predicted from MODIS satellite data and ecosystem modeling. *Earth Interactions* 11, Article No. 13, DOI 10.1175/EI228.1.

PRISM Climate Group (2022) PRISM Climate Data, Oregon State University, http://prism.oregonstate.edu, downloaded January 2022.

Pukelsheim, F. (1994) "The 3-Sigma-Rule." American Statistician 48:88-91

Soil Survey Staff (2020) Gridded Soil Survey Geographic (gSSURGO) Database for the Conterminous United States. United States Department of Agriculture, Natural Resources Conservation Service, Accessed February 2020 (FY2020 official release), Available online at https://gdg.sc.egov.usda.gov/.

Spencer, S., S.M. Ogle, F.J. Breidt, J. Goebel, and K. Paustian. (2011) "Designing a national soil carbon monitoring network to support climate change policy: a case example for US agricultural lands." Greenhouse Gas Management & Measurement 1: 167-178.

Towery, D. (2001) Personal Communication. Dan Towery regarding adjustments to the CTIC (1998) tillage data to reflect long-term trends, Conservation Technology Information Center, West Lafayette, IN, and Marlen Eve, National Resource Ecology Laboratory, Fort Collins, CO. February 2001.

USDA-ERS (2020) Agricultural Resource Management Survey (ARMS) Farm Financial and Crop Production Practices: Tailored Reports. Available online at: https://www.ers.usda.gov/data-products/arms-farm-financial-and-crop-production-practices/.

USDA-ERS (2018) Agricultural Resource Management Survey (ARMS) Farm Financial and Crop Production Practices: Tailored Reports. Available online at: https://www.ers.usda.gov/data-products/arms-farm-financial-and-crop-production-practices/.

USDA-ERS (1997) Cropping Practices Survey Data—1995. Economic Research Service, United States Department of Agriculture. Available online at: http://www.ers.usda.gov/data/archive/93018/.

USDA Forest Service. (2022) Forest Inventory and Analysis National Program: FIA Data Mart. U.S. Department of Agriculture Forest Service. Washington, D.C. Available online at: https://apps.fs.usda.gov/fia/datamart/datamart.html. Accessed on 07 October 2022.

USDA-FSA (2015) Conservation Reserve Program Monthly Summary – September 2015. U.S. Department of Agriculture, Farm Service Agency, Washington, D.C. Available online at: https://www.fsa.usda.gov/Assets/USDA-FSA-Public/usdafiles/Conservation/PDF/sep2015summary.pdf.

USDA-NASS (2022) Quick Stats. National Agricultural Statistics Service, United States Department of Agriculture, Washington, D.C., Accessed October 2022, http://quickstats.nass.usda.gov/.

USDA-NASS (2021) Published crop data layer. Available at https://nassgeodata.gmu.edu/CropScape/, Accessed July 2021, USDA-NASS, Washington, DC.

USDA-NASS (2017) 2017 Census of Agriculture. USDA National Agricultural Statistics Service, Complete data available at http://www.nass.usda.gov/AgCensus.

USDA-NASS (2012) 2012 Census of Agriculture. USDA National Agricultural Statistics Service, Complete data available at http://www.nass.usda.gov/AgCensus.

USDA-NASS (2004) Agricultural Chemical Usage: 2003 Field Crops Summary. Report AgCh1(04)a. National Agricultural Statistics Service, U.S. Department of Agriculture, Washington, D.C. Available online at: http://usda.mannlib.cornell.edu/reports/nassr/other/pcu-bb/agcs0504.pdfH.

USDA-NASS (1999) Agricultural Chemical Usage: 1998 Field Crops Summary. Report AgCH1(99). National Agricultural Statistics Service, U.S. Department of Agriculture, Washington, DC. Available online at: http://usda.mannlib.cornell.edu/reports/nassr/other/pcu-bb/agch0599.pdf.

USDA-NASS (1992) Agricultural Chemical Usage: 1991 Field Crops Summary. Report AgCh1(92). National Agricultural Statistics Service, U.S. Department of Agriculture, Washington, D.C. Available online at: http://usda.mannlib.cornell.edu/reports/nassr/other/pcu-bb/agch0392.txtH.

USDA-NRCS (2020) Summary Report: 2017 National Resources Inventory. Natural Resources Conservation Service, Washington, DC, and Center for Survey Statistics and Methodology, Iowa State University, Ames, Iowa, https://www.nrcs.usda.gov/sites/default/files/2022-10/2017NRISummary_Final.pdf.

USDA-NRCS (2018) CEAP Cropland Farmer Surveys. USDA Natural Resources Conservation Service. https://www.nrcs.usda.gov/wps/portal/nrcs/detail/national/technical/nra/ceap/na/?cid=nrcs143_014163.

USDA-NRCS (2012) Assessment of the Effects of Conservation Practices on Cultivated Cropland in the Upper Mississippi River Basin. U.S. Department of Agriculture, Natural Resources Conservation Service, https://www.nrcs.usda.gov/Internet/FSE_DOCUMENTS/stelprdb1042093.pdf.

Yang, L., Jin, S., Danielson, P., Homer, C., Gass, L., Bender, S. M., Case, A., Costello, C., Dewitz, J., Fry, J., Funk, M., Granneman, B., Liknes, G. C., Rigge, M. & Xian, G. (2018) "A new generation of the United States National Land Cover Database: Requirements, research priorities, design, and implementation strategies." *ISPRS Journal of Photogrammetry and Remote Sensing* 146: 108-123.

Land Converted to Cropland

Sampson and D. Hair, (eds.). *Forest and Global Change*, Volume 2: Forest Management Opportunities for Mitigating Carbon Emissions. American Forests. Washington, D.C., 1-26 and 261-379 (appendices 262 and 263).

Brockwell, Peter J., and Richard A. Davis (2016) *Introduction to time series and forecasting*. Springer.

Del Grosso, S.J., W.J. Parton, A.R. Mosier, M.D. Hartman, J. Brenner, D.S. Ojima, and D.S. Schimel (2001) "Simulated Interaction of Carbon Dynamics and Nitrogen Trace Gas Fluxes Using the DAYCENT Model." In *Modeling Carbon and Nitrogen Dynamics for Soil Management*, Schaffer, M., L. Ma, S. Hansen, (eds.). CRC Press, Boca Raton, Florida, pp. 303-332.

Del Grosso, S.J., S.M. Ogle, W.J. Parton (2011) "Soil organic matter cycling and greenhouse gas accounting methodologies." Chapter 1, pp 3-13 DOI: 10.1021/bk-2011-1072.ch001. In: *Understanding Greenhouse Gas Emissions from Agricultural Management* (L. Guo, A. Gunasekara, L. McConnell. Eds.), American Chemical Society, Washington, D.C.

Del Grosso, S.J., W.J. Parton, A.R. Mosier, M.D. Hartman, J. Brenner, D.S. Ojima, and D.S. Schimel (2001) "Simulated Interaction of Carbon Dynamics and Nitrogen Trace Gas Fluxes Using the DAYCENT Model." In Schaffer, M., L. Ma, S. Hansen, (eds.); *Modeling Carbon and Nitrogen Dynamics for Soil Management*. CRC Press. Boca Raton, Florida. 303-332.

Domke, G.M., J.E. Smith, and C.W. Woodall. (2011) "Accounting for density reduction and structural loss in standing dead trees: Implications for forest biomass and carbon stock estimates in the United States". *Carbon Balance and Management* 6:14.

Domke, G.M., et al. (2013) "From models to measurements: comparing down dead wood carbon stock estimates in the U.S. forest inventory." *PLoS ONE* 8(3): e59949.

Domke, G.M., Perry, C.H., Walters, B.F., Woodall, C.W., and Smith, J.E. (2016) "A framework for estimating litter carbon stocks in forests of the United States." *Science of the Total Environment* 557–558: 469–478.

Fry, J., Xian, G., Jin, S., Dewitz, J., Homer, C., Yang, L., Barnes, C., Herold, N., and Wickham, J. (2011) "Completion of the 2006 National Land Cover Database for the Conterminous United States." *PE&RS*, Vol. 77(9):858-864.

Harmon, M.E., C.W. Woodall, B. Fasth, J. Sexton, M. Yatkov. (2011) Differences between standing and downed dead tree wood density reduction factors: A comparison across decay classes and tree species. Res. Paper. NRS-15. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northern Research Station. 40 p.

Homer, C., Dewitz, J., Fry, J., Coan, M., Hossain, N., Larson, C., Herold, N., McKerrow, A., VanDriel, J.N., and Wickham, J. (2007) "Completion of the 2001 National Land Cover Database for the Conterminous United States." *Photogrammetric Engineering and Remote Sensing*, Vol. 73, No. 4, pp 337-341.

Homer, C.G., Dewitz, J.A., Yang, L., Jin, S., Danielson, P., Xian, G., Coulston, J., Herold, N.D., Wickham, J.D., and Megown, K. (2015) "Completion of the 2011 National Land Cover Database for the conterminous United States-Representing a decade of land cover change information." *Photogrammetric Engineering and Remote Sensing* 81: 345-354.

Houghton, R.A., et al. (1983) "Changes in the carbon content of terrestrial biota and soils between 1860 and 1980: a net release of CO_2 to the atmosphere." *Ecological Monographs* 53: 235-262.

Houghton, R. A. and Nassikas, A. A. (2017) "Global and regional fluxes of carbon from land use and land cover change 1850–2015." *Global Biogeochemical Cycles* 31(3): 456-472.

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change. [H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (eds.)]. Hayama, Kanagawa, Japan.

Jenkins, J.C., D.C. Chojnacky, L.S. Heath, and R.A. Birdsey (2003) "National-scale biomass estimators for United States tree species." *Forest Science* 49(1):12-35.

Metherell, A.K., L.A. Harding, C.V. Cole, and W.J. Parton (1993) *CENTURY Soil Organic Matter Model Environment. Agroecosystem version 4.0.* Technical documentation, GPSR Tech. Report No. 4, USDA/ARS, Ft. Collins, CO.Ogle, S.M., Breidt, F.J., Del Grosso, S., Gurung, R., Marx, E., Spencer, S., Williams, S., Manning, D. (2023) "Counterfactual scenarios reveal historical impact of cropland management on soil organic carbon stocks in the United States." Scientific Reports 13(1):14564.

Ogle, S.M., F.J. Breidt, M. Easter, S. Williams, K. Killian, and K. Paustian (2010) "Scale and uncertainty in modeled soil organic carbon stock changes for U.S. croplands using a process-based model." *Global Change Biology* 16:810-820.

Ogle, S.M., M.D. Eve, F.J. Breidt, and K. Paustian (2003) "Uncertainty in estimating land use and management impacts on soil organic carbon storage for U.S. agroecosystems between 1982 and 1997." *Global Change Biology* 9:1521-1542.

Ogle, S.M., F.J. Breidt, and K. Paustian (2006) "Bias and variance in model results due to spatial scaling of measurements for parameterization in regional assessments." *Global Change Biology* 12:516-523.

Parton, W.J., M.D. Hartman, D.S. Ojima, and D.S. Schimel (1998) "DAYCENT: Its Land Surface Submodel: Description and Testing". *Glob. Planet. Chang*. 19: 35-48.

Parton, W.J., D.S. Ojima, C.V. Cole, and D.S. Schimel (1994) "A General Model for Soil Organic Matter Dynamics: Sensitivity to litter chemistry, texture and management," in *Quantitative Modeling of Soil Forming Processes.* Special Publication 39, Soil Science Society of America, Madison, WI, 147-167.

Parton, W.J., D.S. Schimel, C.V. Cole, D.S. Ojima (1987) "Analysis of factors controlling soil organic matter levels in Great Plains grasslands." *Soil Science Society of America Journal* 51:1173-1179.

Parton, W.J., J.W.B. Stewart, C.V. Cole. (1988) "Dynamics of C, N, P, and S in grassland soils: a model." *Biogeochemistry* 5:109-131.

PRISM Climate Group (2022) PRISM Climate Data, Oregon State University, http://prism.oregonstate.edu, downloaded January 2022.

Smith, J.E.; Heath, L.S.; Skog, K.E.; Birdsey, R.A. (2006) Methods for calculating forest ecosystem and harvested carbon with standard estimates for forest types of the United States. Gen. Tech. Rep. NE-343. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northeastern Research Station. 216 p.

Tubiello, F. N., et al. (2015) "The Contribution of Agriculture, Forestry and other Land Use activities to Global Warming, 1990-2012." *Global Change Biology* 21:2655-2660.

USDA Forest Service (2023) Forest Inventory and Analysis National Program: FIA Data Mart v2.0.1. U.S. Department of Agriculture Forest Service. Washington, D.C. Available online at: https://apps.fs.usda.gov/fia/datamart/datamart.html Accessed on 13 September 2023.

USDA-NASS (2021) Published crop data layer. Available at https://nassgeodata.gmu.edu/CropScape/, Accessed July 2021, USDA-NASS, Washington, DC.

USDA-NRCS (2020) Summary Report: 2017 National Resources Inventory. Natural Resources Conservation Service, Washington, DC, and Center for Survey Statistics and Methodology, Iowa State University, Ames, Iowa. https://www.nrcs.usda.gov/wps/portal/nrcs/main/national/technical/nra/nri/results/.

USDA-NRCS (2018) *Summary Report: 2015 National Resources Inventory*. Natural Resources Conservation Service, Washington, D.C., and Center for Survey Statistics and Methodology, Iowa State University, Ames, Iowa. https://www.nrcs.usda.gov/Internet/FSE_DOCUMENTS/nrcseprd1422028.pdf.

Westfall, J.A., Coulston, J.W., Gray, A.N., Shaw, J.D., Radtke, P.J., Walker, D.M., Weiskittel, A.R., MacFarlane, D.W., Affleck, D.L.R., Zhao, D., Temesgen, H., Poudel, K.P., Frank, J.M., Prisley, S.P., Wang, Y., Sánchez Meador, A.J., Auty, D., and Domke, G.M. (2023) A national-scale tree volume, biomass, and carbon modeling system for the United States. Gen. Tech. Rep. WO-XX

Woodall, C.W., and V.J. Monleon (2008) Sampling protocol, estimation, and analysis procedures for the down woody materials indicator of the FIA program. Gen. Tech. Rep. NRS-22. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northern Research Station. 68 p.

Woodall, C.W., L.S. Heath, G.M. Domke, and M.C. Nichols (2011) Methods and equations for estimating aboveground volume, biomass, and carbon for trees in the U.S. forest inventory, 2010. Gen. Tech. Rep. NRS-88. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northern Research Station. 30 p.

Yang, L., Jin, S., Danielson, P., Homer, C., Gass, L., Bender, S. M., Case, A., Costello, C., Dewitz, J., Fry, J., Funk, M., Granneman, B., Liknes, G. C., Rigge, M. & Xian, G. (2018) "A new generation of the United States National Land Cover Database: Requirements, research priorities, design, and implementation strategies." *ISPRS Journal of Photogrammetry and Remote Sensing* 146: 108-123.

Grassland Remaining Grassland: Soil Carbon Stock Changes

Brockwell, Peter J., and Richard A. Davis (2016) Introduction to time series and forecasting. Springer.

Del Grosso, S.J., S.M. Ogle, W.J. Parton (2011) Soil organic matter cycling and greenhouse gas accounting methodologies, Chapter 1, pp 3-13 DOI: 10.1021/bk-2011-1072.ch001. In: Understanding Greenhouse Gas Emissions from Agricultural Management (L. Guo, A. Gunasekara, L. McConnell. Eds.), American Chemical Society, Washington, D.C.

Del Grosso, S.J., W.J. Parton, A.R. Mosier, M.D. Hartman, J. Brenner, D.S. Ojima, and D.S. Schimel (2001) "Simulated Interaction of Carbon Dynamics and Nitrogen Trace Gas Fluxes Using the DAYCENT Model." In Modeling Carbon and Nitrogen Dynamics for Soil Management, Schaffer, M., L. Ma, S. Hansen, (eds.). CRC Press, Boca Raton, Florida, pp. 303-332.

Edmonds, L., R. L. Kellogg, B. Kintzer, L. Knight, C. Lander, J. Lemunyon, D. Meyer, D.C. Moffitt, and J. Schaefer (2003) "Costs associated with development and implementation of Comprehensive Nutrient Management Plans." Part I—Nutrient management, land treatment, manure and wastewater handling and storage, and recordkeeping. Natural Resources Conservation Service, U.S. Department of Agriculture. Available online at: http://www.nrcs.usda.gov/technical/land/pubs/cnmp1.html.

EPA (1999) Biosolids Generation, Use and Disposal in the United States. Office of Solid Waste, U.S. Environmental Protection Agency. Available online at: http://biosolids.policy.net/relatives/18941.PDF.

Fry, J., Xian, G., Jin, S., Dewitz, J., Homer, C., Yang, L., Barnes, C., Herold, N., and Wickham, J. (2011) Completion of the 2006 National Land Cover Database for the Conterminous United States, PE&RS, Vol. 77(9):858-864.

Homer, C., Dewitz, J., Fry, J., Coan, M., Hossain, N., Larson, C., Herold, N., McKerrow, A., VanDriel, J.N., and Wickham, J. (2007) Completion of the 2001 National Land Cover Database for the Conterminous United States. Photogrammetric Engineering and Remote Sensing, Vol. 73, No. 4, pp 337-341.

Homer, C.G., Dewitz, J.A., Yang, L., Jin, S., Danielson, P., Xian, G., Coulston, J., Herold, N.D., Wickham, J.D., and Megown, K. (2015) Completion of the 2011 National Land Cover Database for the conterminous United States-Representing a decade of land cover change information. Photogrammetric Engineering and Remote Sensing, v. 81, no. 5, p. 345-354.

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change. [H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (eds.)]. Hayama, Kanagawa, Japan.

Kellogg, R.L., C.H. Lander, D.C. Moffitt, and N. Gollehon (2000) Manure Nutrients Relative to the Capacity of Cropland and Pastureland to Assimilate Nutrients: Spatial and Temporal Trends for the United States. U.S. Department of Agriculture, Washington, D.C. Publication number nps00-0579.

Metherell, A.K., L.A. Harding, C.V. Cole, and W.J. Parton (1993) "CENTURY Soil Organic Matter Model Environment." Agroecosystem version 4.0. Technical documentation, GPSR Tech. Report No. 4, USDA/ARS, Ft. Collins, CO.NEBRA (2007) A National Biosolids Regulation, Quality, End Use & Disposal Survey. North East Biosolids and Residuals Association. July 21, 2007.

Nusser, S.M. and J.J. Goebel (1997) The national resources inventory: a long-term multi-resource monitoring programme. *Environmental and Ecological Statistics* 4:181-204.

Ogle, S.M., F.J. Breidt, M. Easter, S. Williams, K. Killian, and K. Paustian (2010) "Scale and uncertainty in modeled soil organic carbon stock changes for U.S. croplands using a process-based model." *Global Change Biology* 16:810-820.

Ogle, S.M., M.D. Eve, F.J. Breidt, and K. Paustian (2003) "Uncertainty in estimating land use and management impacts on soil organic carbon storage for U.S. agroecosystems between 1982 and 1997." *Global Change Biology* 9:1521-1542.

Parton, W.J., D.S. Ojima, C.V. Cole, and D.S. Schimel (1994) "A General Model for Soil Organic Matter Dynamics: Sensitivity to litter chemistry, texture and management," in Quantitative Modeling of Soil Forming Processes. Special Publication 39, *Soil Science Society of America*, Madison, WI, 147-167.

Parton, W.J., D.S. Schimel, C.V. Cole, D.S. Ojima (1987) "Analysis of factors controlling soil organic matter levels in Great Plains grasslands." *Soil Science Society of America Journal* 51:1173-1179.

Parton, W.J., J.W.B. Stewart, C.V. Cole. (1988) "Dynamics of C, N, P, and S in grassland soils: a model." *Biogeochemistry* 5:109-131.

Parton, W.J., M.D. Hartman, D.S. Ojima, and D.S. Schimel (1998) "DAYCENT: Its Land Surface Submodel: Description and Testing". *Glob. Planet. Chang*. 19: 35-48.PRISM Climate Group, Oregon State University, http://prism.oregonstate.edu, created 24 July 2015.

PRISM Climate Group (2022) PRISM Climate Data, Oregon State University, http://prism.oregonstate.edu, downloaded January 2022.

United States Bureau of Land Management (BLM) (2014) *Rangeland Inventory, Monitoring, and Evaluation Reports*. Bureau of Land Management. U.S. Department of the Interior. Available online at: http://www.blm.gov/wo/st/en/prog/more/rangeland_management/rangeland_inventory.html.

USDA-NASS (2021) Published crop data layer. Available at https://nassgeodata.gmu.edu/CropScape/, Accessed July 2021, USDA-NASS, Washington, DC.

USDA-NRCS (2020) Summary Report: 2017 National Resources Inventory. Natural Resources Conservation Service, Washington, DC, and Center for Survey Statistics and Methodology, Iowa State University, Ames, Iowa. https://www.nrcs.usda.gov/wps/portal/nrcs/main/national/technical/nra/nri/results/.

USDA Forest Service (2023) Forest Inventory and Analysis National Program: FIA Data Mart v2.0.1. U.S. Department of Agriculture Forest Service. Washington, D.C. Available online at: https://apps.fs.usda.gov/fia/datamart/datamart.html Accessed on 13 September 2023.

Yang, L., Jin, S., Danielson, P., Homer, C., Gass, L., Bender, S. M., Case, A., Costello, C., Dewitz, J., Fry, J., Funk, M., Granneman, B., Liknes, G. C., Rigge, M. & Xian, G. (2018) "A new generation of the United States National Land Cover Database: Requirements, research priorities, design, and implementation strategies." *ISPRS Journal of Photogrammetry and Remote Sensing* 146: 108-123.

Grassland Remaining Grassland: Non-CO_2 Emissions from Grassland Fires

Anderson, R.C. Evolution and origin of the Central Grassland of North America: climate, fire and mammalian grazers. *Journal of the Torrey Botanical Society* 133: 626-647.

Andreae, M.O. and P. Merlet (2001) Emission of trace gases and aerosols from biomass burning. *Global Biogeochemical Cycles* 15:955-966.

Brockwell, Peter J., and Richard A. Davis (2016) Introduction to time series and forecasting. Springer.

Chapin, F.S., S.F. Trainor, O. Huntington, A.L. Lovecraft, E. Zavaleta, D.C. Natcher, A.D. McGuire, J.L. Nelson, L. Ray, M. Calef, N. Fresco, H. Huntington, T.S. Rupp, L. DeWilde, and R.L. Naylor (2008) Increasing wildfires in Alaska's Boreal Forest: Pathways to potential solutions of a wicked problem. *Bioscience* 58:531-540.

Daubenmire, R. (1968) Ecology of fire in grasslands. *Advances in Ecological Research* 5:209-266.

Fry, J., Xian, G., Jin, S., Dewitz, J., Homer, C., Yang, L., Barnes, C., Herold, N., and Wickham, J. (2011) Completion of the 2006 National Land Cover Database for the Conterminous United States, PE&RS, Vol. 77(9):858-864.

Homer, C., Dewitz, J., Fry, J., Coan, M., Hossain, N., Larson, C., Herold, N., McKerrow, A., VanDriel, J.N., and Wickham, J. (2007) Completion of the 2001 National Land Cover Database for the Conterminous United States. Photogrammetric Engineering and Remote Sensing, Vol. 73, No. 4, pp 337-341.

Homer, C.G., Dewitz, J.A., Yang, L., Jin, S., Danielson, P., Xian, G., Coulston, J., Herold, N.D., Wickham, J.D., and Megown, K. (2015) Completion of the 2011 National Land Cover Database for the conterminous United States-Representing a decade of land cover change information. Photogrammetric Engineering and Remote Sensing, v. 81, no. 5, p. 345-354.

IPCC (2013) *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1535 pp.

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change. [H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (eds.)]. Hayama, Kanagawa, Japan.

MTBS (2023) Burned Areas Boundaries Dataset. (2023, August – last revised). MTBS Project (USDA Forest Service/U.S. Geological Survey). Available online: https://mtbs.gov/direct-download Accessed: August 9, 2023.

Ogle, S.M., S. Spencer, M. Hartman, L. Buendia, L. Stevens, D. du Toit, J. Witi (2016) "Developing national baseline GHG emissions and analyzing mitigation potentials for agriculture and forestry using an advanced national GHG inventory software system." In Advances in Agricultural Systems Modeling 6, *Synthesis and Modeling of Greenhouse Gas Emissions and Carbon Storage in Agricultural and Forestry Systems to Guide Mitigation and Adaptation*, S. Del Grosso, L.R. Ahuja and W.J. Parton (eds.), American Society of Agriculture, Crop Society of America and Soil Science Society of America, pp. 129-148.

Nusser, S.M. and J.J. Goebel (1997) The national resources inventory: a long-term multi-resource monitoring programme. *Environmental and Ecological Statistics* 4:181-204.

Picotte, J.J., K. Bhattarai, D. Howard, J. Lecker, J. Epting, B. Quayle, N. Benson, and K. Nelson (2020) "Changes to the Monitoring Trends in Burn Severity program mapping production procedures and data products." *Fire Ecology*. 16:16. https://doi.org/10.1186/s42408-020-00076-y.

USDA-NRCS (2015) Summary Report: 2012 National Resources Inventory, Natural Resources Conservation Service, Washington, D.C., and Center for Survey Statistics and Methodology, Iowa State University, Ames, Iowa. Available online at: http://www.nrcs.usda.gov/Internet/FSE_DOCUMENTS/nrcseprd396218.pdf.

Land Converted to Grassland

Asner, G.P., Archer, S., Hughes, R.F., Ansley, R.J. and Wessman, C.A. (2003) "Net changes in regional woody vegetation cover and carbon storage in Texas drylands, 1937–1999." *Global Change Biology* 9(3): 316-335.

Birdsey, R. (1996) "Carbon Storage for Major Forest Types and Regions in the Conterminous United States." In R.N. Sampson and D. Hair, (eds.). Forest and Global Change, Volume 2: Forest Management Opportunities for Mitigating Carbon Emissions. American Forests. Washington, D.C., 1-26 and 261-379 (appendices 262 and 263).

Breshears, D.D., Knapp, A.K., Law, D.J., Smith, M.D., Twidwell, D. and Wonkka, C.L., 2016. Rangeland Responses to Predicted Increases in Drought Extremity. Rangelands, 38(4), pp.191-196.

Brockwell, Peter J., and Richard A. Davis (2016) Introduction to time series and forecasting. Springer.

Del Grosso, S.J., S.M. Ogle, W.J. Parton. (2011) Soil organic matter cycling and greenhouse gas accounting methodologies, Chapter 1, pp 3-13 DOI: 10.1021/bk-2011-1072.ch001. In: Understanding Greenhouse Gas Emissions from Agricultural Management (L. Guo, A. Gunasekara, L. McConnell. Eds.), American Chemical Society, Washington, D.C.

Del Grosso, S.J., W.J. Parton, A.R. Mosier, M.D. Hartman, J. Brenner, D.S. Ojima, and D.S. Schimel (2001) "Simulated Interaction of Carbon Dynamics and Nitrogen Trace Gas Fluxes Using the DAYCENT Model." In Modeling Carbon and Nitrogen Dynamics for Soil Management (Schaffer, M., L. Ma, S. Hansen, (eds.). CRC Press, Boca Raton, Florida, pp. 303-332.

Domke, G.M., J.E. Smith, and C.W. Woodall. (2011) Accounting for density reduction and structural loss in standing dead trees: Implications for forest biomass and carbon stock estimates in the United States. Carbon Balance and Management. 6:14.

Domke, G.M., et al. (2013) From models to measurements: comparing down dead wood carbon stock estimates in the U.S. forest inventory. PLoS ONE 8(3): e59949.

Domke, G.M., Perry, C.H., Walters, B.F., Woodall, C.W., and Smith, J.E. (2016) A framework for estimating litter carbon stocks in forests of the United States. Science of the Total Environment 557–558: 469–478.

Domke, G.M., Walters, B.F., Smith, J.E., Woodall, C.W. (2022) Chapter 6: FIA Carbon Attributes. In Westfall, J.A.; Coulston, J.W.; Moisen, G.G.; Andersen, H.-E., eds. 2022. Sampling and estimation documentation for the Enhanced Forest Inventory and Analysis Program: 2022. Gen. Tech. Rep. NRS-GTR-207, Madison, WI: U.S. Department of Agriculture, Forest Service, Northern Research Station. 129 p. https://doi.org/10.2737/NRS-GTR-207.

Epstein, H.E., Gill, R.A., Paruelo, J.M., Lauenroth, W.K., Jia, G.J. and Burke, I.C. (2002) The relative abundance of three plant functional types in temperate grasslands and shrublands of North and South America: effects of projected climate change. Journal of Biogeography, 29(7), pp.875-888.

Fry, J., Xian, G., Jin, S., Dewitz, J., Homer, C., Yang, L., Barnes, C., Herold, N., and Wickham, J. (2011) Completion of the 2006 National Land Cover Database for the Conterminous United States, *PE&RS*, Vol. 77(9):858-864.

Harmon, M.E., C.W. Woodall, B. Fasth, J. Sexton, M. Yatkov. (2011) Differences between standing and downed dead tree wood density reduction factors: A comparison across decay classes and tree species. Res. Paper. NRS-15. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northern Research Station. 40 p.

Homer, C., Dewitz, J., Fry, J., Coan, M., Hossain, N., Larson, C., Herold, N., McKerrow, A., VanDriel, J.N., and Wickham, J. (2007) Completion of the 2001 National Land Cover Database for the Conterminous United States. *Photogrammetric Engineering and Remote Sensing*, Vol. 73, No. 4, pp 337-341.

Homer, C.G., Dewitz, J.A., Yang, L., Jin, S., Danielson, P., Xian, G., Coulston, J., Herold, N.D., Wickham, J.D., and Megown, K. (2015) Completion of the 2011 National Land Cover Database for the conterminous United States-Representing a decade of land cover change information. *Photogrammetric Engineering and Remote Sensing*, v. 81, no. 5, p. 345-354.

Houghton, R.A., et al. (1983) "Changes in the carbon content of terrestrial biota and soils between 1860 and 1980: a net release of CO_2 to the atmosphere." *Ecological Monographs* 53: 235-262.

Houghton, R. A. and Nassikas, A. A. (2017) "Global and regional fluxes of carbon from land use and land cover change 1850–2015." *Global Biogeochemical Cycles* 31(3): 456-472.

Huang, C.Y., Asner, G.P., Martin, R.E., Barger, N.N. and Neff, J.C. (2009) "Multiscale analysis of tree cover and aboveground carbon stocks in pinyon-juniper woodlands." *Ecological Applications* 19(3): 668-681.

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change, [H.S. Eggleston, L. Buendia, K. Miwa, T Ngara, and K. Tanabe (eds.)]. Hayama, Kanagawa, Japan.

Jenkins, J.C., D.C. Chojnacky, L.S. Heath, and R.A. Birdsey (2003) "National-scale biomass estimators for United States tree species." Forest Science 49(1):12-35.

Jurena, P.N. and Archer, S., (2003) Woody plant establishment and spatial heterogeneity in grasslands. Ecology, 84(4), pp.907-919.

Lenihan, J.M., Drapek, R., Bachelet, D. and Neilson, R.P., (2003) Climate change effects on vegetation distribution, carbon, and fire in California. Ecological Applications, 13(6), pp.1667-1681.

Metherell, A.K., L.A. Harding, C.V. Cole, and W.J. Parton (1993) "CENTURY Soil Organic Matter Model Environment." Agroecosystem version 4.0. Technical documentation, GPSR Tech. Report No. 4, USDA/ARS, Ft. Collins, CO.

Ogle, S.M., F.J. Breidt, M. Easter, S. Williams, K. Killian, and K. Paustian (2010) "Scale and uncertainty in modeled soil organic carbon stock changes for U.S. croplands using a process-based model." *Global Change Biology* 16:810-820.

Ogle, S.M., M.D. Eve, F.J. Breidt, and K. Paustian (2003) "Uncertainty in estimating land use and management impacts on soil organic carbon storage for U.S. agroecosystems between 1982 and 1997." *Global Change Biology* 9:1521-1542.

Parton, W.J., D.S. Ojima, C.V. Cole, and D.S. Schimel (1994) "A General Model for Soil Organic Matter Dynamics: Sensitivity to litter chemistry, texture and management," in Quantitative Modeling of Soil Forming Processes. Special Publication 39, *Soil Science Society of America*, Madison, WI, 147-167.

Parton, W.J., D.S. Schimel, C.V. Cole, D.S. Ojima (1987) "Analysis of factors controlling soil organic matter levels in Great Plains grasslands." *Soil Science Society of America Journal* 51:1173-1179.

Parton, W.J., J.W.B. Stewart, C.V. Cole (1988) "Dynamics of C, N, P, and S in grassland soils: a model." *Biogeochemistry* 5:109-131.

Parton, W.J., M.D. Hartman, D.S. Ojima, and D.S. Schimel (1998) "DAYCENT: Its Land Surface Submodel: Description and Testing". *Glob. Planet. Chang*. 19: 35-48.

PRISM Climate Group (2022) PRISM Climate Data, Oregon State University, http://prism.oregonstate.edu, downloaded January 2022.

Scholes, R.J. and Archer, S.R. (1997) Tree-grass interactions in savannas 1. Annual review of Ecology and Systematics, 28(1), pp.517-544.

Sims, P.L., Singh, J.S. and Lauenroth, W.K. (1978) The structure and function of ten western North American grasslands: I. Abiotic and vegetational characteristics. The Journal of Ecology, pp.251-285.

Smith, J.E.; Heath, L.S.; Skog, K.E.; Birdsey, R.A. (2006) Methods for calculating forest ecosystem and harvested carbon with standard estimates for forest types of the United States. Gen. Tech. Rep. NE-343. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northeastern Research Station. 216 p.

Tarhouni, M., et al. (2016) Measurement of the aboveground biomass of some rangeland species using a digital non-destructive technique. *Botany Letters* 163(3):281-287.

Tubiello, F. N., et al. (2015) "The Contribution of Agriculture, Forestry and other Land Use activities to Global Warming, 1990-2012." *Global Change Biology* 21:2655-2660.

United States Bureau of Land Management (BLM) (2014) *Rangeland Inventory, Monitoring, and Evaluation Reports*. Bureau of Land Management. U.S. Department of the Interior. Available online at: http://www.blm.gov/wo/st/en/prog/more/rangeland_management/rangeland_inventory.html.

USDA Forest Service (2023) Forest Inventory and Analysis National Program: FIA Data Mart v2.0.1. U.S. Department of Agriculture Forest Service. Washington, D.C. Available online at: https://apps.fs.usda.gov/fia/datamart/datamart.html Accessed on 13 September 2023.

USDA-NASS (2021) Published crop data layer. Available at https://nassgeodata.gmu.edu/CropScape/, Accessed July 2021, USDA-NASS, Washington, DC.

USDA-NRCS (2020) Summary Report: 2017 National Resources Inventory. Natural Resources Conservation Service, Washington, DC, and Center for Survey Statistics and Methodology, Iowa State University, Ames, Iowa. https://www.nrcs.usda.gov/wps/portal/nrcs/main/national/technical/nra/nri/results/.

USDA-NRCS (2018) *Summary Report: 2015 National Resources Inventory*. Natural Resources Conservation Service, Washington, D.C., and Center for Survey Statistics and Methodology, Iowa State University, Ames, Iowa. https://www.nrcs.usda.gov/Internet/FSE_DOCUMENTS/nrcseprd1422028.pdf.

Woodall, C.W., and V.J. Monleon (2008) Sampling protocol, estimation, and analysis procedures for the down woody materials indicator of the FIA program. Gen. Tech. Rep. NRS-22. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northern Research Station. 68 p.

Woodall, C.W., L.S. Heath, G.M. Domke, and M.C. Nichols. (2011) Methods and equations for estimating aboveground volume, biomass, and carbon for trees in the U.S. forest inventory, 2010. Gen. Tech. Rep. NRS-88. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northern Research Station. 30 p.

Yang, L., Jin, S., Danielson, P., Homer, C., Gass, L., Bender, S. M., Case, A., Costello, C., Dewitz, J., Fry, J., Funk, M., Granneman, B., Liknes, G. C., Rigge, M. & Xian, G. (2018) "A new generation of the United States National Land Cover Database: Requirements, research priorities, design, and implementation strategies." *ISPRS Journal of Photogrammetry and Remote Sensing* 146: 108-123.

Wetlands Remaining Wetlands: CO_2, CH_4, and N_2O Emissions from Peatlands Remaining Peatlands

Apodaca, L. (2011) Email correspondence. Lori Apodaca, Peat Commodity Specialist, USGS and Emily Rowan, ICF International. November.

Apodaca, L. (2008) E-mail correspondence. Lori Apodaca, Peat Commodity Specialist, USGS and Emily Rowan, ICF International. October and November.

Cleary, J., N. Roulet and T.R. Moore (2005) "Greenhouse gas emissions from Canadian peat extraction, 1990-2000: A life-cycle analysis." *Ambio* 34:456–461.

Division of Geological & Geophysical Surveys (DGGS), Alaska Department of Natural Resources (1997–2015) *Alaska's Mineral Industry Report (1997–2014).* Alaska Department of Natural Resources, Fairbanks, AK. Available online at http://www.dggs.dnr.state.ak.us/pubs/pubs?reqtype=minerals.

IPCC (2014) *Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. R.K. Pachauri and L.A. Meyer (eds.). IPCC, Geneva, Switzerland.

IPCC (2013) *2013 Supplement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories: Wetlands*. Hiraishi, T., Krug, T., Tanabe, K., Srivastava, N., Baasansuren, J., Fukuda, M. and Troxler, T.G. (eds.). Published: IPCC, Switzerland.

IPCC (2007) *Climate Change 2007: Synthesis Report. Contribution of Working Groups I, II and III to the Fourth Assessment Report (AR4) of the IPCC*. The Intergovernmental Panel on Climate Change, R.K. Pachauri, A. Resinger (eds.). Geneva, Switzerland.

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change. H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (eds.). Hayama, Kanagawa, Japan.

Szumigala, D.J. (2011) Phone conversation. Dr. David Szumigala, Division of Geological and Geophysical Surveys, Alaska Department of Natural Resources and Emily Rowan, ICF International. January 18, 2011.

Szumigala, D.J. (2008) Phone conversation. Dr. David Szumigala, Division of Geological and Geophysical Surveys, Alaska Department of Natural Resources and Emily Rowan, ICF International. October 17, 2008.

USGS (1991–2018) *Minerals Yearbook: Peat (1994–2018).* United States Geological Survey, Reston, VA. Available online at http://minerals.usgs.gov/minerals/pubs/commodity/peat/index.html.

USGS (2023a) *Minerals Yearbook: Peat (2019) Tables-only release.* United States Geological Survey, Reston, VA. Available online at https://www.usgs.gov/centers/nmic/peat-statistics-and-information.

USGS (2023b) *Minerals Yearbook: Peat (2020) Tables-only release.* United States Geological Survey, Reston, VA. Available online at https://www.usgs.gov/centers/nmic/peat-statistics-and-information.

USGS (2023c) *Mineral Commodity Summaries: Peat (1996-2023).* United States Geological Survey, Reston, VA. Available online at https://www.usgs.gov/centers/nmic/peat-statistics-and-information.

USGS (2023d) Email correspondence. Amanda Brioche, Mineral Commodity Specialist, USGS. August 2023.

Wetlands Remaining Coastal Wetlands: Emissions and Removals from Coastal Wetlands Remaining Coastal Wetlands

Abbott, K. M., Elsey-Quirk, T., and DeLaune, R. D. (2019) Factors influencing blue carbon accumulation across a 32-year chronosequence of created coastal marshes. Ecosphere, 10(8): e02828.

Allen, J. R., Cornwell, J. C., and Baldwin, A. H. (2021) Contributions of organic and mineral matter to vertical accretion in tidal wetlands across a Chesapeake Bay subestuary. Journal of Marine Science and Engineering 9(7): 751.

Arias-Ortiz, A., Oikawa, P. Y., Carlin, J., Masqué, P., Shahan, J., Kanneg, S., ... and Baldocchi, D. D. (2021) Tidal and nontidal marsh restoration: a trade-off between carbon sequestration, methane emissions, and soil accretion. Journal of Geophysical Research: Biogeosciences, 126(12): e2021JG006573.

Arriola, J. M., and Cable, J. E. (2017) Variations in carbon burial and sediment accretion along a tidal creek in a Florida salt marsh. Limnology and Oceanography 62(S1): S15-S28.

Baustian, M. M., Stagg, C. L., Perry, C. L., Moss, L. C., and Carruthers, T. J. (2021) Long-term carbon sinks in marsh soils of coastal Louisiana are at risk to wetland loss. Journal of Geophysical Research: Biogeosciences 126(3): e2020JG005832.

Bianchi, T. S., Allison, M. A., Zhao, J., Li, X., Comeaux, R. S., Feagin, R. A., & Kulawardhana, R. W. (2013) Historical reconstruction of mangrove expansion in the Gulf of Mexico: linking climate change with carbon sequestration in coastal wetlands. Estuarine, Coastal and Shelf Science 119: 7-16.

Boyd, B. (2012) Comparison of sediment accumulation and accretion in impounded and unimpounded marshes of the Delaware Estuary. Doctoral dissertation, University of Delaware.

Boyd, B. M. and Sommerfield, C. K. (2016) Marsh accretion and sediment accumulation in a managed tidal wetland complex of Delaware Bay. Ecological Engineering, 92: 37-46.

Boyd, B. M., Sommerfield, C. K., and Elsey-Quirk, T. (2017) Hydrogeomorphic influences on salt marsh sediment

accumulation and accretion in two estuaries of the US Mid-Atlantic coast. Marine Geology, 383: 132-145.

Breithaupt, J. L., Smoak, J. M., Smith III, T. J., and Sanders, C. J. (2014) Temporal variability of carbon and nutrient burial, sediment accretion, and mass accumulation over the past century in a carbonate platform mangrove forest of the Florida Everglades. Journal of Geophysical Research: Biogeosciences, 119(10): 2032-2048.

Byrd, K. B., Ballanti, L. R., Thomas, N. M., Nguyen, D. K., Holmquist, J. R., Simard, M., Windham-Myers, L., Schile, L. M., Parker, V. T., … and Castaneda-Moya, E. (2017) Biomass/Remote Sensing dataset: 30m resolution tidal marsh biomass samples and remote sensing data for six regions in the conterminous United States: U.S. Geological Survey data release, https://doi.org/10.5066/F77943K8.

Byrd, K. B., Ballanti, L., Thomas, N., Nguyen, D., Holmquist, J.R., Simard, M., and Windham-Myers, L. (2018) A remote sensing-based model of tidal marsh aboveground carbon stocks for the conterminous United States. ISPRS Journal of Photogrammetry and Remote Sensing 139: 255-271.

Byrd, K. B., Ballanti, L., Thomas, N., Nguyen, D., Holmquist, J.R., Simard, M., and Windham-Myers, L. (2020) Corrigendum to “A remote sensing-based model of tidal marsh aboveground carbon stocks for the conterminous United States”. ISPRS Journal of Photogrammetry and Remote Sensing 166: 63-67.

Callaway, J. C., Borgnis, E. L., Turner, R. E. & Milan, C. S. (2012a) Carbon sequestration and sediment accretion in San Francisco Bay tidal wetlands. Estuaries and Coasts 35(5): 1163-1181.

Callaway, J. C., Borgnis, E. L., Turner, R. E., Milan, C. S., Goodfriend, W., & Richmond, S. (2012b) "Wetland Sediment Accumulation at Corte Madera Marsh and Muzzi Marsh". San Francisco Bay Conservation and Development Commission.

Church, T. M., Sommerfield, C. K., Velinsky, D. J., Point, D., Benoit, C., Amouroux, D. & Donard, O. F. X. (2006) Marsh sediments as records of sedimentation, eutrophication and metal pollution in the urban Delaware Estuary. Marine Chemistry 102(1-2): 72-95.

Couvillion, B. R., Barras, J. A., Steyer, G. D., Sleavin, W., Fischer, M., Beck, H., & Heckman, D. (2011) Land area change in coastal Louisiana (1932 to 2010) (pp. 1-12). U.S. Department of the Interior, U.S. Geological Survey.

Couvillion, B. R., Fischer, M. R., Beck, H. J. and Sleavin, W. J. (2016) Spatial Configuration Trends in Coastal Louisiana from 1986 to 2010. Wetlands 1-13.

Craft, C. B., & Richardson, C. J. (1998) Recent and long-term organic soil accretion and nutrient accumulation in the Everglades. Soil Science Society of America Journal 62(3): 834-843.

Crooks, S., Findsen, J., Igusky, K., Orr, M. K. and Brew, D. (2009) Greenhouse Gas Mitigation Typology Issues Paper: Tidal Wetlands Restoration. Report by PWA and SAIC to the California Climate Action Reserve.

Crooks, S., Rybczyk, J., O’Connell, K., Devier, D. L., Poppe, K., Emmett-Mattox, S. (2014) Coastal Blue Carbon Opportunity Assessment for the Snohomish Estuary: The Climate Benefits of Estuary Restoration. Report by Environmental Science Associates, Western Washington University, EarthCorps, and Restore America’s Estuaries.

DeLaune, R. D., & White, J. R. (2012) Will coastal wetlands continue to sequester carbon in response to an increase in global sea level?: A case study of the rapidly subsiding Mississippi river deltaic plain. Climatic Change, 110(1), 297-314.

Drexler, J. Z., de Fontaine, C. S., and Brown, T. A. (2009) Peat accretion histories during the past 6,000 years in marshes of the Sacramento–San Joaquin Delta, CA, USA. Estuaries and Coasts 32: 871-892.

Drexler, J. Z., Krauss, K. W., Sasser, M. C., Fuller, C. C., Swarzenski, C. M., Powell, A., ... and Orlando, J. (2013) A long-term comparison of carbon sequestration rates in impounded and naturally tidal freshwater marshes along the lower Waccamaw River, South Carolina. Wetlands 33: 965-974.

Drexler, J. Z., Woo, I., Fuller, C. C., and Nakai, G. (2019) Carbon accumulation and vertical accretion in a restored versus historic salt marsh in southern Puget Sound, Washington, United States. Restoration Ecology 27(5): 1117-1127.

Ensign, S. H., Noe, G. B., Hupp, C. R., and Skalak, K. J. (2015) Head-of-tide bottleneck of particulate material transport from watersheds to estuaries. Geophysical Research Letters 42(24): 10-671.

Gerlach, M. J., Engelhart, S. E., Kemp, A. C., Moyer, R. P., Smoak, J. M., Bernhardt, C. E., and Cahill, N. (2017) Reconstructing Common Era relative sea-level change on the Gulf Coast of Florida. Marine Geology 390: 254-269.

Giblin, A., Forbrich, I., & LTER, P. I. E. (2018) PIE LTER high marsh sediment chemistry and activity measurements, Nelson Island Creek marsh, Rowley, MA.

Holmquist, J. R., Windham-Myers, L., Bliss, N., Crooks, S., Morris, J. T., Megonigal, J. P. & Woodrey, M. (2018) Accuracy and Precision of Tidal Wetland Soil Carbon Mapping in the Conterminous United States. Scientific reports 8(1): 9478.

Hu, Z., Lee, J. W., Chandran, K., Kim, S. and Khanal, S. K. (2012) N_2O Emissions from Aquaculture: A Review. Environmental Science & Technology 46(12): 6470-6480.

Hussein, A. H., Rabenhorst, M. C. & Tucker, M. L. (2004) Modeling of carbon sequestration in coastal marsh soils. Soil Science Society of America Journal 68(5): 1786-1795.

IPCC (2014) *2013 Supplement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories: Wetlands*. Hiraishi, T., Krug, T., Tanabe, K., Srivastava, N., Baasansuren, J., Fukuda, M. and Troxler, T.G. (eds.). Published: IPCC, Switzerland.

IPCC (2013) *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change.* Stocker, T., Qin, D., Plattner, G.-K., Tignor, M. Allen, S.K., Boschung, J., Nauels, A., Xia, Y., Bex, V. and Midgley, P.M. (eds.). Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

IPCC (2006) *IPCC Guidelines for National Greenhouse Gas Inventories.* Prepared by the National Greenhouse Gas Inventories Programme, Eggleston H.S., Buendia L., Miwa K., Ngara T. and Tanabe K. (eds). IGES, Japan.

IPCC (2003) *Good Practice Guidance for Land Use, Land-Use Change and Forestry*. LUCF Sector Good Practice Guidance, Chapter 3. Penman, J., Gytarsky, M., Hiraishi, T., Krug, T., Kruger, D., Pipatti, R., Buendia, L., Miwa, K., Ngara, T., Tanabe, K. and Wagner, F. (eds). Institute of Global Environmental Strategies (IGES), on behalf of the Intergovernmental Panel on Climate Change (IPCC): Hayama, Japan.

IPCC (2000) *Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories*. Quantifying Uncertainties in Practice, Chapter 6. Penman, J., Kruger, D., Galbally, I., Hiraishi, T., Nyenzi, B., Emmanuel, S., Buendia, L., Hoppaus, R., Martinsen, T., Meijer, J., Miwa, K. and Tanabe, K. (eds). Institute of Global Environmental Strategies (IGES), on behalf of the Intergovernmental Panel on Climate Change (IPCC): Hayama, Japan.

Kearney, M. S. & Stevenson, J. C. (1991) Island land loss and marsh vertical accretion rate evidence for historical sea-level changes in Chesapeake Bay. Journal of Coastal Research 7(2): 403-415.

Kemp, A. C., Sommerfield, C. K., Vane, C. H., Horton, B. P., Chenery, S., Anisfeld, S., and Nikitina, D. (2012) Use of lead isotopes for developing chronologies in recent salt-marsh sediments. Quaternary Geochronology 12: 40-49.

Köster, D., Lichter, J., Lea, P. D., & Nurse, A. (2007) Historical eutrophication in a river–estuary complex in mid-coast Maine. Ecological Applications 17(3): 765-778.

Krauss, K. W., Noe, G. B., Duberstein, J. A., Conner, W. H., Stagg, C. L., and Jones, M. C. (2018) Carbon budget assessment of tidal freshwater forested wetland and oligohaline marsh ecosystems along the Waccamaw and Savannah Rivers, USA (2005–2016). US Geological Survey Data Release. https://doi.Org/10.5066/F7TM7930.

Lagomasino, D., Corbett, D. R., and Walsh, J. P. (2013) Influence of wind-driven inundation and coastal geomorphology on sedimentation in two microtidal marshes, Pamlico River Estuary, NC. Estuaries and Coasts 36: 1165-1180.

Lu, M & Megonigal, J. P. (2017) Final Report for RAE Baseline Assessment Project. Memo to Silvestrum Climate

Associates by Smithsonian Environmental Research Center, Maryland.

Lynch, J. C. (1989) Sedimentation and nutrient accumulation in mangrove ecosystems of the Gulf of Mexico. M.S. thesis, Univ. of Southwestern Louisiana, Lafayette, LA.

Luk, S. Y., Todd-Brown, K., Eagle, M., McNichol, A. P., Sanderman, J., Gosselin, K., and Spivak, A. C. (2021) Soil organic carbon development and turnover in natural and disturbed salt marsh environments. Geophysical Research Letters 48(2): e2020GL090287.

Marchio, D. A., Savarese, M., Bovard, B., & Mitsch, W. J. (2016) Carbon sequestration and sedimentation in mangrove swamps influenced by hydrogeomorphic conditions and urbanization in Southwest Florida. Forests 7: 116-135.

McCombs, J. W., Herold, N. D., Burkhalter, S. G. and Robinson C. J. (2016) Accuracy Assessment of NOAA Coastal Change Analysis Program 2006-2010 Land Cover and Land Cover Change Data. Photogrammetric Engineering & Remote Sensing. 82:711-718.

McTigue, N., Davis, J., Rodriguez, A. B., McKee, B., Atencio, A., and Currin, C. (2019) Sea level rise explains changing carbon accumulation rates in a salt marsh over the past two millennia. JGR Biogeosciences.

Merrill, J. Z. (1999) Tidal Freshwater Marshes as Nutrient Sinks: particulate Nutrient Burial and Denitrification. Ph.D. Dissertation, University of Maryland, College Park, MD, 342 pp.

Miller, C. B., Rodriguez, A. B., Bost, M. C., McKee, B. A., and McTigue, N. D. (2022) Carbon accumulation rates are highest at young and expanding salt marsh edges. Communications Earth & Environment 3(1): 173.

National Marine Fisheries Service (2022). Fisheries of the United States, 2020. U.S. Department of Commerce, NOAA Current Fishery Statistics No. 2020. Available at: https://www.fisheries.noaa.gov/ national/sustainable-fisheries/fisheries-united-states.

National Oceanic and Atmospheric Administration, Office for Coastal Management (2020) Coastal Change Analysis Program (C-CAP) Regional Land Cover. Charleston, SC: NOAA Office for Coastal Management. Accessed October 2020 at www.coast.noaa.gov/htdata/raster1/landcover/bulkdownload/30m_lc/.

Noe, G. B., Hupp, C. R., Bernhardt, C. E., & Krauss, K. W. (2016) Contemporary deposition and long-term accumulation of sediment and nutrients by tidal freshwater forested wetlands impacted by sea level rise. Estuaries and Coasts 39(4): 1006-1019.

Orson, R. A., Simpson, R. L., & Good, R. E. (1990) Rates of sediment accumulation in a tidal freshwater marsh. Journal of Sedimentary Research 60(6): 859-869.

Orson, R., Warren, R. & Niering, W. (1998) Interpreting sea level rise and rates of vertical marsh accretion in a southern New England tidal salt marsh. Estuarine, Coastal and Shelf Science 47(4): 419-429.

Peck, E. K., Wheatcroft, R. A., and Brophy, L. S. (2020) Controls on sediment accretion and blue carbon burial in tidal saline wetlands: insights from the Oregon Coast, USA. Journal of Geophysical Research: Biogeosciences 125(2): e2019JG005464.

Poppe, K. L., and Rybczyk, J. M. (2021) Tidal marsh restoration enhances sediment accretion and carbon accumulation in the Stillaguamish River estuary, Washington. PloS one 16(9): e0257244.

Roman, C., Peck, J., Allen, J., King, J. & Appleby, P. (1997) Accretion of a New England (USA) salt marsh in response to inlet migration, storms, and sea-level rise. Estuarine, Coastal and Shelf Science 45(6): 717-727.

Smith, K. E., Flocks, J. G., Steyer, G. D., and Piazza, S. C. (2015) Wetland Paleoecological Study of Southwest Coastal Louisiana: Sediment Cores and Diatom Calibration Dataset. US Department of the Interior, US Geological Survey.

Thom, R. M. (1992) Accretion rates of low intertidal salt marshes in the Pacific Northwest. Wetlands 12: 147-156.

Vaughn, D. R., Bianchi, T. S., Shields, M. R., Kenney, W. F., and Osborne, T. Z. (2020) Increased organic carbon burial in northern Florida mangrove-salt marsh transition zones. Global Biogeochemical Cycles 34(5): e2019GB006334.

Villa, J. A. & Mitsch W. J. (2015) Carbon sequestration in different wetland plant communities of Southwest Florida. International Journal for Biodiversity Science, Ecosystems Services and Management 11: 17-28

Watson, E. B., and Byrne, R. (2013) Late Holocene Marsh Expansion in Southern San Francisco Bay, California. Estuaries and Coasts 36: 643-653.

Weis, D. A., Callaway, J. C., and Gersberg, R. M. (2001) Vertical accretion rates and heavy metal chronologies in wetland sediments of the Tijuana Estuary. Estuaries 24: 840-850.

Weston, N. B., Neubauer, S. C., Velinsky, D. J., & Vile, M. A. (2014) Net ecosystem carbon exchange and the greenhouse gas balance of tidal marshes along an estuarine salinity gradient. Biogeochemistry 120: 163-189.

Weston, N. B., Rodriguez, E., Donnelly, B., Solohin, E., Jezycki, K., Demberger, S., ... and Craft, C. B. (2023) Recent acceleration of wetland accretion and carbon accumulation along the US East Coast. Earth's Future 11(3): e2022EF003037.

Wetlands Remaining Wetlands: Flooded Land Remaining Flooded Land

Abril, G., Gu´erin, F., Richard, S., Delmas, R., Galy-Lacaux, C., Gosse, P., et al. (2005) Carbon dioxide and methane emissions and the carbon budget of a 10-year old tropical reservoir (Petit Saut, French Guiana). Global Biogeochem. Cycles 19 (GB4007), 1–16. https://doi.org/10.1029/2005GB002457.

Barros, N., Cole, J.J., Tranvik, L.J., Prairie, Y.T., Bastviken, D., Huszar, V.L.M., et al. (2011) Carbon emission from hydroelectric reservoirs linked to reservoir age and latitude. Nat. Geosci. 4 (9), 593–596. https://doi.org/10.1038/ngeo1211.

Davis, D. W. (1973) Louisiana Canals and Their Influence on Wetland Development. Louisiana State University and Agricultural & Mechanical College. LSU Historical Dissertations and Theses. 2386., Louisiana State University.

IPCC (2019) 2019 Refinement to the 2006 Guidelines for National Greenhouse Gas Inventories. Wetlands, Chapter 7. Lovelock, C. E., Evans, C., Barros, N., Prairie, Y. T., Alm, J., Bastviken, D., Beaulieu, J. J., Garneau, M., Harby, A., Harrison, J. A., Pare, David, Raadal, Hanne Lerche, Sherman, B., Zhang, Chengyi, Ogle, S. M.IPCC (2013) *2013 Supplement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories: Wetlands.* Hiraishi, T., Krug, T., Tanabe, K., Srivastava, N., Baasansuren, J., Fukuda, M. and Troxler, T.G. (eds). In: IPCC, Switzerland.

IPCC (2006) *IPCC Guidelines for National Greenhouse Gas Inventories.* Prepared by the National Greenhouse Gas Inventories Programme, Eggleston H.S., Buendia L., Miwa K., Ngara T. and Tanabe K. (eds). IGES, Japan.

IPCC (2003) *Good Practice Guidance for Land Use, Land-Use Change and Forestry.* LUCF Sector Good Practice Guidance, Chapter 3. Penman, J., Gytarsky, M., Hiraishi, T., Krug, T., Kruger, D., Pipatti, R., Buendia, L., Miwa, K., Ngara, T., Tanabe, K. and Wagner, F. (eds). Institute of Global Environmental Strategies (IGES), on behalf of the Intergovernmental Panel on Climate Change (IPCC): Hayama, Japan.

Lehner B, Reidy Liermann C, Revenga C, Vorosmarty C, Fekete B, Crouzet P, Doll P, et al. (2011b) Global Reservoir and Dam Database, Version 1 (GRanDv1): Dams, Revision 01. In: Palisades, NY: NASA Socioeconomic Data and Applications Center (SEDAC).

Prairie, Y. T., et al. (2017) The GHG Reservoir Tool (G-res) User guide. UNESCO/IHA research project on the GHG status of freshwater reservoirs. Joint publication of the UNESCO Chair in Global Environmental Change and the International Hydropower Association: 38.

Teodoru, C.R., Bastien, J., Bonneville, M.C., Del Giorgio, P.a., Demarty, M., Garneau, M., et al., 2012. The net carbon footprint of a newly created boreal hydroelectric reservoir. Global Biogeochem. Cycles 26 (GB2016), 1–14. https://doi.org/10.1029/2011GB004187.

Land Converted to Wetlands: Emissions and Removals from Land Converted to Vegetated Coastal Wetlands

Abbott, K. M., Elsey-Quirk, T., and DeLaune, R. D. (2019) Factors influencing blue carbon accumulation across a 32-year chronosequence of created coastal marshes. Ecosphere, 10(8): e02828.

Allen, J. R., Cornwell, J. C., and Baldwin, A. H. (2021) Contributions of organic and mineral matter to vertical accretion in tidal wetlands across a Chesapeake Bay subestuary. Journal of Marine Science and Engineering 9(7): 751.

Arias-Ortiz, A., Oikawa, P. Y., Carlin, J., Masqué, P., Shahan, J., Kanneg, S., ... and Baldocchi, D. D. (2021) Tidal and nontidal marsh restoration: a trade-off between carbon sequestration, methane emissions, and soil accretion. Journal of Geophysical Research: Biogeosciences, 126(12): e2021JG006573.

Arriola, J. M., and Cable, J. E. (2017) Variations in carbon burial and sediment accretion along a tidal creek in a Florida salt marsh. Limnology and Oceanography 62(S1): S15-S28.

Baustian, M. M., Stagg, C. L., Perry, C. L., Moss, L. C., and Carruthers, T. J. (2021) Long-term carbon sinks in marsh soils of coastal Louisiana are at risk to wetland loss. Journal of Geophysical Research: Biogeosciences 126(3): e2020JG005832.

Bianchi, T. S., Allison, M. A., Zhao, J., Li, X., Comeaux, R. S., Feagin, R. A., & Kulawardhana, R. W. (2013) Historical reconstruction of mangrove expansion in the Gulf of Mexico: linking climate change with carbon sequestration in coastal wetlands. Estuarine, Coastal and Shelf Science 119: 7-16.

Boyd, B. (2012) Comparison of sediment accumulation and accretion in impounded and unimpounded marshes of the Delaware Estuary. Doctoral dissertation, University of Delaware.

Boyd, B. M. and Sommerfield, C. K. (2016) Marsh accretion and sediment accumulation in a managed tidal wetland complex of Delaware Bay. Ecological Engineering, 92: 37-46.

Boyd, B. M., Sommerfield, C. K., and Elsey-Quirk, T. (2017) Hydrogeomorphic influences on salt marsh sediment accumulation and accretion in two estuaries of the US Mid-Atlantic coast. Marine Geology, 383: 132-145.

Breithaupt, J. L., Smoak, J. M., Smith III, T. J., and Sanders, C. J. (2014) Temporal variability of carbon and nutrient burial, sediment accretion, and mass accumulation over the past century in a carbonate platform mangrove forest of the Florida Everglades. Journal of Geophysical Research: Biogeosciences, 119(10): 2032-2048.

Byrd, K. B., Ballanti, L. R., Thomas, N. M., Nguyen, D. K., Holmquist, J. R., Simard, M., Windham-Myers, L., Schile, L. M., Parker, V. T., … and Castaneda-Moya, E. (2017) Biomass/Remote Sensing dataset: 30m resolution tidal marsh biomass samples and remote sensing data for six regions in the conterminous United States: U.S. Geological Survey data release, https://doi.org/10.5066/F77943K8.

Byrd, K. B., Ballanti, L., Thomas, N., Nguyen, D., Holmquist, J.R., Simard, M., and Windham-Myers, L. (2018) A remote sensing-based model of tidal marsh aboveground carbon stocks for the conterminous United States. ISPRS Journal of Photogrammetry and Remote Sensing 139: 255-271.

Byrd, K. B., Ballanti, L., Thomas, N., Nguyen, D., Holmquist, J.R., Simard, M., and Windham-Myers, L. (2020) Corrigendum to “A remote sensing-based model of tidal marsh aboveground carbon stocks for the conterminous United States”. ISPRS Journal of Photogrammetry and Remote Sensing 166: 63-67.

Callaway, J. C., Borgnis, E. L., Turner, R. E. & Milan, C. S. (2012a) Carbon sequestration and sediment accretion in San Francisco Bay tidal wetlands. Estuaries and Coasts 35(5): 1163-1181.

Callaway, J. C., Borgnis, E. L., Turner, R. E., Milan, C. S., Goodfriend, W., & Richmond, S. (2012b) "Wetland Sediment Accumulation at Corte Madera Marsh and Muzzi Marsh". San Francisco Bay Conservation and Development Commission.

Church, T. M., Sommerfield, C. K., Velinsky, D. J., Point, D., Benoit, C., Amouroux, D. & Donard, O. F. X. (2006) Marsh sediments as records of sedimentation, eutrophication and metal pollution in the urban Delaware Estuary. Marine Chemistry 102(1-2): 72-95.

Craft, C. B., & Richardson, C. J. (1998) Recent and long-term organic soil accretion and nutrient accumulation in the Everglades. Soil Science Society of America Journal 62(3): 834-843.

Crooks, S., Rybczyk, J., O'Connell, K., Devier, D.L., Poppe, K., Emmett-Mattox, S. (2014) Coastal Blue Carbon Opportunity Assessment for the Snohomish Estuary: The Climate Benefits of Estuary Restoration. Report by Environmental Science Associates, Western Washington University, EarthCorps, and Restore America's Estuaries.

Drexler, J. Z., de Fontaine, C. S., and Brown, T. A. (2009) Peat accretion histories during the past 6,000 years in marshes of the Sacramento–San Joaquin Delta, CA, USA. Estuaries and Coasts 32: 871-892.

Drexler, J. Z., Krauss, K. W., Sasser, M. C., Fuller, C. C., Swarzenski, C. M., Powell, A., ... and Orlando, J. (2013) A long-term comparison of carbon sequestration rates in impounded and naturally tidal freshwater marshes along the lower Waccamaw River, South Carolina. Wetlands 33: 965-974.

Drexler, J. Z., Woo, I., Fuller, C. C., and Nakai, G. (2019) Carbon accumulation and vertical accretion in a restored versus historic salt marsh in southern Puget Sound, Washington, United States. Restoration Ecology 27(5): 1117-1127.

Ensign, S. H., Noe, G. B., Hupp, C. R., and Skalak, K. J. (2015) Head-of-tide bottleneck of particulate material transport from watersheds to estuaries. Geophysical Research Letters 42(24): 10-671.

Gerlach, M. J., Engelhart, S. E., Kemp, A. C., Moyer, R. P., Smoak, J. M., Bernhardt, C. E., and Cahill, N. (2017) Reconstructing Common Era relative sea-level change on the Gulf Coast of Florida. Marine Geology 390: 254-269.

Giblin, A., Forbrich, I., & LTER, P. I. E. (2018) PIE LTER high marsh sediment chemistry and activity measurements, Nelson Island Creek marsh, Rowley, MA.

Hussein, A. H., Rabenhorst, M. C. & Tucker, M. L. (2004) Modeling of carbon sequestration in coastal marsh soils. Soil Science Society of America Journal 68(5): 1786-1795.

IPCC (2019) *Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories*, Volume 4: Agriculture, Forestry, and Other Land Use. Calvo Buendia, E., Tanabe K., Kranjc, A., Baasansuren, J., Fukuda, M., Ngarize, S., Osako, A., Pyrozhenko, Y., Shermanau, P., & Federici, S. (eds). IPCC, Switzerland.

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. Prepared by the National Greenhouse Gas Inventories Programme, H.S.Eggleston, L. Buendia, K. Miwa, T. Ngara & K. Tanabe (eds). IGES, Japan.

IPCC (2014) *2013 Supplement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories: Wetlands*. Hiraishi, T., Krug, T., Tanabe, K., Srivastava, N., Baasansuren, J., Fukuda, M. and Troxler, T.G. (eds.). Published: IPCC, Switzerland.

IPCC (2013) *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Stocker, T., Qin, D., Plattner, G.-K., Tignor, M. Allen, S.K., Boschung, J., Nauels, A., Xia, Y., Bex, V. and Midgley, P.M. (eds.). Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

IPCC (2003) *Good Practice Guidance for Land Use, Land-Use Change and Forestry*. LUCF Sector Good Practice Guidance, Chapter 3. Penman, J., Gytarsky, M., Hiraishi, T., Krug, T., Kruger, D., Pipatti, R., Buendia, L., Miwa, K., Ngara, T., Tanabe, K. & F. Wagner (eds). Institute of Global Environmental Strategies (IGES), on behalf of the Intergovernmental Panel on Climate Change (IPCC): Hayama, Japan.

IPCC (2000) *Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories*. Quantifying Uncertainties in Practice, Chapter 6. Penman, J and Kruger, D and Galbally, I and Hiraishi, T and Nyenzi, B and Emmanuel, S and Buendia, L and Hoppaus, R and Martinsen, T and Meijer, J and Miwa, K and Tanabe, K (eds). Institute of Global Environmental Strategies (IGES), on behalf of the Intergovernmental Panel on Climate

Change (IPCC): Hayama, Japan.

Kearney, M. S. & Stevenson, J. C. (1991) Island land loss and marsh vertical accretion rate evidence for historical sea-level changes in Chesapeake Bay. Journal of Coastal Research 7(2): 403-415.

Kemp, A. C., Sommerfield, C. K., Vane, C. H., Horton, B. P., Chenery, S., Anisfeld, S., and Nikitina, D. (2012) Use of lead isotopes for developing chronologies in recent salt-marsh sediments. Quaternary Geochronology 12: 40-49.

Köster, D., Lichter, J., Lea, P. D., & Nurse, A. (2007) Historical eutrophication in a river–estuary complex in mid-coast Maine. Ecological Applications 17(3): 765-778.

Krauss, K. W., Noe, G. B., Duberstein, J. A., Conner, W. H., Stagg, C. L., and Jones, M. C. (2018) Carbon budget assessment of tidal freshwater forested wetland and oligohaline marsh ecosystems along the Waccamaw and Savannah Rivers, USA (2005–2016). US Geological Survey Data Release. https://doi.Org/10.5066/F7TM7930.

Lagomasino, D., Corbett, D. R., and Walsh, J. P. (2013) Influence of wind-driven inundation and coastal geomorphology on sedimentation in two microtidal marshes, Pamlico River Estuary, NC. Estuaries and Coasts 36: 1165-1180.

Lu, M & Megonigal, J.P. (2017) Final Report for RAE Baseline Assessment Project. Memo to Silvestrum Climate Associates by Smithsonian Environmental Research Center, Maryland.

Lynch, J. C. (1989) Sedimentation and nutrient accumulation in mangrove ecosystems of the Gulf of Mexico, M.S. thesis, Univ. of Southwestern Louisiana, Lafayette, La.

Luk, S. Y., Todd-Brown, K., Eagle, M., McNichol, A. P., Sanderman, J., Gosselin, K., and Spivak, A. C. (2021) Soil organic carbon development and turnover in natural and disturbed salt marsh environments. Geophysical Research Letters 48(2): e2020GL090287.

Marchio, D.A., Savarese, M., Bovard, B., & Mitsch, W.J. (2016) Carbon sequestration and sedimentation in mangrove swamps influenced by hydrogeomorphic conditions and urbanization in Southwest Florida. Forests 7: 116-135.

McCombs, J.W., Herold, N.D., Burkhalter, S.G. and Robinson C.J., (2016) Accuracy Assessment of NOAA Coastal Change Analysis Program 2006-2010 Land Cover and Land Cover Change Data. Photogrammetric Engineering & Remote Sensing. 82:711-718.

McTigue, N., Davis, J., Rodriguez, A. B., McKee, B., Atencio, A., and Currin, C. (2019) Sea level rise explains changing carbon accumulation rates in a salt marsh over the past two millennia. JGR Biogeosciences.

Merrill, J. Z. (1999) Tidal Freshwater Marshes as Nutrient Sinks: particulate Nutrient Burial and Denitrification. Ph.D. Dissertation, University of Maryland, College Park, MD, 342pp.

Miller, C. B., Rodriguez, A. B., Bost, M. C., McKee, B. A., and McTigue, N. D. (2022) Carbon accumulation rates are highest at young and expanding salt marsh edges. Communications Earth & Environment 3(1): 173.

National Oceanic and Atmospheric Administration, Office for Coastal Management (2020) Coastal Change Analysis Program (C-CAP) Regional Land Cover. Charleston, SC: NOAA Office for Coastal Management. Accessed October 2020 at www.coast.noaa.gov/htdata/raster1/landcover/bulkdownload/30m_lc/.

Noe, G. B., Hupp, C. R., Bernhardt, C. E., & Krauss, K. W. (2016) Contemporary deposition and long-term accumulation of sediment and nutrients by tidal freshwater forested wetlands impacted by sea level rise. Estuaries and Coasts 39(4): 1006-1019.

Orson, R. A., Simpson, R. L., & Good, R. E. (1990) Rates of sediment accumulation in a tidal freshwater marsh. Journal of Sedimentary Research 60(6): 859-869.

Orson, R., Warren, R. & Niering, W. (1998) Interpreting sea level rise and rates of vertical marsh accretion in a southern New England tidal salt marsh. Estuarine, Coastal and Shelf Science 47(4): 419-429.

Peck, E. K., Wheatcroft, R. A., and Brophy, L. S. (2020) Controls on sediment accretion and blue carbon burial in

tidal saline wetlands: insights from the Oregon Coast, USA. Journal of Geophysical Research: Biogeosciences 125(2): e2019JG005464.

Poppe, K. L., and Rybczyk, J. M. (2021) Tidal marsh restoration enhances sediment accretion and carbon accumulation in the Stillaguamish River estuary, Washington. PloS one 16(9): e0257244.

Roman, C., Peck, J., Allen, J., King, J. & Appleby, P. (1997) Accretion of a New England (USA) salt marsh in response to inlet migration, storms, and sea-level rise. Estuarine, Coastal and Shelf Science 45(6): 717-727.

Smith, K. E., Flocks, J. G., Steyer, G. D., and Piazza, S. C. (2015) Wetland Paleoecological Study of Southwest Coastal Louisiana: Sediment Cores and Diatom Calibration Dataset. US Department of the Interior, US Geological Survey.

Thom, R. M. (1992 Accretion rates of low intertidal salt marshes in the Pacific Northwest. Wetlands 12: 147-156.

Vaughn, D. R., Bianchi, T. S., Shields, M. R., Kenney, W. F., and Osborne, T. Z. (2020) Increased organic carbon burial in northern Florida mangrove-salt marsh transition zones. Global Biogeochemical Cycles 34(5): e2019GB006334.

Villa, J. A. & Mitsch W. J. (2015) "Carbon sequestration in different wetland plant communities of Southwest Florida". International Journal for Biodiversity Science, Ecosystems Services and Management 11: 17-28.

Watson, E. B., and Byrne, R. (2013) Late Holocene Marsh Expansion in Southern San Francisco Bay, California. Estuaries and Coasts 36: 643-653.

Weis, D. A., Callaway, J. C., and Gersberg, R. M. (2001) Vertical accretion rates and heavy metal chronologies in wetland sediments of the Tijuana Estuary. Estuaries 24: 840-850.

Weston, N. B., Neubauer, S. C., Velinsky, D. J., & Vile, M. A. (2014) Net ecosystem carbon exchange and the greenhouse gas balance of tidal marshes along an estuarine salinity gradient. Biogeochemistry 120: 163-189.

Weston, N. B., Rodriguez, E., Donnelly, B., Solohin, E., Jezycki, K., Demberger, S., ... and Craft, C. B. (2023) Recent acceleration of wetland accretion and carbon accumulation along the US East Coast. Earth's Future 11(3): e2022EF003037.

Land Converted to Wetlands: Land Converted to Flooded Land

Abril, G., Gu´erin, F., Richard, S., Delmas, R., Galy-Lacaux, C., Gosse, P., et al. (2005) Carbon dioxide and methane emissions and the carbon budget of a 10-year old tropical reservoir (Petit Saut, French Guiana). Global Biogeochem. Cycles 19 (GB4007), 1–16. https://doi.org/10.1029/2005GB002457.

Barros, N., Cole, J.J., Tranvik, L.J., Prairie, Y.T., Bastviken, D., Huszar, V.L.M., et al. (2011). Carbon emission from hydroelectric reservoirs linked to reservoir age and latitude. Nat. Geosci. 4 (9), 593–596. https://doi.org/10.1038/ngeo1211.

IPCC (2019) *2019 Refinement to the 2006 Guidelines for National Greenhouse Gas Inventories*. Wetlands, Chapter 7. Lovelock, C. E., Evans, C., Barros, N., Prairie, Y. T., Alm, J., Bastviken, D., Beaulieu, J. J., Garneau, M., Harby, A., Harrison, J. A., Pare, David, Raadal, Hanne Lerche, Sherman, B., Zhang, Chengyi, Ogle, S. M.

IPCC (2013) *2013 Supplement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories: Wetlands*. Hiraishi, T., Krug, T., Tanabe, K., Srivastava, N., Baasansuren, J., Fukuda, M. and Troxler, T.G. (eds). In: IPCC, Switzerland.

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. Prepared by the National Greenhouse Gas Inventories Programme, H.S.Eggleston, L. Buendia, K. Miwa, T. Ngara & K. Tanabe (eds). IGES, Japan.

IPCC (2003) *Good Practice Guidance for Land Use, Land-Use Change and Forestry*. LUCF Sector Good Practice Guidance, Chapter 3. Penman, J., Gytarsky, M., Hiraishi, T., Krug, T., Kruger, D., Pipatti, R., Buendia, L., Miwa, K., Ngara, T., Tanabe, K. and Wagner, F. (eds). Institute of Global Environmental Strategies (IGES), on behalf of the Intergovernmental Panel on Climate Change (IPCC): Hayama, Japan.

Lehner B, Reidy Liermann C, Revenga C, Vorosmarty C, Fekete B, Crouzet P, Doll P, et al. (2011b) Global Reservoir and Dam Database, Version 1 (GRanDv1): Dams, Revision 01. In: Palisades, NY: NASA Socioeconomic Data and Applications Center (SEDAC).

Prairie, Y. T., et al. (2017) The GHG Reservoir Tool (G-res) User guide. UNESCO/IHA research project on the GHG status of freshwater reservoirs. Joint publication of the UNESCO Chair in Global Environmental Change and the International Hydropower Association**:** 38.

Teodoru, C.R., Bastien, J., Bonneville, M.C., Del Giorgio, P.a., Demarty, M., Garneau, M., et al. (2012). The net carbon footprint of a newly created boreal hydroelectric reservoir. Global Biogeochem. Cycles 26 (GB2016), 1–14. https://doi.org/10.1029/2011GB004187.

Settlements Remaining Settlements: Soil Carbon Stock Changes

AAPFCO (2016 through 2022) Commercial Fertilizers: 2013-2017. Association of American Plant Food Control Officials. University of Missouri. Columbia, MO.

Armentano, T. V., and E.S. Menges (1986) Patterns of change in the carbon balance of organic soil-wetlands of the temperate zone. Journal of Ecology 74: 755-774.

Brady, N.C. and R.R. Weil (1999) The Nature and Properties of Soils. Prentice Hall. Upper Saddle River, NJ, 881.

Brockwell, Peter J., and Richard A. Davis (2016) Introduction to time series and forecasting. Springer.

Fry, J., Xian, G., Jin, S., Dewitz, J., Homer, C., Yang, L., Barnes, C., Herold, N., and J. Wickham. (2011) Completion of the 2006 National Land Cover Database for the Conterminous United States, PE&RS 77(9):858-864.

Homer, C., J. Dewitz, J. Fry, M. Coan, N. Hossain, C. Larson, N. Herold, A. McKerrow, J.N. VanDriel and J. Wickham. (2007) Completion of the 2001 National Land Cover Database for the Conterminous United States. Photogrammetric Engineering and Remote Sensing 73(4): 337-341.

Homer, C.G., Dewitz, J.A., Yang, L., Jin, S., Danielson, P., Xian, G., Coulston, J., Herold, N.D., Wickham, J.D., and Megown, K. (2015) Completion of the 2011 National Land Cover Database for the conterminous United States-Representing a decade of land cover change information. Photogrammetric Engineering and Remote Sensing 81(5):345-354.

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change. H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (eds.). Hayama, Kanagawa, Japan.

Nelson, Mark D.; Riitters, Kurt H.; Coulston, John W.; Domke, Grant M.; Greenfield, Eric J.; Langner, Linda L.; Nowak, David J.; O'Dea, Claire B.; Oswalt, Sonja N.; Reeves, Matthew C.; Wear, David N. 2020. Defining the United States land base: a technical document supporting the USDA Forest Service 2020 RPA assessment. Gen. Tech. Rep. NRS-191. Madison, WI: U.S. Department of Agriculture, Forest Service, Northern Research Station. 70 p. https://doi.org/10.2737/NRS-GTR-191.

NRCS (1999) Soil Taxonomy: A basic system of soil classification for making and interpreting soil surveys, 2nd Edition. Agricultural Handbook Number 436, Natural Resources Conservation Service, U.S. Department of Agriculture, Washington, D.C.

Nusser, S.M. and J.J. Goebel (1997) The national resources inventory: a long-term multi-resource monitoring programme. Environmental and Ecological Statistics 4:181-204.

Ogle, S.M., M.D. Eve, F.J. Breidt, and K. Paustian (2003) Uncertainty in estimating land use and management impacts on soil organic carbon storage for U.S. agroecosystems between 1982 and 1997. Global Change Biology 9:1521-1542.

Ogle, S.M., F.J. Breidt, M. Easter, S. Williams, K. Killian, and K. Paustian (2010) Scale and uncertainty in modeled soil organic carbon stock changes for U.S. croplands using a process-based model. Global Change Biology 16:810-822.

Särndal C-E, Swensson B, Wretman, J (1992). Model Assisted Survey Sampling. Springer, New York.

Soil Survey Staff (2020) Gridded Soil Survey Geographic (gSSURGO) Database for the Conterminous United States. United States Department of Agriculture, Natural Resources Conservation Service, Accessed February 2020 (FY2020 official release), Available online at https://gdg.sc.egov.usda.gov/.

USDA-NRCS (2020) Summary Report: 2017 National Resources Inventory. Natural Resources Conservation Service, Washington, DC, and Center for Survey Statistics and Methodology, Iowa State University, Ames, Iowa. https://www.nrcs.usda.gov/wps/portal/nrcs/main/national/technical/nra/nri/results/.

Yang, L., Jin, S., Danielson, P., Homer, C., Gass, L., Bender, S. M., Case, A., Costello, C., Dewitz, J., Fry, J., Funk, M., Granneman, B., Liknes, G. C., Rigge, M. & Xian, G. (2018) A new generation of the United States National Land Cover Database: Requirements, research priorities, design, and implementation strategies. ISPRS Journal of Photogrammetry and Remote Sensing 146: 108-123.

Settlements Remaining Settlements: Changes in Carbon Stocks in Settlement Trees

deVries R.E. (1987) A Preliminary Investigation of the Growth and Longevity of Trees in Central Park. M.S. thesis, Rutgers University, New Brunswick, NJ.

Fleming, L.E. (1988) Growth Estimation of Street Trees in Central New Jersey. M.S. thesis, Rutgers University, New Brunswick, NJ.

Frelich, L.E. (1992) Predicting Dimensional Relationships for Twin Cities Shade Trees. University of Minnesota, Department of Forest Resources, St. Paul, MN, p. 33.

IPCC (2006) *2006 IPCC Guidelines* for National Greenhouse Gas Inventories. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change. H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (eds.). Hayama, Kanagawa, Japan.

MRLC (2013) National Land Cover Database 2001 (NLCD2001). Available online at: http://www.mrlc.gov/nlcd2001.php. Accessed August 2013.

Nowak, D.J. (1986) Silvics of an Urban Tree Species: Norway maple (Acer platanoides L.). M.S. thesis, College of Environmental Science and Forestry, State University of New York, Syracuse, NY.

Nowak, D.J. (1994) Atmospheric carbon dioxide reduction by Chicago's urban forest. In: Chicago's Urban Forest Ecosystem: Results of the Chicago Urban Forest Climate Project. E.G. McPherson, D.J. Nowak, and R.A. Rowntree (eds.). General Technical Report NE-186. U.S. Department of Agriculture Forest Service, Radnor, PA. pp. 83–94.

Nowak, D.J. (2012) Contrasting natural regeneration and tree planting in 14 North American cities. Urban Forestry and Urban Greening. 11: 374– 382.

Nowak, D.J. and D.E. Crane (2002) Carbon storage and sequestration by urban trees in the United States. Environmental Pollution 116(3):381–389.

Nowak, D.J. and E. Greenfield (2010) Evaluating the National Land Cover Database tree canopy and impervious cover estimates across the conterminous United States: A comparison with photo-interpreted estimates. Environmental Management. 46: 378-390.

Nowak, D.J. and E.J. Greenfield (2018a) U.S. urban forest statistics, values and projections. Journal of Forestry. 116(2):164–177

Nowak, D.J. and E.J. Greenfield (2018b) Declining urban and community tree cover in the United States. Urban Forestry and Urban Greening. 32:32-55.

Nowak, D.J., D.E. Crane, J.C. Stevens, and M. Ibarra (2002) Brooklyn's Urban Forest. General Technical Report NE-290. U.S. Department of Agriculture Forest Service, Newtown Square, PA.

Nowak, D.J., R.E. Hoehn, D.E. Crane, J.C. Stevens, J.T. Walton, and J. Bond (2008) A ground-based method of assessing urban forest structure and ecosystem services. Arboric. Urb. For. 34(6): 347-358.

Nowak, D.J., E.J. Greenfield, R.E. Hoehn, and E. Lapoint (2013) Carbon storage and sequestration by trees in urban and community areas of the United States." Environmental Pollution 178: 229-236.

Nowak, D.J. A.R. Bodine, R.E. Hoehn, C.B. Edgar, D.R. Hartel, T.W. Lister, T.J. Brandeis (2016) Austin's Urban Forest, 2014. USDA Forest Service, Northern Research Station Resources Bulletin. NRS-100. Newtown Square, PA. 55 p.

Nowak, D.J. A.R. Bodine, R.E. Hoehn, C.B. Edgar, G. Riley, D.R. Hartel, K.J. Dooley, S.M. Stanton, M.A. Hatfield, T.J. Brandeis, T.W. Lister (2017) Houston's Urban Forest, 2015. USDA Forest Service, Southern Research Station Resources Bulletin. SRS-211. Newtown Square, PA. 91 p.

Smith, W.B. and S.R. Shifley (1984) Diameter Growth, Survival, and Volume Estimates for Trees in Indiana and Illinois. Research Paper NC-257. North Central Forest Experiment Station, U.S. Department of Agriculture Forest Service, St. Paul, MN.

U.S. Department of Interior (2018) National Land Cover Database 2011 (NLCD2011). Accessed online August 16, 2018. Available online at: https://www.mrlc.gov/nlcd11_leg.php.

Settlements Remaining Settlements: N_2O Emissions from Soils

AAPFCO (2016 through 2022) Commercial Fertilizers: 2013-2017. Association of American Plant Food Control Officials. University of Missouri. Columbia, MO.

Brakebill, J.W. and Gronberg, J.M. (2017) County-Level Estimates of Nitrogen and Phosphorus from Commercial Fertilizer for the Conterminous United States, 1987-2012. U.S. Geological Survey, https://doi.org/10.5066/F7H41PKX.

Brockwell, Peter J., and Richard A. Davis (2016) Introduction to time series and forecasting. Springer.

IPCC (2013) *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1535 pp.

IPCC (2007) *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. [S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds.)]. Cambridge University Press. Cambridge, United Kingdom 996 pp.

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change. H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (eds.). Hayama, Kanagawa, Japan.

Nelson, Mark D.; Riitters, Kurt H.; Coulston, John W.; Domke, Grant M.; Greenfield, Eric J.; Langner, Linda L.; Nowak, David J.; O'Dea, Claire B.; Oswalt, Sonja N.; Reeves, Matthew C.; Wear, David N. 2020. Defining the United States land base: a technical document supporting the USDA Forest Service 2020 RPA assessment. Gen. Tech. Rep. NRS-191. Madison, WI: U.S. Department of Agriculture, Forest Service, Northern Research Station. 70 p. https://doi.org/10.2737/NRS-GTR-191.

Ogle, S.M., F.J. Breidt, M. Easter, S. Williams, K. Killian, and K. Paustian (2010) Scale and uncertainty in modeled soil organic carbon stock changes for U.S. croplands using a process-based model. Global Change Biology 16:810-822.

Särndal C-E, Swensson B, Wretman, J (1992). Model Assisted Survey Sampling. Springer, New York.

Soil Survey Staff (2020) Gridded Soil Survey Geographic (gSSURGO) Database for the Conterminous United States. United States Department of Agriculture, Natural Resources Conservation Service, Accessed February 2020 (FY2020 official release), Available online at https://gdg.sc.egov.usda.gov/.

USDA-NRCS (2020) Summary Report: 2017 National Resources Inventory. Natural Resources Conservation Service, Washington, DC, and Center for Survey Statistics and Methodology, Iowa State University, Ames, Iowa. https://www.nrcs.usda.gov/wps/portal/nrcs/main/national/technical/nra/nri/results/

Yang, L., et al. (2018). "A new generation of the United States National Land Cover Database: Requirements, research priorities, design, and implementation strategies." ISPRS Journal of Photogrammetry and Remote Sensing 146: 108-123.

Settlements Remaining Settlements: Changes in Yard Trimmings and Food Scrap Carbon Stocks in Landfills

Barlaz, M.A. (2008) "Re: Corrections to Previously Published Carbon Storage Factors." Memorandum to Randall Freed, ICF International. February 28, 2008.

Barlaz, M.A. (2005) "Decomposition of Leaves in Simulated Landfill." Letter report to Randall Freed, ICF Consulting. June 29, 2005.

Barlaz, M.A. (1998) "Carbon Storage during Biodegradation of Municipal Solid Waste Components in Laboratory-Scale Landfills." *Global Biogeochemical Cycles* 12:373–380.

De la Cruz, F.B. and M.A. Barlaz (2010) "Estimation of Waste Component Specific Landfill Decay Rates Using Laboratory-Scale Decomposition Data" *Environmental Science & Technology* 44:4722– 4728.

Eleazer, W.E., W.S. Odle, Y. Wang, and M.A. Barlaz (1997) "Biodegradability of Municipal Solid Waste Components in Laboratory-Scale Landfills." *Environmental Science & Technology* 31:911–917.

EPA (2020) *Advancing Sustainable Materials Management: Facts and Figures 2018*. U.S. Environmental Protection Agency, Office of Solid Waste and Emergency Response, Washington, D.C. Available online at https://www.epa.gov/smm/advancing-sustainable-materials-management-facts-and-figures-report.

EPA (2019) *Advancing Sustainable Materials Management: Facts and Figures*. U.S. Environmental Protection Agency, Office of Solid Waste and Emergency Response, Washington, D.C. Available online at https://www.epa.gov/smm/advancing-sustainable-materials-management-facts-and-figures-report.

EPA (2016) *Municipal Solid Waste Generation, Recycling, and Disposal in the United States: Facts and Figures*. U.S. Environmental Protection Agency, Office of Solid Waste and Emergency Response, Washington, D.C. Available online at https://archive.epa.gov/epawaste/nonhaz/municipal/web/html/msw99.html.

EPA (1995) *Compilation of Air Pollutant Emission Factors*. U.S. Environmental Protection Agency, Office of Air Quality Planning and Standards, Research Triangle Park, NC. AP-42 Fifth Edition. Available online at http://www3.epa.gov/ttnchie1/ap42/.

EPA (1991) *Characterization of Municipal Solid Waste in the United States: 1990 Update*. U.S. Environmental Protection Agency, Office of Solid Waste and Emergency Response, Washington, D.C. EPA/530-SW-90-042.

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change. H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (eds.). Hayama, Kanagawa, Japan.

IPCC (2003) *Good Practice Guidance for Land Use, Land-Use Change, and Forestry*. The Intergovernmental Panel on Climate Change, National Greenhouse Gas Inventories Programme, J. Penman et al. (eds.). Available online at http://www.ipcc-nggip.iges.or.jp/public/gpglulucf/gpglulucf.htm.

Oshins, C. and D. Block (2000) "Feedstock Composition at Composting Sites." *Biocycle* 41(9):31–34.

Tchobanoglous, G., H. Theisen, and S.A. Vigil (1993) *Integrated Solid Waste Management, 1st edition*. McGraw-Hill, NY. Cited by Barlaz (1998) "Carbon Storage during Biodegradation of Municipal Solid Waste Components in Laboratory-Scale Landfills." *Global Biogeochemical Cycles* 12:373–380.

Land Converted to Settlements

Birdsey, R. (1996) "Carbon Storage for Major Forest Types and Regions in the Conterminous United States." In R.N. Sampson and D. Hair, (eds.). Forest and Global Change, Volume 2: Forest Management Opportunities for Mitigating Carbon Emissions. American Forests. Washington, D.C., 1-26 and 261-379 (appendices 262 and 263).

Brockwell, Peter J., and Richard A. Davis (2016) Introduction to time series and forecasting. Springer. Domke, G.M., Perry, C.H., Walters, B.F., Woodall, C.W., and Smith, J.E. (2016) A framework for estimating litter carbon stocks in forests of the United States. Science of the Total Environment 557–558: 469–478.

Domke, G.M., J.E. Smith, and C.W. Woodall. (2011) Accounting for density reduction and structural loss in standing dead trees: Implications for forest biomass and carbon stock estimates in the United States. Carbon Balance and Management. 6:14.

Domke, G.M., Woodall, C.W., Walters, B.F., Smith, J.E. (2013) From models to measurements: comparing down dead wood carbon stock estimates in the U.S. forest inventory. PLoS ONE 8(3): e59949.

Domke, G.M., Perry, C.H., Walters, B.F., Woodall, C.W., and Smith, J.E. (2016) A framework for estimating litter carbon stocks in forests of the United States. Science of the Total Environment 557–558: 469–478.

Fry, J., Xian, G., Jin, S., Dewitz, J., Homer, C., Yang, L., Barnes, C., Herold, N., and Wickham, J. (2011) Completion of the 2006 National Land Cover Database for the Conterminous United States, PE&RS, Vol. 77(9):858-864.

Harmon, M.E., C.W. Woodall, B. Fasth, J. Sexton, M. Yatkov. (2011) Differences between standing and downed dead tree wood density reduction factors: A comparison across decay classes and tree species. Res. Paper. NRS-15. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northern Research Station. 40 p.

Homer, C., Dewitz, J., Fry, J., Coan, M., Hossain, N., Larson, C., Herold, N., McKerrow, A., VanDriel, J.N., and Wickham, J. (2007) Completion of the 2001 National Land Cover Database for the Conterminous United States. Photogrammetric Engineering and Remote Sensing, Vol. 73, No. 4, pp 337-341.

Homer, C.G., Dewitz, J.A., Yang, L., Jin, S., Danielson, P., Xian, G., Coulston, J., Herold, N.D., Wickham, J.D., and Megown, K. (2015) Completion of the 2011 National Land Cover Database for the conterminous United States-Representing a decade of land cover change information. Photogrammetric Engineering and Remote Sensing, v. 81, no. 5, p. 345-354.

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change, H.S. Eggleston, L. Buendia, K. Miwa, T Ngara, and K. Tanabe (eds.). Hayama, Kanagawa, Japan.

Jenkins, J.C., D.C. Chojnacky, L.S. Heath, and R.A. Birdsey (2003) "National-scale biomass estimators for United States tree species." Forest Science 49(1):12-35.

Ogle, S.M., M.D. Eve, F.J. Breidt, and K. Paustian (2003) "Uncertainty in estimating land use and management impacts on soil organic carbon storage for U.S. agroecosystems between 1982 and 1997." Global Change Biology 9:1521-1542.

Ogle, S.M., F.J. Breidt, and K. Paustian (2006) “Bias and variance in model results due to spatial scaling of measurements for parameterization in regional assessments.” Global Change Biology 12:516-523.

Schimel, D.S. (1995) "Terrestrial ecosystems and the carbon cycle." Global Change Biology 1: 77-91.

Smith, J.E.; Heath, L.S.; Skog, K.E.; Birdsey, R.A. (2006) Methods for calculating forest ecosystem and harvested carbon with standard estimates for forest types of the United States. Gen. Tech. Rep. NE-343. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northeastern Research Station. 216 p.

Tubiello, F. N., et al. (2015) "The Contribution of Agriculture, Forestry and other Land Use activities to Global Warming, 1990-2012." Global Change Biology 21:2655-2660.

USDA Forest Service. (2022) Forest Inventory and Analysis National Program: FIA Data Mart. U.S. Department of Agriculture Forest Service. Washington, D.C. Available online at: https://apps.fs.usda.gov/fia/datamart/datamart.html. Accessed on 07 October 2022.

USDA-NRCS (2020) Summary Report: 2017 National Resources Inventory. Natural Resources Conservation Service, Washington, DC, and Center for Survey Statistics and Methodology, Iowa State University, Ames, Iowa. https://www.nrcs.usda.gov/wps/portal/nrcs/main/national/technical/nra/nri/results/.

USDA-NRCS (1997) “National Soil Survey Laboratory Characterization Data,” Digital Data, Natural Resources Conservation Service, U.S. Department of Agriculture. Lincoln, NE.

Westfall, J.A., Coulston, J.W., Gray, A.N., Shaw, J.D., Radtke, P.J., Walker, D.M., Weiskittel, A.R., MacFarlane, D.W., Affleck, D.L.R., Zhao, D., Temesgen, H., Poudel, K.P., Frank, J.M., Prisley, S.P., Wang, Y., Sánchez Meador, A.J., Auty, D., and Domke, G.M. 2023. A national-scale tree volume, biomass, and carbon modeling system for the United States. Gen. Tech. Rep. WO-XX.

Woodall, C.W., L.S. Heath, G.M. Domke, and M.C. Nichols. (2011) Methods and equations for estimating aboveground volume, biomass, and carbon for trees in the U.S. forest inventory, 2010. Gen. Tech. Rep. NRS-88. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northern Research Station. 30 p.

Woodall, C.W., and V.J. Monleon (2008) Sampling protocol, estimation, and analysis procedures for the down woody materials indicator of the FIA program. Gen. Tech. Rep. NRS-22. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northern Research Station. 68 p.

Yang, L., Jin, S., Danielson, P., Homer, C., Gass, L., Bender, S. M., Case, A., Costello, C., Dewitz, J., Fry, J., Funk, M., Granneman, B., Liknes, G. C., Rigge, M. & Xian, G. (2018) A new generation of the United States National Land Cover Database: Requirements, research priorities, design, and implementation strategies. ISPRS Journal of Photogrammetry and Remote Sensing 146: 108-123.

Waste

Landfills

40 CFR Part 60, Subpart WWW (2005) Standards of Performance for Municipal Solid Waste Landfills, 60.750--60.759, Code of Federal Regulations, Title 40. Available online at: https://www.ecfr.gov/current/title-40/chapter-I/subchapter-C/part-60/subpart-WWW.

40 CFR Part 258, Subtitle D of RCRA (2012) Criteria for Municipal Solid Waste Landfills, 258.1—258.75, Code of Federal Regulations, Title 40. Available online at: https://www.ecfr.gov/cgi-bin/text-idx?node=pt40.25.258..

BioCycle (2010) "The State of Garbage in America" By L. Arsova, R. Van Haaren, N. Goldstein, S. Kaufman, and N. Themelis. *BioCycle.* December 2010. Available online at: https://www.biocycle.net/2010/10/26/the-state-of-garbage-in-america-4/.

Bronstein, K., Coburn, J., and R. Schmeltz (2012) "Understanding the EPA's Inventory of U.S. Greenhouse Gas Emissions and Sinks and Mandatory GHG Reporting Program for Landfills: Methodologies, Uncertainties, Improvements and Deferrals." Prepared for the U.S. EPA International Emissions Inventory Conference, August 2012, Tampa, Florida. Available online at: https://www3.epa.gov/ttnchie1/conference/ei20/session3/kbronstein.pdf.

Czepiel, P., B. Mosher, P. Crill, and R. Harriss (1996) "Quantifying the Effect of Oxidation on Landfill Methane Emissions." *Journal of Geophysical Research*, 101(D11):16721-16730.Dou, Z.; Ferguson, J. D.; Galligan, D. T.; Kelly, A. M.; Finn, S. T.; Giegengack, R. (2016) "Assessing U.S. food wastage and opportunities for reduction." Global Food Security Volume 8, March 2016, Pages 19-26. https://doi.org/10.1016/j.gfs.2016.02.001.

EIA (2007) Voluntary Greenhouse Gas Reports for EIA Form 1605B (Reporting Year 2006). Available online at: https://www.eia.gov/environment/pdfpages/0608s(2009)index.php.

EPA (2023a) Greenhouse Gas Reporting Program (GHGRP). 2022 Amazon S3 Data. Subpart HH: Municipal Solid Waste Landfills and Subpart TT: Industrial Waste Landfills. Accessed on August 8, 2023.

EPA (2023b) Landfill Methane Outreach Program (LMOP). 2023 Landfill and Project Level Data. July 2023. Available online at: https://www.epa.gov/lmop/landfill-gas-energy-project-data.

EPA (2020a) Wasted Food Measurement Methodology Scoping Memo. July 2020. Available online at https://www.epa.gov/sites/production/files/2020-06/documents/food_measurement_methodology_scoping_memo-6-18-20.pdf.

EPA (2020b) Advancing Sustainable Materials Management: Facts and Figures 2018. December 2020. Available online at: https://www.epa.gov/sites/production/files/2020-11/documents/2018_tables_and_figures_fnl_508.pdf.

EPA (2020c) Advancing Sustainable Materials Management: Facts and Figures 2016 and 2017. November 2019. Available online at: https://www.epa.gov/sites/default/files/2021-01/documents/2018_tables_and_figures_dec_2020_fnl_508.pdf.

EPA (2018) Advancing Sustainable Materials Management: Facts and Figures 2015. July 2018. Available online at: https://www.epa.gov/sites/production/files/2018-07/documents/smm_2015_tables_and_figures_07252018_fnl_508_0.pdf.

EPA (2016a) Industrial and Construction and Demolition Landfills. Available online at: https://www.epa.gov/landfills/industrial-and-construction-and-demolition-cd-landfills.

EPA (2016b) Advancing Sustainable Materials Management: Facts and Figures 2014. December 2016. Available online at: https://www.epa.gov/sites/production/files/2016-11/documents/2014_smm_tablesfigures_508.pdf.

EPA (2014) Advancing Sustainable Materials Management: Facts and Figures 2014. February 2014. Available online at: https://www.epa.gov/sites/production/files/2015-09/documents/2012_msw_dat_tbls.pdf.

EPA (2008) *Compilation of Air Pollution Emission Factors, Publication AP-42*, Draft Section 2.4 Municipal Solid Waste Landfills. October 2008.

EPA (1993) *Anthropogenic Methane Emissions in the United States, Estimates for 1990: Report to Congress*, U.S. Environmental Protection Agency, Office of Air and Radiation. Washington, D.C. EPA/430-R-93-003. April 1993.

EPA (1988) *National Survey of Solid Waste (Municipal) Landfill Facilities*, U.S. Environmental Protection Agency. Washington, D.C. EPA/530-SW-88-011. September 1988.

EREF (The Environmental Research & Education Foundation) (2016) Municipal Solid Waste Management in the United States: 2010 & 2013.

ERG (2023) Production Data Supplied by ERG for 1990-2022 for Pulp and Paper, Fruits and Vegetables, and Meat. September 7, 2021.

Food Waste Reduction Alliance (FWRA) (2016) Analysis of U.S. Food Waste Among Food Manufacturers, Retailers, and Restaurants. A joint project by the Food Marketing Institute, the Grocery Manufacturers Association, and the National Restaurant Association. Available online at: https://foodwastealliance.org/wp-content/uploads/2020/05/FWRA-Food-Waste-Survey-2016-Report_Final.pdf.

IPCC (2019) *2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories.* Calvo Buendia, E., Tanabe, K., Kranjc, A., Baasansuren, J., Fukuda, M., Ngarize, S., Osako, A., Pyrozhenko, Y., Shermanau, P. and Federici, S. (eds). Published: IPCC, Switzerland.

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change. [H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (eds.)]. Hayama, Kanagawa, Japan.

Mancinelli, R. and C. McKay (1985) "Methane-Oxidizing Bacteria in Sanitary Landfills." *Proc. First Symposium on Biotechnical Advances in Processing Municipal Wastes for Fuels and Chemicals*, Minneapolis, MN, 437-450. August.

RTI (2018) Methodological changes to the scale-up factor used to estimate emissions from municipal solid waste landfills in the Inventory. Memorandum prepared by K. Bronstein and M. McGrath for R. Schmeltz (EPA). March 22, 2018.

RTI (2017) Methodological changes to the methane emissions from municipal solid waste landfills as reflected in the public review draft of the 1990-2015 Inventory. Memorandum prepared by K. Bronstein and M. McGrath for R. Schmeltz (EPA). March 31, 2017.

RTI (2011) Updated Research on Methane Oxidation in Landfills. Memorandum prepared by K. Weitz (RTI) for R. Schmeltz (EPA). January 14, 2011.

Waste Business Journal (WBJ) (2021) Directory of Waste Processing & Disposal Sites 2021.

WBJ (2016) Directory of Waste Processing & Disposal Sites 2016.

WBJ (2010) Directory of Waste Processing & Disposal Sites 2010.

Wastewater Treatment and Discharge

AF&PA (2022) "AF&PA Members Achieve Progress on Water Stewardship Goal for 2020." American Forest & Paper Association. Available online at: https://www.afandpa.org/statistics-resources/afpa-members-achieve-progress-water-stewardship-goal-2020. Accessed July 2022.

AF&PA (2020) "2020 AF&PA Sustainability Report: Advancing the sustainability of an essential industry." American Forest & Paper Association. Available online at: https://www.afandpa.org/sites/default/files/2021-07/2020_AF-PA-Sustainability-Report.pdf. Accessed June 2021.

AF&PA (2018) "2018 AF&PA Sustainability Report: Advancing U.S. Paper and Wood Products Industry Sustainability Performance." American Forest & Paper Association. Available online at: http://sustainability.afandpa.org/wp-content/uploads/2018/06/2018SustainabilityReport_PAGES.pdf. Accessed July 2019.

AF&PA (2016) "2016 AF&PA Sustainability Report: Advancing U.S. Paper and Wood Products Industry Sustainability Performance." American Forest & Paper Association.

AF&PA (2014) "2014 AF&PA Sustainability Report." American Forest & Paper Association.

Beecher et al. (2007) "A National Biosolids Regulation, Quality, End Use & Disposal Survey, Preliminary Report." Northeast Biosolids and Residuals Association, April 14, 2007. Available online at: https://static1.squarespace.com/static/54806478e4b0dc44e1698e88/t/5480c7a2e4b0787f2c73ad81/1417725858575/NtlBiosldsRpt-AppD-FINAL.pdf. Accessed August 2021.

Beer Institute (2011) Brewers Almanac. Available online at: http://www.beerinstitute.org/multimedia/brewers-almanac.

Benyahia, F., M. Abdulkarim, A. Embaby, and M. Rao. (2006) Refinery Wastewater Treatment: A true Technological Challenge. Presented at the Seventh Annual U.A.E. University Research Conference.

BIER (2021) 2021 Benchmarking Study Trends & Observations. Available online at https://www.bieroundtable.com/publication/2021-water-and-energy-use-benchmarking-study/. Accessed September 2023.

Brewers Association (2021) Statistics: Number of Breweries. Available online at: https://www.brewersassociation.org/statistics-and-data/national-beer-stats/. Accessed August 2021.

Brewers Association (2016a) 2015 Sustainability Benchmarking Report. Available online at: https://www.brewersassociation.org/best-practices/sustainability/sustainability-benchmarking-tools. Accessed March 2018.

Brewers Association (2016b) Wastewater Management Guidance Manual. Available online at: https://www.brewersassociation.org/educational-publications/wastewater-management-guidance-manual. Accessed September 2017.

Cabrera (2017) "Pulp Mill Wastewater: Characteristics and Treatment." Biological Wastewater Treatment and Resource Recovery. InTech. pp. 119–139.

CAST (1995) Council for Agricultural Science and Technology. Waste Management and Utilization in Food Production and Processing. U.S.A. October 1995. ISBN 1-887383-02-6. Available online at: https://www.cast-science.org/publication/waste-management-and-utilization-in-food-production-and-processing/.

Climate Action Reserve (CAR) (2011) Landfill Project Protocol V4.0, June 2011. Available online at: http://www.climateactionreserve.org/how/protocols/us-landfill/.

Cooper (2018) Email correspondence. Geoff Cooper, Renewable Fuels Association to Kara Edquist, ERG. "Wet Mill vs. Dry Mill Ethanol Production." May 18, 2018.

DOE (2013) U.S. Department of Energy Bioenergy Technologies Office. Biofuels Basics. Available online at: http://energy.gov/eere/bioenergy/biofuels-basics. Accessed September 2013.

Donovan (1996) Siting an Ethanol Plant in the Northeast. C.T. Donovan Associates, Inc. Report presented to Northeast Regional Biomass Program (NRBP). (April). Available online at: https://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.614.856&rep=rep1&type=pdf. Accessed October 2006.

EIA (2023) Energy Information Administration. U.S. Refinery and Blender Net Production of Crude Oil and Petroleum Products (Thousand Barrels). Available online at: https://www.eia.gov/dnav/pet/pet_pnp_refp_dc_nus_mbbl_m.htm. Accessed August 2023.

EPA (2019) Preliminary Effluent Guidelines Program Plan 14. EPA-821-R-19-005. Office of Water, U.S. Environmental Protection Agency. Washington, DC. October 2019. Available online at: https://www.epa.gov/sites/production/files/2019-10/documents/prelim-eg-plan-14_oct-2019.pdf. Accessed July 2020.

EPA (2013) U.S. Environmental Protection Agency. Report on the Performance of Secondary Treatment Technology. EPA-821-R-13-001. Office of Water, U.S. Environmental Protection Agency. Washington, D.C. March 2013. Available online at: https://www.epa.gov/sites/production/files/2015-11/documents/npdes_secondary_treatment_report_march2013.pdf.

EPA (2012) U.S. Environmental Protection Agency. Clean Watersheds Needs Survey 2012 – Report to Congress. U.S. Environmental Protection Agency, Office of Wastewater Management. Washington, D.C. Available online at: https://www.epa.gov/cwns/clean-watersheds-needs-survey-cwns-2012-report-and-data#access. Accessed February 2016.

EPA (2010) U.S. Environmental Protection Agency. Nutrient Control Design Manual. U.S. Environmental Protection Agency, Office of Research and Development. Washington, D.C. EPA600-R-10-100. Available online at: https://www.epa.gov/sites/default/files/2019-08/documents/nutrient_control_design_manual.pdf. Accessed December 2023.

EPA (2008) U.S. Environmental Protection Agency. Clean Watersheds Needs Survey 2008 – Report to Congress. U.S. Environmental Protection Agency, Office of Wastewater Management. Washington, D.C. Available online at: https://www.epa.gov/cwns/clean-watersheds-needs-survey-cwns-2008-report-and-data. Accessed December 2015.

EPA (2004) U.S. Environmental Protection Agency. Clean Watersheds Needs Survey 2004 – Report to Congress. U.S. Environmental Protection Agency, Office of Wastewater Management. Washington, D.C. Available online at: https://www.epa.gov/cwns/clean-watersheds-needs-survey-cwns-report-congress-2004.

EPA (2000) U.S. Environmental Protection Agency. Clean Watersheds Needs Survey 2000 - Report to Congress. Office of Wastewater Management, U.S. Environmental Protection Agency. Washington, D.C. Available online at: https://www.epa.gov/cwns/clean-watersheds-needs-survey-cwns-2000-report-and-data. Accessed July 2007.

EPA (1999) U.S. Environmental Protection Agency. Biosolids Generation, Use and Disposal in the United States. Office of Solid Waste and Emergency Response, U.S. Environmental Protection Agency. Washington, D.C. EPA530-R-99-009. September 1999.

EPA (1998) U.S. Environmental Protection Agency. "AP-42 Compilation of Air Pollutant Emission Factors." Chapter 2.4, Table 2.4-3, page 2.4-13. Available online at: https://www.epa.gov/sites/default/files/2020-10/documents/c02s04.pdf.

EPA (1997a) U.S. Environmental Protection Agency. Estimates of Global Greenhouse Gas Emissions from Industrial and Domestic Wastewater Treatment. EPA-600/R-97-091. Office of Policy, Planning, and Evaluation, U.S. Environmental Protection Agency. Washington, D.C. September 1997.

EPA (1997b) U.S. Environmental Protection Agency. Supplemental Technical Development Document for Effluent Guidelines and Standards (Subparts B & E). EPA-821-R-97-011. Office of Water, U.S. Environmental Protection Agency. Washington, D.C. October 1997.

EPA (1996) U.S. Environmental Protection Agency. 1996 Clean Water Needs Survey Report to Congress. Assessment of Needs for Publicly Owned Wastewater Treatment Facilities, Correction of Combined Sewer Overflows, and Management of Storm Water and Nonpoint Source Pollution in the United States. Office of Wastewater Management, U.S. Environmental Protection Agency. Washington, D.C.

EPA (1993a) U.S. Environmental Protection Agency, "Anthropogenic Methane Emissions in the U.S.: Estimates for 1990, Report to Congress." Office of Air and Radiation, Washington, DC. April 1993.

EPA (1993b) U.S. Environmental Protection Agency. Development Document for the Proposed Effluent Limitations Guidelines and Standards for the Pulp, Paper and Paperboard Point Source Category. EPA-821-R-93-019. Office of Water, U.S. Environmental Protection Agency. Washington, D.C. October 1993.

EPA (1993c) Standards for the Use and Disposal of Sewage Sludge. 40 CFR Part 503.

EPA (1992) U.S. Environmental Protection Agency. Clean Watersheds Needs Survey 1992 – Report to Congress. Office of Wastewater Management, U.S. Environmental Protection Agency. Washington, D.C.

EPA (1982) U.S. Environmental Protection Agency. Development Document for Effluent Limitations Guidelines and standards for the Petroleum Refining. United States Environmental Protection Agency, Office of Water. EPA-440/1-82-014. Washington D.C. October 1982.

EPA (1975) U.S. Environmental Protection Agency. Development Document for Interim Final and Proposed Effluent Limitations Guidelines and New Source Performance Standards for the Fruits, Vegetables, and Specialties Segment

of the Canned and Preserved Fruits and Vegetables Point Source Category. United States Environmental Protection Agency, Office of Water. EPA-440/1-75-046. Washington D.C. October 1975.

EPA (1974) U.S. Environmental Protection Agency. Development Document for Effluent Limitations Guidelines and New Source Performance Standards for the Apple, Citrus, and Potato Processing Segment of the Canned and Preserved Fruits and Vegetables Point Source Category. Office of Water, U.S. Environmental Protection Agency, Washington, D.C. EPA-440/1-74-027-a. March 1974.

ERG (2023) Memorandum: Improvements to the 1990-2021 Wastewater Treatment and Discharge Greenhouse Gas Inventory. February 2023.

ERG (2021a) Revised Memorandum: Improvements to the 1990-2019 Wastewater Treatment and Discharge Greenhouse Gas Inventory. March 2021.

ERG (2021b) Draft Memorandum: Improvements to the 1990-2020 Wastewater Treatment and Discharge Greenhouse Gas Inventory. July 2021.

ERG (2021c) Draft Memorandum: Expert Judgement Documentation for the Wastewater Treatment and Discharge Greenhouse Gas Inventory Uncertainties, August 2021.

ERG (2019) Memorandum: Recommended Improvements to the 1990-2018 Wastewater Greenhouse Gas Inventory. August 2019.

ERG (2018a) Memorandum: Updates to Domestic Wastewater BOD Generation per Capita. August 2018.

ERG (2018b) Memorandum: Inclusion of Wastewater Treatment Emissions from Breweries. July 2018.

ERG (2016) Revised Memorandum: Recommended Improvements to the 1990-2015 Wastewater Greenhouse Gas Inventory. November 2016.

ERG (2013a) Memorandum: Revisions to Pulp and Paper Wastewater Inventory. October 2013.

ERG (2013b) Memorandum: Revisions to the Petroleum Refinery Wastewater Inventory. October 2013.

ERG (2008a) Memorandum: Planned Revisions of the Industrial Wastewater Inventory Emission Estimates for the 1990-2007 Inventory. 10 August 2008.

ERG (2008b) Memorandum: Estimation of Onsite Treatment at Industrial Facilities and Review of Wastewater Characterization Data. 15 April 2008.

ERG (2006a) Memorandum: Recommended Improvements to EPA's Wastewater Inventory for Industrial Wastewater. Prepared for Melissa Weitz, EPA. 11 August 2006.

ERG (2006b) Memorandum: Assessment of Greenhouse Gas Emissions from Wastewater Treatment of U.S. Ethanol Production Wastewaters. Prepared for Melissa Weitz, EPA. 10 October 2006.

FAO (2023a) FAOSTAT-Forestry Database. Available online at: http://www.fao.org/faostat/en/#data/FO. Accessed September 2023.

FAO (2023b) "Pulp and Paper Capacities Report." United States. From 1998 – 2003, 2000 – 2005, 2001 – 2006, 2002 – 2007, 2003 – 2008, 2010 – 2015, 2011 – 2016, 2012 – 2017, 2013 – 2018, 2014 – 2019, 2015 – 2020, 2016 – 2021, 2017 – 2022, 2018 – 2023, 2019 – 2024, 2020-2025, 2021-2026 reports. Available online at: http://www.fao.org/forestry/statistics/80571/en/. Accessed September 2023.

FAO (2022) FAOSTAT-Food Balance Sheets. Available online at: http://www.fao.org/faostat/en/#data/FBS. Accessed September 2023.

Foley et al. (2015) *N_2O and CH_4 Emission from Wastewater Collection and Treatment Systems: State of the Science Report and Technical Report*. GWRC Report Series. IWA Publishing, London, UK.

Great Lakes-Upper Mississippi River Board of State and Provincial Public Health and Environmental Managers. (2004) Recommended Standards for Wastewater Facilities (Ten-State Standards).

Guisasola et al. (2008) Methane formation in sewer systems. *Water Research* 42(6–7): 1421-1430.

Instituto de Estadísticas de Puerto Rico (2021) Population of Puerto Rico from 1990-1999 from "Estimados anuales poblacionales de los municipios desde 1950." Accessed February 2021. Available online at: https://censo.estadisticas.pr/EstimadosPoblacionales.

IPCC (2022) Emission factor database: Emission Factor Detail (ID:625621). The Intergovernmental Panel on Climate Change. Available online at: https://www.ipcc-nggip.iges.or.jp/EFDB/ef_detail.php.

IPCC (2019) *2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change. [CalvoBuendia, E., Tanabe, K., Kranjc, A., Baasansuren, J., Fukuda, M., Ngarize S., Osako, A., Pyrozhenko, Y., Shermanau, P. and Federici, S. (eds)]. Switzerland.

IPCC (2014) *2013 Supplement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories: Wetlands*. [Hiraishi, T., Krug, T., Tanabe, K., Srivastava, N., Baasansuren, J., Fukuda, M. and Troxler, T.G. (eds.)]. Published: IPCC, Switzerland.

IPCC (2013) *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1535 pp.

IPCC (2007) Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the *Fourth Assessment Report* of the Intergovernmental Panel on Climate Change. [S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds.)]. Cambridge University Press. Cambridge, United Kingdom 996 pp.

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change. [H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (eds.)]. Hayama, Kanagawa, Japan.

Kenari et. al (2010) An Investigation on the Nitrogen Content of a Petroleum Refinery Wastewater and its Removal by Biological Treatment. Journal of Environmental Health, Sciences, and Engineering. 7(1): 391-394.

Leverenz, H.L., G. Tchobanoglous, and J.L. Darby (2010) "Evaluation of Greenhouse Gas Emissions from Septic Systems." Water Environment Research Foundation. Alexandria, VA.

Lewis, A. (2019) Email correspondence. Ann Lewis, RFA to Kara Edquist, ERG. "Wet Mill vs Dry Mill Ethanol Production." August 20, 2019.

Malmberg, B. (2018) Draft Pulp and Paper Information for Revision of EPA Inventory of U.S. Greenhouse Gas Emissions and Sinks, Waste Chapter. National Council for Air and Stream Improvement, Inc. Prepared for Rachel Schmeltz, EPA. June 13, 2018.

Merrick (1998) Wastewater Treatment Options for the Biomass-to-Ethanol Process. Report presented to National Renewable Energy Laboratory (NREL). Merrick & Company. Subcontract No. AXE-8-18020-01. October 22, 1998.

Metcalf & Eddy, Inc. (2014) Wastewater Engineering: Treatment and Resource Recovery, 5th ed. McGraw Hill Publishing.

Metcalf & Eddy, Inc. (2003) Wastewater Engineering: Treatment, Disposal and Reuse, 4th ed. McGraw Hill Publishing.

NEBRA (2022) "U.S. National Biosolids Data." Northeast Biosolids and Residuals Associations. Available online at: https://static1.squarespace.com/static/601837d1c67bcc4e1b11862f/t/62f4f5fbae32804dd9f51ef6/1660220925356/National_BiosolidsDataSummary_NBDP_20220811.pdf

Nemerow, N.L. and A. Dasgupta (1991) Industrial and Hazardous Waste Treatment. Van Nostrand Reinhold. NY. ISBN 0-442-31934-7.

NRBP (2001) Northeast Regional Biomass Program. An Ethanol Production Guidebook for Northeast States. Washington, D.C. (May 3).

Rendleman, C.M. and Shapouri, H. (2007) New Technologies in Ethanol Production. USDA Agricultural Economic Report Number 842.

RFA (2023a) Renewable Fuels Association. Annual U.S. Fuel Ethanol Production. Available online at: https://ethanolrfa.org/statistics/annual-ethanol-production. Accessed August 2023.

RFA (2023b) Renewable Fuels Association. Monthly Grain Use for U.S. Ethanol Production Report. Available online at: https://ethanolrfa.org/statistics/feedstock-use-co-product-output. Accessed August 2023.

Ruocco (2006a) Email correspondence. Dr. Joe Ruocco, Phoenix Bio-Systems to Sarah Holman, ERG. "Capacity of Bio-Methanators (Dry Milling)." October 6, 2006.

Ruocco (2006b) Email correspondence. Dr. Joe Ruocco, Phoenix Bio-Systems to Sarah Holman, ERG. "Capacity of Bio-Methanators (Wet Milling)." October 16, 2006.

Short et al. (2017) Dissolved Methane in the Influent of Three Australian Wastewater Treatment Plants Fed by Gravity Sewers. *Sci Total Environ* 599-600: 85-93.

Short et al. (2014) Municipal Gravity Sewers: an Unrecognised Source of Nitrous Oxide. *Sci Total Environ* 468-469: 211-218.

Stier, J. (2018) Personal communications between John Stier, Brewers Association Sustainability Mentor and Amie Aguiar, ERG. Multiple dates.

Sullivan (SCS Engineers) (2010) The Importance of Landfill Gas Capture and Utilization in the U.S. Presented to SWICS, April 6, 2010. Available online at: https://www.scsengineers.com/scs-white-papers/the-importance-of-landfill-gas-capture-and-utilization-in-the-u-s/.

Sullivan (SCS Engineers) (2007) Current MSW Industry Position and State of the Practice on Methane Destruction Efficiency in Flares, Turbines, and Engines. Presented to Solid Waste Industry for Climate Solutions (SWICS). July 2007. Available online at: https://www.scsengineers.com/wp-content/uploads/2015/03/Sullivan_LFG_Destruction_Efficiency_White_Paper.pdf.

TTB (2022) Alcohol and Tobacco Tax and Trade Bureau. Beer Statistics. Available online at: https://www.ttb.gov/beer/beer-stats.shtml. Accessed July 2021.

UNFCCC (2012) CDM Methodological tool, Project emissions from flaring (Version 02.0.0). EB 68 Report. Annex 15. Available online at: http://cdm.unfccc.int/methodologies/PAmethodologies/tools/am-tool-06-v1.pdf/history_view.

U.S. Census Bureau (2023) International Database. Available online at: https://www.census.gov/data-tools/demo/idb/#/trends?YR_ANIM=2020&dashPages=DASH&FIPS_SINGLE=US&COUNTRY_YEAR=2022&menu=trendsViz&TREND_RANGE=1990,2022&TREND_STEP=5&TREND_ADD_YRS=&FIPS=AQ,GQ,CQ,RQ,VQ&measures=POP&CCODE=AS,GU,MP,PR,US,VI&CCODE_SINGLE=US&COUNTRY_YR_ANIM=2022. Accessed September 2023.

U.S. Census Bureau (2022) Annual Estimates of the Resident Population for the United States, Regions, States, District of Columbia, and Puerto Rico: April 1, 2020 to July 1, 2021. Available online at: https://www.census.gov/data/tables/time-series/demo/popest/2020s-national-total.html. Accessed July 2023.

U.S. Census Bureau (2021a) "American Housing Survey." Table 1A-4: Selected Equipment and Plumbing--All Housing Units. From 1989, 1991, 1993, 1995, 1997, 1999, 2001, 2003, 2005, 2007, and 2009 reports. Table C-04-AO Plumbing, Water, and Sewage Disposal--All Occupied Units. From 2011, 2013, 2015, 2017, 2019 and 2021 reports. Available online at http://www.census.gov/programs-surveys/ahs/data.html. Accessed August 2023.

U.S. Census Bureau (2021b) Annual Estimates of the Resident Population for the United States, Regions, States, and Puerto Rico: April 1, 2010 to July 1, 2020. Available online at: https://www.census.gov/data/tables/time-series/demo/popest/2010s-state-total.html.

U.S. Census Bureau (2013) "American Housing Survey." Table 1A-4: Selected Equipment and Plumbing--All Housing Units. From 1989, 1991, 1993, 1995, 1997, 1999, 2001, 2003, 2005, 2007, and 2009 reports. Table C-04-AO Plumbing, Water, and Sewage Disposal--All Occupied Units. From 2011, and 2013 reports. Available online at http://www.census.gov/programs-surveys/ahs/data.html. Accessed May 2020.

U.S. Census Bureau, Population Division (2011) Table 1. Intercensal Estimates of the Resident Population for the United States, Regions, States, and Puerto Rico: April 1, 2000 to July 1, 2010 (ST-EST00INT-01), Release Date: September 2011. Available online at: https://www2.census.gov/programs-surveys/popest/datasets/2000-2010/intercensal/state/st-est00int- alldata.csv.

U.S. Census Bureau, Population Division (2002) Table CO-EST2001-12-00 - Time Series of Intercensal State Population Estimates: April 1, 1990 to April 1, 2000.Available online at: https://www2.census.gov/programs-surveys/popest/tables/1990-2000/intercensal/st- co/co-est2001-12-00.pdf.

USDA (U.S. Department of Agriculture) (2023a) *Livestock Slaughter 2022 Summary.* Available online at: https://downloads.usda.library.cornell.edu/usda-esmis/files/r207tp32d/8p58qs65g/g445dv089/lsan0423.pdf

USDA (U.S. Department of Agriculture) (2023b) *Poultry Slaughter 2022 Summary.* Available online at: https://downloads.usda.library.cornell.edu/usda-esmis/files/pg15bd88s/m613p944x/ht24xx05j/pslaan23.pdf

USDA (U.S. Department of Agriculture) (2023c) *Vegetables 2022 Summary.* Available online at: https://downloads.usda.library.cornell.edu/usda-esmis/files/02870v86p/hq37x121v/4b29ck28c/vegean23.pdf

USDA (U.S. Department of Agriculture) (2023d) *Noncitrus Fruits and Nuts 2022 Summary*. Available online at: https://downloads.usda.library.cornell.edu/usda-esmis/files/zs25x846c/zk51wx21m/k356bk214/ncit0523.pdf

USDA (U.S. Department of Agriculture) (2022a) *Potato Annual 2021 Summary.* Available online at: https://downloads.usda.library.cornell.edu/usda-esmis/files/fx719m44h/gb19gf71k/37721m72q/pots0922.pdf

USDA (U.S. Department of Agriculture) (2022b) *Citrus Fruits 2022 Summary*. Available online at: https://downloads.usda.library.cornell.edu/usda-esmis/files/j9602060k/pn89ff24k/zp38xm24q/cfrt0922.pdf

USDA (2015) U.S. Department of Agriculture. Economic Research Service. Nutrient Availability (food energy, nutrients, and dietary components). Washington D.C. Available online at: https://www.ers.usda.gov/data-products/food-availability-per-capita-data-system/food-availability-per-capita-data-system. Accessed September 2023.

U.S. Poultry (2006) Email correspondence. John Starkey, USPOULTRY to D. Bartram, ERG. 30 August 2006.

White and Johnson (2003) White, P.J. and Johnson, L.A. Editors. Corn: Chemistry and Technology. 2nd ed. AACC Monograph Series. American Association of Cereal Chemists. St. Paul, MN.

World Bank (1999) Pollution Prevention and Abatement Handbook 1998, Toward Cleaner Production. The International Bank for Reconstruction and Development/The WORLDBANK. 1818 H Street, N.W. Washington, DC. 20433, USA. ISBN 0-8213-3638-X.

Composting

BioCycle (2023) BioCycle Nationwide Survey: Full-Scale Food Waste Composting Infrastructure in the U.S. Prepared by N. Goldstein, P. Luu, and S. Motta. Available online at: https://www.biocycle.net/us-food-waste-composting-infrastructure/.

BioCycle (2018a) Organic Waste Bans and Recycling Laws to Tackle Food Waste. Prepared by E. Broad Lieb, K. Sandson, L. Macaluso, and C. Mansell. Available online at: https://www.biocycle.net/2018/09/11/organic-waste-bans-recycling-laws-tackle-food-waste/.

BioCycle (2018b) State Food Waste Recycling Data Collection, Reporting Analysis. Prepared by Nora Goldstein. Available online at: http://compostcolab.wpengine.com/wp-content/uploads/2018/11/State-Food-Waste-Recycling-Data-Collection-Reporting-Analysis.pdf.

BioCycle (2017) The State of Organics Recycling in the U.S. Prepared by Nora Goldstein. Available online at http://www.biocycle.net/17_10_06_1/0001/BioCycle_StateOfOrganicsUS.pdf.

BioCycle (2010) The State of Garbage in America. Prepared by Rob van Haaren, Nickolas Themelis and Nora Goldstein. Available online at http://www.biocycle.net/images/art/1010/bc101016_s.pdf.

Cornell Composting (1996) Monitoring Compost Moisture. Cornell Waste Management Institute. Available online at: http://compost.css.cornell.edu/monitor/monitormoisture.html.

Cornell Waste Management Institute (2007) The Science of Composting. Available online at http://cwmi.css.cornell.edu/chapter1.pdf.

EPA (2020) *Advancing Sustainable Materials Management: 2018 Tables and Figures*. Office of Solid Waste and Emergency Response, U.S. Environmental Protection Agency, Washington, D.C. Available online at: https://www.epa.gov/sites/default/files/2021-01/documents/2018_tables_and_figures_dec_2020_fnl_508.pdf.

EPA (2018) *Advancing Sustainable Materials Management: 2015 Tables and Figures*. Office of Solid Waste and Emergency Response, U.S. Environmental Protection Agency, Washington, D.C. Available online at https://www.epa.gov/sites/production/files/2018-07/documents/smm_2015_tables_and_figures_07252018_fnl_508_0.pdf.

EPA (2016) *Advancing Sustainable Materials Management: Facts and Figures 2014*. Office of Solid Waste and Emergency Response, U.S. Environmental Protection Agency, Washington, D.C. Available online at https://www.epa.gov/sites/production/files/2016-11/documents/2014_smm_tablesfigures_508.pdf.

EPA (2014) *Municipal Solid Waste in the United States: 2012 Facts and Figures*. Office of Solid Waste and Emergency Response, U.S. Environmental Protection Agency, Washington, D.C. Available online at https://www.epa.gov/sites/default/files/2015-09/documents/2012_msw_fs.pdf.

Harvard Law School and Center for EcoTechnology (CET) (2019) Bans and Beyond: Designing and Implementing Organic Waste Bans and Mandatory Organics Recycling Laws. Prepared by Katie Sandson and Emily Broad Leib, Harvard Law School Food Law and Policy Clinic, with input from Lorenzo Macaluso and Coryanne Mansell, Center for EcoTechnology (CET). Available online at https://wastedfood.cetonline.org/wp-content/uploads/2019/07/Harvard-Law-School-FLPC-Center-for-EcoTechnology-CET-Organic-Waste-Bans-Toolkit.pdf.

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. Volume 5: Waste, Chapter 4: Biological Treatment of Solid Waste, Table 4.1. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change, H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (eds.). Hayama, Kanagawa, Japan. Available online at https://www.ipcc-nggip.iges.or.jp/public/2006gl/pdf/5_Volume5/V5_4_Ch4_Bio_Treat.pdf.

Kijanka (2020) Email correspondence. Kenin Kijanka, EPA Region 2 to Rachel Schmeltz, EPA HQ. "Puerto Rico Composting Operations." November 13, 2020.

University of Maine (2016) Compost Report Interpretation Guide. Soil Testing Lab. Available online at: https://umaine.edu/soiltestinglab/wp-content/uploads/sites/227/2016/07/Compost-Report-Interpretation-Guide.pdf.

U.S. Census Bureau, Population Division (2023) Table 1. Annual Estimates of the Resident Population for the United States, Regions, States, the District of Columbia, and Puerto Rico: April 1, 2020 to July 1, 2022 (NST-EST2022-POP). Available online at https://www.census.gov/data/tables/time-series/demo/popest/2020s-state-total.html.

U.S. Census Bureau, Population Division (2022) Table 1. Annual Estimates of the Resident Population for the United States, Regions, States, the District of Columbia, and Puerto Rico: April 1, 2020 to July 1, 2021 (NST-EST2021-POP). Available online at https://www.census.gov/data/datasets/time-series/demo/popest/2020s-national-total.html.

U.S. Census Bureau (2021) Table 1. Annual Estimates of the Resident Population for the United States, Regions, States, the District of Columbia, and Puerto Rico: April 1, 2010 to July 1, 2019; April 1, 2020; and July 1, 2020 (NST-EST2020). Available online at https://www.census.gov/programs-surveys/popest/technical-documentation/research/evaluation-estimates/2020-evaluation-estimates/2010s-totals-national.html.

U.S. Composting Council (2022) State and City Organics Bans, as of June 2021. Accessed on September 29, 2022. Available at https://www.compostingcouncil.org/page/organicsbans.

U.S. Composting Council (2010) Yard Trimmings Bans: Impact and Support. Prepared by Stuart Buckner, Executive Director, U.S., Composting Council. Available online at https://cdn.ymaws.com/www.compostingcouncil.org/resource/resmgr/images/advocacy/Yard-Trimmings-Ban-Impacts-a.pdf.

Anaerobic Digestion at Biogas Facilities

Bronstein, Kate (2021) Expert Judgement Uncertainty of quantity of materials digested. RTI International, Solid Waste Management GHG Expert.

EPA (2023) Anaerobic Digestion Facilities Processing Food Waste in the United States (2019): Survey Results. April 2023 EPA 530-R-23-003. April 2023. Available online at https://www.epa.gov/system/files/documents/2023-04/Anaerobic_Digestion_Facilities_Processing_Food_Waste_in_the_United_States_2019_20230404_508.pdf.

EPA (2021) Anaerobic Digestion Facilities Processing Food Waste in the United States (2017 & 2018): Survey Results. January 2021 EPA/903/S-21/001. Available online at https://www.epa.gov/sites/default/files/2021-02/documents/2021_final_ad_report_feb_2_with_links.pdf.

EPA (2020) Types of Anaerobic Digesters: Common Ways to Describe Digesters. Available online at https://www.epa.gov/anaerobic-digestion/types-anaerobic-digesters.

EPA (2019) Anaerobic Digestion Facilities Processing Food Waste in the United States in 2016: Survey Results. September 2019 EPA/903/S-19/001. Available online at https://www.epa.gov/sites/production/files/2018-08/documents/ad_data_report_final_508_compliant_no_password.pdf.

EPA (2018) Anaerobic Digestion Facilities Processing Food Waste in the United States in 2015: Survey Results. May 2018 EPA/903/S-18/001. Available online at https://www.epa.gov/sites/production/files/2019-09/documents/ad_data_report_v10_-_508_comp_v1.pdf.

EPA (2016) Frequently Asked Questions About Anaerobic Digestion. Available online at https://www.epa.gov/anaerobic-digestion/frequent-questions-about-anaerobic-digestion#codigestion.

EPA (1993) Anthropogenic Methane Emissions in the U.S.: Estimates for 1990, Report to Congress. Office of Air and Radiation, Washington, DC. April 1993.

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories. Volume 5: Waste, Chapter 4: Biological Treatment of Solid Waste, Table 4.1*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change, H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (eds.). Hayama, Kanagawa, Japan. Available online at https://www.ipcc-nggip.iges.or.jp/public/2006gl/pdf/5_Volume5/V5_4_Ch4_Bio_Treat.pdf.

Water Environment Federation (WEF) (2012) What Every Operator Should Know about Anaerobic Digestion. Available online at https://www.wef.org/globalassets/assets-wef/direct-download-library/public/operator-essentials/wet-operator-essentials---anaerobic-digestion---dec12.pdf.

Waste Incineration

RTI (2009) Hospital/Medical/Infectious Waste Incinerators: Summary of Requirements for Revised or New Section 111(d)/129 State Plans Following Amendments to the Emission Guidelines. Available online at https://nepis.epa.gov/Exe/ZyPDF.cgi/P1009ZW6.PDF?Dockey=P1009ZW6.PDF.

Waste Sources of Precursor Greenhouse Gas Emissions

EPA (2023a) "Criteria pollutants National Tier 1 for 1970 - 2023." National Emissions Inventory (NEI) Air Pollutant Emissions Trends Data. Office of Air Quality Planning and Standards, March 2024. Available online at: https://www.epa.gov/air-emissions-inventories/air-pollutant-emissions-trends-data.

EPA (2023b) "2020 National Emissions Inventory Technical Support Document: Introduction." Office of Air Quality Planning and Standards, March 2023. Available online at: https://www.epa.gov/system/files/documents/2023-01/NEI2020_TSD_Section1_Introduction.pdf.

Recalculations and Improvements

IPCC (2019) *2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change. Calvo Buendia, E., Tanabe, K., Kranjc, A., Baasansuren, J., Fukuda, M., Ngarize, S., Osako, A., Pyrozhenko, Y., Shermanau, P. and Federici, S. (eds). Published: IPCC, Switzerland. IPCC (2013) *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1535 pp.

IPCC (2007) *Climate Change 2007: The Physical Science Basis*. Contribution of Working Group I to the *Fourth Assessment Report* of the Intergovernmental Panel on Climate Change. [S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds.)]. Cambridge University Press. Cambridge, United Kingdom 996 pp.

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change. [H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (eds.)]. Hayama, Kanagawa, Japan.

Abbreviations

ABS	Acrylonitrile butadiene styrene
AC	Air conditioner
ACC	American Chemistry Council
AEDT	FAA Aviation Environmental Design Tool
AEO	Annual Energy Outlook
AER	All-electric range
AF&PA	American Forest and Paper Association
AFEAS	Alternative Fluorocarbon Environmental Acceptability Study
AFOLU	Agriculture, Forestry, and Other Land Use
AFV	Alternative fuel vehicle
AGA	American Gas Association
AGR	Acid gas removal
AHEF	Atmospheric and Health Effects Framework
AHRI	Air-Conditioning, Heating, and Refrigeration Institute
AIM Act	American Innovation and Manufacturing Act
AISI	American Iron and Steel Institute
ALU	Agriculture and Land Use
ANGA	American Natural Gas Alliance
ANL	Argonne National Laboratory
APC	American Plastics Council
API	American Petroleum Institute
APTA	American Public Transportation Association
AR4	IPCC *Fourth Assessment Report*
AR5	IPCC *Fifth Assessment Report*
AR6	IPCC *Sixth Assessment Report*
ARI	Advanced Resources International
ARMA	Autoregressive moving-average
ARMS	Agricultural Resource Management Surveys
ASAE	American Society of Agricultural Engineers
ASLRRA	American Short-line and Regional Railroad Association
ASR	Annual Statistical Report
ASTM	American Society for Testing and Materials
AZR	American Zinc Recycling
BCEF	Biomass conversion and expansion factors
BEA	Bureau of Economic Analysis, U.S. Department of Commerce
BIER	Beverage Industry Environmental Roundtable
BLM	Bureau of Land Management
BoC	Bureau of Census
BOD	Biological oxygen demand
BOD5	Biochemical oxygen demand over a 5-day period
BOEM	Bureau of Ocean Energy Management
BOEMRE	Bureau of Ocean Energy Management, Regulation and Enforcement
BOF	Basic oxygen furnace
BRS	Biennial Reporting System
BSEE	Bureau of Safety and Environmental Enforcement
BTS	Bureau of Transportation Statistics, U.S. Department of Transportation
Btu	British thermal unit
C	Carbon
C&D	Construction and demolition waste
C&EN	Chemical and Engineering News
CAAA	Clean Air Act Amendments of 1990
CAFOS	Concentrated Animal Feeding Operations
CAGR	Compound Annual Growth Rate
CaO	Calcium oxide
CAPP	Canadian Association of Petroleum Producers
CARB	California Air Resources Board
CBI	Confidential business information
C-CAP	Coastal Change Analysis Program
CDAT	Chemical Data Access Tool
CEAP	USDA-NRCS Conservation Effects Assessment Program
CEFM	Cattle Enteric Fermentation Model
CEMS	Continuous emission monitoring system
CFC	Chlorofluorocarbon
CFR	Code of Federal Regulations
CGA	Compressed Gas Association
CH_4	Methane
CHAPA	California Health and Productivity Audit
CHP	Combined heat and power
CI	Confidence interval
CIGRE	International Council on Large Electric Systems
CKD	Cement kiln dust
CLE	Crown Light Exposure
CMA	Chemical Manufacturer's Association
CMM	Coal mine methane
CMOP	Coalbed Methane Outreach Program
CMR	Chemical Market Reporter
CNG	Compressed natural gas
CO	Carbon monoxide
CO_2	Carbon dioxide
COD	Chemical oxygen demand
COGCC	Colorado Oil and Gas Conservation Commission
CONUS	Continental United States
CRF	Common Reporting Format
CRM	Component ratio method
CRP	Conservation Reserve Program
CSRA	Carbon Sequestration Rural Appraisals
CTIC	Conservation Technology Information Center
CVD	Chemical vapor deposition
CWNS	Clean Watershed Needs Survey
d.b.h	Diameter breast height
DE	Digestible energy

DESC	Defense Energy Support Center-DoD's Defense Logistics Agency
DFAMS	Defense Fuels Automated Management System
DGGS	Division of Geological & Geophysical Surveys
DHS	Department of Homeland Security
DLA	DoD's Defense Logistics Agency
DM	Dry matter
DOC	Degradable organic carbon
DOC	U.S. Department of Commerce
DoD	U.S. Department of Defense
DOE	U.S. Department of Energy
DOI	U.S. Department of the Interior
DOM	Dead organic matter
DOT	U.S. Department of Transportation
DRE	Destruction or removal efficiencies
DRI	Direct Reduced Iron
EAF	Electric arc furnace
EDB	Aircraft Engine Emissions Databank
EDF	Environmental Defense Fund
EER	Energy economy ratio
EF	Emission factor
EFMA	European Fertilizer Manufacturers Association
EJ	Exajoule
EGR	Exhaust gas recirculation
EGU	Electric generating unit
EIA	Energy Information Administration, U.S. Department of Energy
EIIP	Emissions Inventory Improvement Program
EOR	Enhanced oil recovery
EPA	U.S. Environmental Protection Agency
EPRI	Electric Power Research Institute
EREF	Environment Research & Education Foundation
ERS	Economic Research Service
ETMS	Enhanced Traffic Management System
EV	Electric vehicle
EVI	Enhanced Vegetation Index
FAA	Federal Aviation Administration
FAO	Food and Agricultural Organization
FAOSTAT	Food and Agricultural Organization database
FAS	Fuels Automated System
FCCC	Framework Convention on Climate Change
FEB	Fiber Economics Bureau
FEMA	Federal Emergency Management Agency
FERC	Federal Energy Regulatory Commission
FGD	Flue gas desulfurization
FHWA	Federal Highway Administration
FIA	Forest Inventory and Analysis
FIADB	Forest Inventory and Analysis Database
FIPR	Florida Institute of Phosphate Research
FOD	First order decay
FOEN	Federal Office for the Environment
FOKS	Fuel Oil and Kerosene Sales
FQSV	First-quarter of silicon volume
FSA	Farm Service Agency
FTA	Federal Transit Authority
FTP	Federal Test Procedure
g	Gram
G&B	Gathering and boosting
GaAs	Gallium arsenide
GCV	Gross calorific value
GDP	Gross domestic product
GEI	Gulfwide Emissions Inventory
GHG	Greenhouse gas
GHGRP	EPA's Greenhouse Gas Reporting Program
GIS	Geographic Information Systems
GJ	Gigajoule
GOADS	Gulf Offshore Activity Data System
GOM	Gulf of Mexico
GPG	Good Practice Guidance
GRI	Gas Research Institute
GSAM	Gas Systems Analysis Model
GTI	Gas Technology Institute
GWP	Global warming potential
ha	Hectare
HBFC	Hydrobromofluorocarbon
HC	Hydrocarbon
HCFC	Hydrochlorofluorocarbon
HCFO	Hydrochlorofluoroolefin
HDDV	Heavy duty diesel vehicle
HDGV	Heavy duty gas vehicle
HDPE	High density polyethylene
HF	Hydraulically fractured
HFC	Hydrofluorocarbon
HFO	Hydrofluoroolefin
HFE	Hydrofluoroether
HHV	Higher Heating Value
HMA	Hot Mix Asphalt
HMIWI	Hospital/medical/infectious waste incinerator
HTF	Heat Transfer Fluid
HTS	Harmonized Tariff Schedule
HVAE	High Voltage Anode Effects
HWP	Harvested wood product
IBF	International bunker fuels
IC	Integrated Circuit
ICAO	International Civil Aviation Organization
ICBA	International Carbon Black Association
ICE	Internal combustion engine
ICR	Information Collection Request
IEA	International Energy Agency
IFO	Intermediate Fuel Oil
IGES	Institute of Global Environmental Strategies
IISRP	International Institute of Synthetic Rubber Products
ILENR	Illinois Department of Energy and Natural Resources
IMO	International Maritime Organization
IPAA	Independent Petroleum Association of America
IPCC	Intergovernmental Panel on Climate Change

IPPU	Industrial Processes and Product Use
ISO	International Organization for Standardization
ITC	U.S. International Trade Commission
ITRS	International Technology Roadmap for Semiconductors
JWR	Jim Walters Resources
KCA	Key category analysis
kg	Kilogram
kt	Kiloton
kWh	Kilowatt hour
LDPE	Low density polyethylene
LDT	Light-duty truck
LDV	Light-duty vehicle
LEV	Low emission vehicles
LFG	Landfill gas
LFGTE	Landfill gas-to-energy
LHV	Lower Heating Value
LKD	Lime kiln dust
LLDPE	Linear low density polyethylene
LMOP	EPA's Landfill Methane Outreach Program
LNG	Liquefied natural gas
LPG	Liquefied petroleum gas(es)
LTO	Landing and take-off
LULUCF	Land Use, Land-Use Change, and Forestry
LVAE	Low Voltage Anode Effects
M&R	Metering and regulating
MARPOL	International Convention for the Prevention of Pollution from Ships
MC	Motorcycle
MCF	Methane conversion factor
MCL	Maximum Contaminant Levels
MCFD	Thousand cubic feet per day
MDI	Metered dose inhalers
MDP	Management and design practices
MECS	EIA Manufacturer's Energy Consumption Survey
MEMS	Micro-electromechanical systems
MER	Monthly Energy Review
MGO	Marine gas oil
MgO	Magnesium oxide
MJ	Megajoule
MLRA	Major Land Resource Area
mm	Millimeter
MMBtu	Million British thermal units
MMCF	Million cubic feet
MMCFD	Million cubic feet per day
MMS	Minerals Management Service
MMT	Million metric tons
MMTCE	Million metric tons carbon equivalent
MMT CO_2 Eq.	Million metric tons carbon dioxide equivalent
MODIS	Moderate Resolution Imaging Spectroradiometer
MoU	Memorandum of Understanding
MOVES	U.S. EPA's Motor Vehicle Emission Simulator model
MPG	Miles per gallon
MRLC	Multi-Resolution Land Characteristics Consortium
MRV	Monitoring, reporting, and verification
MSHA	Mine Safety and Health Administration
MSW	Municipal solid waste
MT	Metric ton
MTBE	Methyl Tertiary Butyl Ether
MTBS	Monitoring Trends in Burn Severity
MVAC	Motor vehicle air conditioning
MY	Model year
N_2O	Nitrous oxide
NA	Not applicable; Not available
NACWA	National Association of Clean Water Agencies
NAFTA	North American Free Trade Agreement
NAHMS	National Animal Health Monitoring System
NAICS	North American Industry Classification System
NAPAP	National Acid Precipitation and Assessment Program
NARR	North American Regional Reanalysis Product
NAS	National Academies of Sciences, Engineering, and Medicine
NASA	National Aeronautics and Space Administration
NASF	National Association of State Foresters
NASS	USDA's National Agriculture Statistics Service
NC	No change
NCASI	National Council of Air and Stream Improvement
NCV	Net calorific value
ND	No data
NE	Not estimated
NEH	National Engineering Handbook
NEI	National Emissions Inventory
NEMA	National Electrical Manufacturers Association
NEMS	National Energy Modeling System
NESHAP	National Emission Standards for Hazardous Air Pollutants
NEU	Non-Energy Use
NEV	Neighborhood Electric Vehicle
NF_3	Nitrogen trifluoride
NFI	National forest inventory
NGL	Natural gas liquids
NGO	Non-Governmental Organization
NID	National inventory of Dams
NIR	National Inventory Report
NLA	National Lime Association
NLCD	National Land Cover Dataset
NMOC	Non-methane organic compounds
NMVOC	Non-methane volatile organic compound
NMOG	Non-methane organic gas
NO	Not occurring
NO_2	Nitrogen dioxide

NO_x	Nitrogen oxides
NOAA	National Oceanic and Atmospheric Administration
NOF	Not on feed
NPDES	National Pollutant Discharge Elimination System
NPP	Net primary productivity
NPRA	National Petroleum and Refiners Association
NRBP	Northeast Regional Biomass Program
NRC	National Research Council
NRCS	Natural Resources Conservation Service
NREL	National Renewable Energy Laboratory
NRI	National Resources Inventory
NSCEP	National Service Center for Environmental Publications
NSCR	Non-selective catalytic reduction
NSPS	New source performance standards
NWS	National Weather Service
OAG	Official Airline Guide
OAP	EPA Office of Atmospheric Programs
OAQPS	EPA Office of Air Quality Planning and Standards
ODP	Ozone depleting potential
ODS	Ozone depleting substances
OECD	Organization of Economic Co-operation and Development
OEM	Original equipment manufacturers
OGJ	Oil & Gas Journal
OGOR	Oil and Gas Operations Reports
OH	Hydroxyl radical
OPEC	Organization of Petroleum-Exporting Countries
OMS	EPA Office of Mobile Sources
ORNL	Oak Ridge National Laboratory
OSHA	Occupational Safety and Health Administration
OTA	Office of Technology Assessment
OTAQ	EPA Office of Transportation and Air Quality
OVS	Offset verification statement
PADUS	Protected Areas Database of the United States
PAH	Polycyclic aromatic hydrocarbons
PCA	Portland Cement Association
PCC	Precipitate calcium carbonate
PDF	Probability Density Function
PECVD	Plasma enhanced chemical vapor deposition
PET	Polyethylene terephthalate
PET	Potential evapotranspiration
PEVM	PFC Emissions Vintage Model
PFC	Perfluorocarbon
PFPE	Perfluoropolyether
PHEV	Plug-in hybrid vehicles
PHMSA	Pipeline and Hazardous Materials Safety Administration
PI	Productivity index
PLS	Pregnant liquor solution
PM	Particulate matter
POTW	Publicly Owned Treatment Works
ppbv	Parts per billion (10^9) by volume
ppm	Parts per million
ppmv	Parts per million (10^6) by volume
pptv	Parts per trillion (10^{12}) by volume
PRCI	Pipeline Research Council International
PRP	Pasture/Range/Paddock
PS	Polystyrene
PSU	Primary Sample Unit
PU	Polyurethane
PVC	Polyvinyl chloride
PV	Photovoltaic
QA/QC	Quality Assurance and Quality Control
QBtu	Quadrillion Btu
R&D	Research and Development
RECs	Reduced Emissions Completions
RCRA	Resource Conservation and Recovery Act
RFA	Renewable Fuels Association
RFS	Renewable Fuel Standard
RMA	Rubber Manufacturers' Association
RPA	Resources Planning Act
RTO	Regression-through-the-origin
SAE	Society of Automotive Engineers
SAGE	System for assessing Aviation's Global Emissions
SAIC	Science Applications International Corporation
SAN	Styrene Acrylonitrile
SAR	IPCC Second Assessment Report
SCR	Selective catalytic reduction
SCSE	South central and southeastern coastal
SDR	Steel dust recycling
SEC	Securities and Exchange Commission
SEMI	Semiconductor Equipment and Materials Industry
SF_6	Sulfur hexafluoride
SIA	Semiconductor Industry Association
SiC	Silicon carbide
SICAS	Semiconductor International Capacity Statistics
SNAP	Significant New Alternative Policy Program
SNG	Synthetic natural gas
SO_2	Sulfur dioxide
SOC	Soil Organic Carbon
SOG	State of Garbage survey
SOHIO	Standard Oil Company of Ohio
SSURGO	Soil Survey Geographic Database
STMC	Scrap Tire Management Council
SULEV	Super Ultra Low Emissions Vehicle
SWANA	Solid Waste Association of North America
SWDS	Solid waste disposal sites
SWICS	Solid Waste Industry for Climate Solutions
TA	Treated anaerobically (wastewater)
TAM	Typical animal mass
TAME	Tertiary amyl methyl ether
TAR	IPCC Third Assessment Report
TBtu	Trillion Btu
TDN	Total digestible nutrients
TEDB	Transportation Energy Data Book

TFI	The Fertilizer Institute
TIGER	Topologically Integrated Geographic Encoding and Referencing survey
TJ	Terajoule
TLEV	Traditional low emissions vehicle
TMLA	Total Manufactured Layer Area
TOW	Total organics in wastewater
TPO	Timber Product Output
TRI	Toxic Release Inventory
TSDF	Hazardous waste treatment, storage, and disposal facility
TTB	Tax and Trade Bureau
TVA	Tennessee Valley Authority
UAN	Urea ammonium nitrate
UDI	Utility Data Institute
UFORE	U.S. Forest Service's Urban Forest Effects model
UG	Underground (coal mining)
U.S.	United States
U.S. ITC	United States International Trade Commission
UEP	United Egg Producers
ULEV	Ultra low emission vehicle
UNEP	United Nations Environmental Programme
UNFCCC	United Nations Framework Convention on Climate Change
USAA	U.S. Aluminum Association
USAF	United States Air Force
USDA	United States Department of Agriculture
USFS	United States Forest Service
USGS	United States Geological Survey
USITC	U.S. International Trade Commission
VAIP	EPA's Voluntary Aluminum Industrial Partnership
VAM	Ventilation air methane
VKT	Vehicle kilometers traveled
VMT	Vehicle miles traveled
VOCs	Volatile organic compounds
VS	Volatile solids
WBJ	Waste Business Journal
WEF	Water Environment Federation
WERF	Water Environment Research Federation
WFF	World Fab Forecast (previously WFW, World Fab Watch)
WGC	World Gas Conference
WIP	Waste-in-place
WMO	World Meteorological Organization
WMS	Waste management systems
WRRF	Water resource recovery facilities
WTE	Waste-to-energy
WW	Wastewater
WWTP	Wastewater treatment plant
ZEVs	Zero emissions vehicles

ENVIRONMENTAL HEALTH

Understanding Concentrated Animal Feeding Operations and Their Impact on Communities



NALBOH
National Association of Local Boards of Health

Understanding Concentrated Animal Feeding Operations and Their Impact on Communities

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Foreword

The National Association of Local Boards of Health (NALBOH) is pleased to provide *Understanding Concentrated Animal Feeding Operations and Their Impact on Communities* to assist local boards of health who have concerns about concentrated animal feeding operations (CAFOs) or large industrial animal farms in their communities. The Environmental Health Services Branch of the Centers for Disease Control and Prevention (CDC), National Center for Environmental Health (NCEH) encouraged the development of this product and provided technical oversight and financial support. This publication was supported by Cooperative Agreement Number 5U38HM000512. Its contents are solely the responsibility of the authors and do not necessarily represent the official views of the CDC.

The mission of NALBOH is to strengthen boards of health, enabling them to promote and protect the health of their communities, through education, technical assistance, and advocacy. Boards of health are responsible for fulfilling three public health core functions: assessment, policy development, and assurance. For a health agency, this includes overseeing and ensuring that there are sufficient resources, effective policies and procedures, partnerships with other organizations and agencies, and regular evaluation of an agency's services.

NALBOH is confident that *Understanding Concentrated Animal Feeding Operations and Their Impact on Communities* will help local board of health members understand their role in developing ways to mitigate potential problems associated with CAFOs. We trust that the information provided in this guide will enable board of health members to develop and sustain monitoring programs, investigate developing policy related to CAFOs, and create partnerships with other local and state agencies and officials to improve the health and well-being of communities everywhere.

A special thanks to Jeffrey Neistadt (NALBOH's Director – Education and Training), NALBOH's Environmental Health subcommittee, and any local board of health members and health department staff who were contacted during the development of this document for their contributions and support.

Notes

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Introduction

Livestock farming has undergone a significant transformation in the past few decades. Production has shifted from smaller, family-owned farms to large farms that often have corporate contracts. Most meat and dairy products now are produced on large farms with single species buildings or open-air pens (MacDonald & McBride, 2009). Modern farms have also become much more efficient. Since 1960, milk production has doubled, meat production has tripled, and egg production has quadrupled (Pew Commission on Industrial Animal Farm Production, 2009). Improvements to animal breeding, mechanical innovations, and the introduction of specially formulated feeds and animal pharmaceuticals have all increased the efficiency and productivity of animal agriculture. It also takes much less time to raise a fully grown animal. For example, in 1920, a chicken took approximately 16 weeks to reach 2.2 lbs., whereas now they can reach 5 lbs. in 7 weeks (Pew, 2009).

New technologies have allowed farmers to reduce costs, which mean bigger profits on less land and capital. The current agricultural system rewards larger farms with lower costs, which results in greater profit and more incentive to increase farm size.

AFO vs. CAFO

A CAFO is a specific type of large-scale industrial agricultural facility that raises animals, usually at high-density, for the consumption of meat, eggs, or milk. To be considered a CAFO, a farm must first be categorized as an animal feeding operation (AFO). An AFO is a lot or facility where animals are kept confined and fed or maintained for 45 or more days per year, and crops, vegetation, or forage growth are not sustained over a normal growing period (Environmental Protection Agency [EPA], 2009). CAFOs are classified by the type and number of animals they contain, and the way they discharge waste into the water supply. CAFOs are AFOs that contain at least a certain number of animals, or have a number of animals that fall within a range and have waste materials that come into contact with the water supply. This contact can either be through a pipe that carries manure or wastewater to surface water, or by animal contact with surface water that runs through their confined area. (See Appendix A)

History

AFOs were first identified as potential pollutants in the 1972 Clean Water Act. Section 502 identified "feedlots" as "point sources" for pollution along with other industries, such as fertilizer manufacturing. Consequently, a permit program entitled the National Pollutant Discharge Elimination System (NPDES) was created which set effluent limitation guidelines and standards (ELGs) for CAFOs. CAFOs have since been regulated by NPDES or a state equivalent since the mid-1970s. The definitions of what was considered an AFO or CAFO were created by the EPA for the NPDES process in 1976. These regulations remained in effect for more than 25 years, but increases and changes to farm size and production methods required an update to the permit system.

The regulations guiding CAFO permits and operations were revised in 2003. New inclusions in the 2003 regulations were that all CAFOs had to apply for a NPDES permit even if they only discharged in the event of a large storm. Large poultry operations were included in the regulations, regardless of their waste disposal system, and all CAFOs that held a NPDES permit were required to develop and implement a nutrient management plan. These plans had CAFOs identify ways to treat or process waste in a way that maintained nutrient levels at the appropriate amount.

The 2003 CAFO rule was subsequently challenged in court. A Second Circuit Court of Appeals decision required alteration to the CAFO permitting system. In *Water Keeper et al. vs. the EPA*, the court directed the EPA to remove the requirement for all CAFOs to apply for NPDES. Instead, the court required that nutrient management plans be submitted with the permit application, reviewed by officials and the public, and the terms of the plan be incorporated into the permit.

As a result of this court decision, the CAFO rule was again updated. The current final CAFO rule, which was revised in 2008, requires that only CAFOs which discharge or propose to discharge waste apply for permits. The EPA has also provided clarification in the discussion surrounding the rule on how CAFOs should assess whether they discharge or propose to discharge. There is also the opportunity to receive a no discharge certification for CAFOs that do not discharge or propose to discharge. This certification demonstrates that the CAFO is not required to acquire a permit. And while CAFOs were required to create nutrient management plans under the 2003 rule, these plans were now included with permit applications, and had a built-in time period for public review and comment.

Benefits of CAFOs

When properly managed, located, and monitored, CAFOs can provide a low-cost source of meat, milk, and eggs, due to efficient feeding and housing of animals, increased facility size, and animal specialization. When CAFOs are proposed in a local area, it is usually argued that they will enhance the local economy and increase employment. The effects of using local materials, feed, and livestock are argued to ripple throughout the economy, and increased tax expenditures will lead to increase funds for schools and infrastructure.

Environmental Health Effects

The most pressing public health issue associated with CAFOs stems from the amount of manure they produce. CAFO manure contains a variety of potential contaminants. It can contain plant nutrients such as nitrogen and phosphorus, pathogens such as *E. coli*, growth hormones, antibiotics, chemicals used as additives to the manure or to clean equipment, animal blood, silage leachate from corn feed, or copper sulfate used in footbaths for cows.

Depending on the type and number of animals in the farm, manure production can range between 2,800 tons and 1.6 million tons a year (Government Accountability Office [GAO], 2008). Large farms can produce more waste than some U.S. cities—a feeding operation with 800,000 pigs could produce over 1.6 million tons of waste a year. That amount is one and a half times more than the annual sanitary waste produced by the city of Philadelphia, Pennsylvania (GAO, 2008). Annually, it is estimated that livestock animals in the U.S. produce each year somewhere between 3 and 20 times more manure than people in the U.S. produce, or as much as 1.2–1.37 billion tons of waste (EPA, 2005). Though sewage treatment plants are required for human waste, no such treatment facility exists for livestock waste.

While manure is valuable to the farming industry, in quantities this large it becomes problematic. Many farms no longer grow their own feed, so they cannot use all the manure they produce as fertilizer. CAFOs must find a way to manage the amount of manure produced by their animals. Ground application of untreated manure is one of the most common disposal methods due to its low cost. It has limitations, however, such as the inability to apply manure while the ground is frozen. There are also limits as to how many nutrients from manure a land area can handle. Over application of livestock wastes can overload

soil with macronutrients like nitrogen and phosphorous and micronutrients that have been added to animal feed like heavy metals (Burkholder et al., 2007). Other manure management strategies include pumping liquefied manure onto spray fields, trucking it off-site, or storing it until it can be used or treated. Manure can be stored in deep pits under the buildings that hold animals, in clay or concrete pits, treatment lagoons, or holding ponds.

Animal feeding operations are developing in close proximity in some states, and fields where manure is applied have become clustered. When manure is applied too frequently or in too large a quantity to an area, nutrients overwhelm the absorptive capacity of the soil, and either run off or are leached into the groundwater. Storage units can break or become faulty, or rainwater can cause holding lagoons to overflow. While CAFOs are required to have permits that limit the levels of manure discharge, handling the large amounts of manure inevitably causes accidental releases which have the ability to potentially impact humans.

The increased clustering and growth of CAFOs has led to growing environmental problems in many communities. The excess production of manure and problems with storage or manure management can affect ground and surface water quality. Emissions from degrading manure and livestock digestive processes produce air pollutants that often affect ambient air quality in communities surrounding CAFOs. CAFOs can also be the source of greenhouse gases, which contribute to global climate change.

All of the environmental problems with CAFOs have direct impact on human health and welfare for communities that contain large industrial farms. As the following sections demonstrate, human health can suffer because of contaminated air and degraded water quality, or from diseases spread from farms. Quality of life can suffer because of odors or insect vectors surrounding farms, and property values can drop, affecting the financial stability of a community. One study found that 82.8% of those living near and 89.5% of those living far from CAFOs believed that their property values decreased, and 92.2% of those living near and 78.9% of those living far from CAFOs believed the odor from manure was a problem. The study found that real estate values had not dropped and odor infestations were not validated by local governmental staff in the areas. However, the concerns show that CAFOs remain contentious in communities (Schmalzried and Fallon, 2007). CAFOs are an excellent example of how environmental problems can directly impact human and community well-being.

Groundwater

Groundwater can be contaminated by CAFOs through runoff from land application of manure, leaching from manure that has been improperly spread on land, or through leaks or breaks in storage or containment units. The EPA's 2000 National Water Quality Inventory found that 29 states specifically identified animal feeding operations, not just concentrated animal feeding operations, as contributing to water quality impairment (Congressional Research Service, 2008). A study of private water wells in Idaho detected levels of veterinary antibiotics, as well as elevated levels of nitrates (Batt, Snow, & Alga, 2006). Groundwater is a major source of drinking water in the United States. The EPA estimates that 53% of the population relies on groundwater for drinking water, often at much higher rates in rural areas (EPA, 2004). Unlike surface water, groundwater contamination sources are more difficult to monitor. The extent and source of contamination are often harder to pinpoint in groundwater than surface water contamination. Regular testing of household water wells for total and fecal coliform bacteria is a crucial element in monitoring groundwater quality, and can be the first step in discovering contamination issues related to CAFO discharge. Groundwater contamination can also affect surface water (Spellman &

Whiting, 2007). Contaminated groundwater can move laterally and eventually enter surface water, such as rivers or streams.

When groundwater is contaminated by pathogenic organisms, a serious threat to drinking water can occur. Pathogens survive longer in groundwater than surface water due to lower temperatures and protection from the sun. Even if the contamination appears to be a single episode, viruses could become attached to sediment near groundwater and continue to leach slowly into groundwater. One pollution event by a CAFO could become a lingering source of viral contamination for groundwater (EPA, 2005).

Groundwater can still be at risk for contamination after a CAFO has closed and its lagoons are empty. When given increased air exposure, ammonia in soil transforms into nitrates. Nitrates are highly mobile in soil, and will reach groundwater quicker than ammonia. It can be dangerous to ignore contaminated soil. The amount of pollution found in groundwater after contamination depends on the proximity of the aquifer to the CAFO, the size of the CAFO, whether storage units or pits are lined, the type of subsoil, and the depth of the groundwater.

If a CAFO has contaminated a water system, community members should be concerned about nitrates and nitrate poisoning. Elevated nitrates in drinking water can be especially harmful to infants, leading to blue baby syndrome and possible death. Nitrates oxidize iron in hemoglobin in red blood cells to methemoglobin. Most people convert methemoglobin back to hemoglobin fairly quickly, but infants do not convert back as fast. This hinders the ability of the infant's blood to carry oxygen, leading to a blue or purple appearance in affected infants. However, infants are not the only ones who can be affected by excess nitrates in water. Low blood oxygen in adults can lead to birth defects, miscarriages, and poor general health. Nitrates have also been speculated to be linked to higher rates of stomach and esophageal cancer (Bowman, Mueller, & Smith, 2000). In general, private water wells are at higher risk of nitrate contamination than public water supplies.

Surface Water

The agriculture sector, including CAFOs, is the leading contributor of pollutants to lakes, rivers, and reservoirs. It has been found that states with high concentrations of CAFOs experience on average 20 to 30 serious water quality problems per year as a result of manure management problems (EPA, 2001). This pollution can be caused by surface discharges or other types of discharges. Surface discharges can be caused by heavy storms or floods that cause storage lagoons to overfill, running off into nearby bodies of water. Pollutants can also travel over land or through surface drainage systems to nearby bodies of water, be discharged through manmade ditches or flushing systems found in CAFOs, or come into contact with surface water that passes directly through the farming area. Soil erosion can contribute to water pollution, as some pollutants can bond to eroded soil and travel to watersheds (EPA, 2001). Other types of discharges occur when pollutants travel to surface water through other mediums, such as groundwater or air.

Contamination in surface water can cause nitrates and other nutrients to build up. Ammonia is often found in surface waters surrounding CAFOs. Ammonia causes oxygen depletion from water, which itself can kill aquatic life. Ammonia also converts into nitrates, which can cause nutrient overloads in surface waters (EPA, 1998). Excessive nutrient concentrations, such as nitrogen or phosphorus, can lead to eutrophication and make water inhabitable to fish or indigenous aquatic life (Sierra Club Michigan Chapter, n.d.). Nutrient over-enrichment causes algal blooms, or a rapid increase of algae growth in an aquatic environment (Science Daily, n.d.). Algal blooms can cause a spiral of environmental problems to an aquatic system. Large groups of algae can block sunlight from underwater plant life, which are

habitats for much aquatic life. When algae growth increases in surface water, it can also dominate other resources and cause plants to die. The dead plants provide fuel for bacteria to grow and increased bacteria use more of the water's oxygen supply. Oxygen depletion once again causes indigenous aquatic life to die. Some algal blooms can contain toxic algae and other microorganisms, including *Pfiesteria*, which has caused large fish kills in North Carolina, Maryland, and the Chesapeake Bay area (Spellman & Whiting, 2007). Eutrophication can cause serious problems in surface waters and disrupt the ecological balance.

Water tests have also uncovered hormones in surface waters around CAFOs (Burkholder et al., 2007). Studies show that these hormones alter the reproductive habits of aquatic species living in these waters, including a significant decrease in the fertility of female fish. CAFO runoff can also lead to the presence of fecal bacteria or pathogens in surface water. One study showed that protozoa such as *Cryptosporidium parvum* and *Giardia* were found in over 80% of surface water sites tested (Spellman & Whiting, 2007). Fecal bacteria pollution in water from manure land application is also responsible for many beach closures and shellfish restrictions.

Air Quality

In addition to polluting ground and surface water, CAFOs also contribute to the reduction of air quality in areas surrounding industrial farms. Animal feeding operations produce several types of air emissions, including gaseous and particulate substances, and CAFOs produce even more emissions due to their size. The primary cause of gaseous emissions is the decomposition of animal manure, while particulate substances are caused by the movement of animals. The type, amount, and rate of emissions created depends on what state the manure is in (solid, slurry, or liquid), and how it is treated or contained after it is excreted. Sometimes manure is "stabilized" in anaerobic lagoons, which reduces volatile solids and controls odor before land application.

The most typical pollutants found in air surrounding CAFOs are ammonia, hydrogen sulfide, methane, and particulate matter, all of which have varying human health risks. Table 1 on page 6 provides information on these pollutants.

Most manure produced by CAFOs is applied to land eventually and this land application can result in air emissions (Merkel, 2002). The primary cause of emission through land application is the volatilization of ammonia when the manure is applied to land. However, nitrous oxide is also created when nitrogen that has been applied to land undergoes nitrification and denitrification. Emissions caused by land application occur in two phases: one immediately following land application and one that occurs later and over a longer period as substances in the soil break down. Land application is not the only way CAFOs can emit harmful air emissions—ventilation systems in CAFO buildings can also release dangerous contaminants. A study by Iowa State University, which was a result of a lawsuit settlement between the Sierra Club and Tyson Chicken, found that two chicken houses in western Kentucky emitted over 10 tons of ammonia in the year they were monitored (Burns et al., 2007).

Most studies that examine the health effects of CAFO air emissions focus on farm workers, however some have studied the effect on area schools and children. While all community members are at risk from lowered air quality, children take in 20-50% more air than adults, making them more susceptible to lung disease and health effects (Kleinman, 2000). Researchers in North Carolina found that the closer children live to a CAFO, the greater the risk of asthma symptoms (Barrett, 2006). Of the 226 schools that were included in the study, 26% stated that there were noticeable odors from CAFOs outdoors, while 8% stated

Table 1 Typical pollutants found in air surrounding CAFOs.

CAFO Emissions	Source	Traits	Health Risks
Ammonia	Formed when microbes decompose undigested organic nitrogen compounds in manure	Colorless, sharp pungent odor	Respiratory irritant, chemical burns to the respiratory tract, skin, and eyes, severe cough, chronic lung disease
Hydrogen Sulfide	Anaerobic bacterial decomposition of protein and other sulfur containing organic matter	Odor of rotten eggs	Inflammation of the moist membranes of eye and respiratory tract, olfactory neuron loss, death
Methane	Microbial degradation of organic matter under anaerobic conditions	Colorless, odorless, highly flammable	No health risks. Is a greenhouse gas and contributes to climate change.
Particulate Matter	Feed, bedding materials, dry manure, unpaved soil surfaces, animal dander, poultry feathers	Comprised of fecal matter, feed materials, pollen, bacteria, fungi, skin cells, silicates	Chronic bronchitis, chronic respiratory symptoms, declines in lung function, organic dust toxic syndrome

they experience odors from CAFOs inside the schools. Schools that were closer to CAFOs were often attended by students of lower socioeconomic status (Mirabelli, Wing, Marshall, & Wilcosky, 2006).

There is consistent evidence suggesting that factory farms increase asthma in neighboring communities, as indicated by children having higher rates of asthma (Sigurdarson & Kline, 2006; Mirabelli et al., 2006). CAFOs emit particulate matter and suspended dust, which is linked to asthma and bronchitis. Smaller particles can actually be absorbed by the body and can have systemic effects, including cardiac arrest. If people are exposed to particulate matter over a long time, it can lead to decreased lung function (Michigan Department of Environmental Quality [MDEQ] Toxics Steering Group [TSG], 2006). CAFOs also emit ammonia, which is rapidly absorbed by the upper airways in the body. This can cause severe coughing and mucous build-up, and if severe enough, scarring of the airways. Particulate matter may lead to more severe health consequences for those exposed by their occupation. Farm workers can develop acute and chronic bronchitis, chronic obstructive airways disease, and interstitial lung disease. Repeated exposure to CAFO emissions can increase the likelihood of respiratory diseases. Occupational asthma, acute and chronic bronchitis, and organic dust toxic syndrome can be as high as 30% in factory farm workers

(Horrigan, Lawrence, & Walker, 2002). Other health effects of CAFO air emissions can be headaches, respiratory problems, eye irritation, nausea, weakness, and chest tightness.

There is evidence that CAFOs affect the ambient air quality of a community. There are three laws that potentially govern CAFO air emissions—the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA, also known as the Superfund Act), the Emergency Planning & Community Right to Know Act (EPCRA), and the Clean Air Act (CAA). However, the EPA passed a rule that exempts all CAFOs from reporting emissions under CERCLA. Only CAFOs that are classified as large are required to report any emission event of 100 pounds of ammonia or hydrogen sulfide or more during a 24-hour period locally or to the state under EPCRA (Michigan State University Extension, n.d.). The EPA has also instituted a voluntary Air Quality Compliance Agreement in which they will monitor some CAFO air emissions, and will not sue offenders but instead charge a small civil penalty. These changes have attracted criticism from environmental and community leaders who state that the EPA has yielded to influence from the livestock industry. The changes also leave ambiguity as to whether emission standards and air quality near CAFOs are being monitored.

Greenhouse Gas and Climate Change

Aside from the possibility of lowering air quality in the areas around them, CAFOs also emit greenhouse gases, and therefore contribute to climate change. Globally, livestock operations are responsible for approximately 18% of greenhouse gas production and over 7% of U.S. greenhouse gas emissions (Massey & Ulmer, 2008). While carbon dioxide is often considered the primary greenhouse gas of concern, manure emits methane and nitrous oxide which are 23 and 300 times more potent as greenhouse gases than carbon dioxide, respectively. The EPA attributes manure management as the fourth leading source of nitrous oxide emissions and the fifth leading source of methane emissions (EPA, 2009).

The type of manure storage system used contributes to the production of greenhouse gases. Many CAFOs store their excess manure in lagoons or pits, where they break down anaerobically (in the absence of oxygen), which exacerbates methane production. Manure that is applied to land or soil has more exposure to oxygen and therefore does not produce as much methane. Ruminant livestock, such as cows, sheep, or goats, also contribute to methane production through their digestive processes. These livestock have a special stomach called a rumen that allows them to digest tough grains or plants that would otherwise be unusable. It is during this process, called enteric fermentation, that methane is produced. The U.S. cattle industry is one of the primary methane producers. Livestock production and meat and dairy consumption has been increasing in the United States, so it can only be assumed that these greenhouse gas emissions will also rise and continue to contribute to climate change.

Odors

One of the most common complaints associated with CAFOs are the odors produced. The odors that CAFOs emit are a complex mixture of ammonia, hydrogen sulfide, and carbon dioxide, as well as volatile and semi-volatile organic compounds (Heederik et al., 2007). These odors are worse than smells formerly associated with smaller livestock farms. The anaerobic reaction that occurs when manure is stored in pits or lagoons for long amounts of time is the primary cause of the smells. Odors from waste are carried away from farm areas on dust and other air particles. Depending on things like weather conditions and farming techniques, CAFO odors can be smelled from as much as 5 or 6 miles away, although 3 miles is a more common distance (State Environmental Resource Center, 2004).

Because CAFOs typically produce malodors, many communities want to monitor emissions and odors. Quantifying odor from industrial farming can be challenging because it is a mixture of free and particle-bound compounds, which can make it hard to identify what specifically is causing the odor. Collecting data on specific gases, such as hydrogen sulfide, can be used as a proxy for odor levels.

CAFO odors can cause severe lifestyle changes for individuals in the surrounding communities and can alter many daily activities. When odors are severe, people may choose to keep their windows closed, even in high temperatures when there is no air conditioning. People also may choose to not let their children play outside and may even keep them home from school. Mental health deterioration and an increased sensitization to smells can also result from living in close proximity to odors from CAFOs. Odor can cause negative mood states, such as tension, depression, or anger, and possibly neurophysciatric abnormalities, such as impaired balance or memory. People who live close to factory farms can develop CAFO-related post traumatic stress disorder, including anxiety about declining quality of life (Donham et al., 2007).

Ten states use direct regulations to control odors emitted by CAFOs. They prohibit odor emissions greater than a set standard. States with direct regulations use scentometers, which measure how many times an odor has to be doused with clean air before the smell is undetectable. An additional 34 states have indirect methods to reduce CAFO odors. These include: setbacks, which specify how far CAFO structures have to be from other buildings; permits, which are the most typical way of regulating CAFOs; public comment or involvement periods; and operator or manure placement training.

Insect Vectors

CAFOs and their waste can be breeding grounds for insect vectors. Houseflies, stable flies, and mosquitoes are the most common insects associated with CAFOs. Houseflies breed in manure, while stable and other flies breed in decaying organic material, such as livestock bedding. Mosquitoes breed in standing water, and water on the edges of manure lagoons can cause mosquito infestations to rise. Flies can change from eggs to adults in only 10 days, which means that substances in which flies breed need to be cleaned up regularly.

Flies are typically considered only nuisances, although insects can agitate livestock and decrease animal health. The John Hopkins Bloomberg School of Public Health found evidence that houseflies near poultry operations may contribute to the dispersion of drug-resistant bacteria (Center for Livable Future, 2009). Since flies are attracted to and eat human food, there is a potential for spreading bacteria or pathogens to humans, including microbes that can cause dysentery and diarrhea (Bowman et al., 2000). Mosquitoes spread zoonotic diseases, such as West Nile virus, St. Louis encephalitis, and equine encephalitis.

Residences closest to the feeding operations experience a much higher fly population than average homes. To lower the rates of insects and any accompanying disease threats, standing water should we cleaned or emptied weekly, and manure or decaying organic matter should be removed twice weekly (Purdue Extension, 2007). For more specific insect vector information, please refer to NALBOH's vector guide (*Vector Control Strategies for Local Boards of Health*).

Pathogens

Pathogens are parasites, bacterium, or viruses that are capable of causing disease or infection in animals or humans. The major source of pathogens from CAFOs is in animal manure. There are over 150 pathogens in manure that could impact human health. Many of these pathogens are concerning because

they can cause severe diarrhea. Healthy people who are exposed to pathogens can generally recover quickly, but those who have weakened immune systems are at increased risk for severe illness or death. Those at higher risk include infants or young children, pregnant women, the elderly, and those who are immunosuppressed, HIV positive, or have had chemotherapy. This risk group now roughly compromises 20% of the U.S. population.

Table 2 Select pathogens found in animal manure.

Pathogen	Disease	Symptoms
Bacillus anthracis	Anthrax	Skin sores, headache, fever, chills, nausea, vomiting
Escherichia coli	Colibacilosis, Coliform mastitis-metris	Diarrhea, abdominal gas
Leptospira pomona	Leptospirosis	Abdominal pain, muscle pain, vomiting, fever
Listeria monocytogenes	Listerosis	Fever, fatigue, nausea, vomiting, diarrhea
Salmonella species	Salmonellosis	Abdominal pain, diarrhea, nausea, chills, fever, headache
Clostirdum tetani	Tetanus	Violent muscle spasms, lockjaw, difficulty breathing
Histoplasma capsulatum	Histoplasmosis	Fever, chills, muscle ache, cough rash, joint pain and stiffness
Microsporum and *Trichophyton*	Ringworm	Itching, rash
Giardia lamblia	Giardiasis	Diarrhea, abdominal pain, abdominal gas, nausea, vomiting, fever
Cryptosporidium species	Cryptosporidosis	Diarrhea, dehydration, weakness, abdominal cramping

Sources of infection from pathogens include fecal-oral transmission, inhalation, drinking water, or incidental water consumption during recreational water activities. The potential for transfer of pathogens among animals is higher in confinement, as there are more animals in a smaller amount of space. Healthy or asymptomatic animals may carry microbial agents that can infect humans, who can then spread that infection throughout a community, before the infection is discovered among animals.

When water is contaminated by pathogens, it can lead to widespread outbreaks of illness. Salmonellosis, cryptosporidiosis, and giardiasis can cause nausea, vomiting, fever, diarrhea, muscle pain, and death, among other symptoms. *E.coli* is another serious pathogen, and can be life-threatening for the young, elderly, and immunocompromised. It can cause bloody diarrhea and kidney failure. Since many CAFO use sub-therapeutic antibiotics with their animals, there is also the possibility that disease-resistant bacteria can emerge in areas surrounding CAFOs. Bacteria that cannot be treated by antibiotics can have very serious effects on human health, potentially even causing death (Pew Charitable Trusts, n.d.).

There is also the possibility of novel (or new) viruses developing. These viruses generate through mutation or recombinant events that can result in more efficient human-to-human transmission. There has been some speculation that the novel H1N1 virus outbreak in 2009 originated in swine CAFOs in Mexico. However, that claim has never been substantiated. CAFOs are not required to test for novel viruses, since they are not on the list of mandatory reportable illness to the World Organization for Animal Health.

Antibiotics

Antibiotics are commonly administered in animal feed in the United States. Antibiotics are included at low levels in animal feed to reduce the chance for infection and to eliminate the need for animals to expend energy fighting off bacteria, with the assumption that saved energy will be translated into growth. The main purposes of using non-therapeutic doses of antimicrobials in animal feed is so that animals will grow faster, produce more meat, and avoid illnesses. Supporters of antibiotic use say that it allows animals to digest their food more efficiently, get the most benefit from it, and grow into strong and healthy animals.

The trend of using antibiotics in feed has increased with the greater numbers of animals held in confinement. The more animals that are kept in close quarters, the more likely it is that infection or bacteria can spread among the animals. Seventy percent of all antibiotics and related drugs used in the U.S. each year are given to beef cattle, hogs, and chickens as feed additives. Nearly half of the antibiotics used are nearly identical to ones given to humans (Kaufman, 2000).

There is strong evidence that the use of antibiotics in animal feed is contributing to an increase in antibiotic-resistant microbes and causing antibiotics to be less effective for humans (Kaufman, 2000). Resistant strains of pathogenic bacteria in animals, which can be transferred to humans thought the handling or eating of meat, have increased recently. This is a serious threat to human health because fewer options exist to help people overcome disease when infected with antibiotic-resistant pathogens. The antibiotics often are not fully metabolized by animals, and can be present in their manure. If manure pollutes a water supply, antibiotics can also leech into groundwater or surface water.

Because of this concern for human health, there is a growing movement to eliminate the non-therapeutic use of antibiotics with animals. In 2001, the American Medical Association approved a resolution to ban all low-level use of antibiotics. The USDA has developed guidelines to limit low-level use, and some major meat buyers (such as McDonald's) have stopped using meat that was given antibiotics that are also used for humans. The World Health Organization is also widely opposed to the use of antibiotics, calling for a cease of their low-level use in 2003. Some U.S. legislators are seeking to ban the routine use of antibiotics with livestock, and there has been legislation proposed to solidify a ban. The Preservation of Antibiotics for Medical Treatment Act (PAMTA), which was introduced in 2009, has the support of over 350 health,

consumer, and environmental groups (H.R. 1549/S. 619). The act, if passed, would ban seven classes of antibiotics important to human health from being used in animals, and would restrict other antibiotics to therapeutic and some preventive uses.

Other Effects – Property Values

Most landowners fear that when CAFOs move into their community their property values will drop significantly. There is evidence that CAFOs do affect property values. The reasons for this are many: the fear of loss of amenities, the risk of air or water pollution, and the increased possibility of nuisances related to odors or insects. CAFOs are typically viewed as a negative externality that can't be solved or cured. There may be stigma that is attached to living by a CAFO.

The most certain fact regarding CAFOs and property values are that the closer a property is to a CAFO, the more likely it will be that the value of the property will drop. The exact impact of CAFOs fluctuates depending on location and local specifics. Studies have found differing results of rates of property value decrease. One study shows that property value declines can range from a decrease of 6.6% within a 3-mile radius of a CAFO to an 88% decrease within 1/10 of a mile from a CAFO (Dakota Rural Action, 2006). Another study found that property value decreases are negligible beyond 2 miles away from a CAFO (Purdue Extension, 2008). A third study found that negative effects are largest for properties that are downwind and closest to livestock (Herriges, Secchi, & Babcock, 2005). The size and type of the feeding operation can affect property value as well. Decreases in property values can also cause property tax rates to drop, which can place stress on local government budgets.

Considerations for Boards of Health

Right-to-Farm Laws

With all of the potential environmental and public health effects from CAFOs, community members and health officials often resort to taking legal action against these industrial animal farms. However, there are some protections for farms in place that can make lawsuits hard to navigate. Right-to-farm laws were created to address conflicts between farmers and non-farming neighbors. They seek to override common laws of nuisance, which forbid people to use their property in ways that are harmful to others, and protect farmers from unreasonable controls on farming.

All 50 states have some form of right-to-farm laws, but most only offer legal protections to farms if they meet certain specifications. Generally, they must be in compliance with all environmental regulations, be properly run, and be present in a region first before suburban developments, often a year before the plaintiff moves to that area. These right-to-farm laws were originally created in the late 1970s and early 1980s to protect family farms from suburban sprawl, at a time when large industrial farms were not the norm. As industrial farms grew in size and number, the agribusiness industry lobbied for and achieved the passage of stricter laws in the 1990s, many of which are now being challenged in court by homeowners and small family farmers. Opponents to these laws argue that they deprive them of their use of property and therefore violate the Fifth Amendment to the Constitution.

Some state courts have overturned their strict right-to-farm laws, such as Iowa, Michigan, Minnesota, and Kansas. Others such as Vermont have rewritten their laws. Vermont's updated right-to-farm bill

protects established farm practices as long as there is not a substantial adverse effect on health, safety, or welfare.

Boards of health need to be aware of what legal protection their state offers farms. Right-to-farm laws can hinder nuisance complaints brought about by community members. State laws can prevent local government or health officials from regulating industrial farms.

Board of Health Involvement with CAFOs

Boards of health are responsible for fulfilling the three public health core functions: assessment, policy development, and assurance. Boards of health can fulfill these functions through addressing problems stemming from CAFOs in their communities. Specific public health services that can tackled regarding CAFOs include monitoring health status, investigating health problems, developing policies, enforcing regulations, informing and educating people about CAFOs, and mobilizing community partnerships to spread awareness about environmental health issues related to CAFOs.

Assessment: Board of health members should ensure that there is an effective method in place for collecting and tracking public complaints about CAFOs and large animal farms. Since environmental health specialists at local health departments are often responsible for investigating complaints, the board of health must take measures to ensure that they are properly trained and educated about CAFOs. It is possible that the board of health may be responsible or choose to do some investigations itself. Schmalzried and Fallon (2008) advocate that local health districts adopt a proactive approach for addressing public concerns about CAFOs, stating that health districts can offer some services that may help ease public frustration with CAFOs. A fly trapping program can establish a baseline for the average number of flies present prior to the start-up of CAFOs or large animal farms, which can then establish if a fly nuisance exists in the area. Testing for water quality and quantity can provide evidence if CAFOs are suspected of affecting private water supplies. Boards of health can also monitor exposure incidences that occur in emergency rooms to determine if migrant or farm workers are developing any adverse health conditions as a result of their work environments. Establishing these programs benefit both members of the community and provide information to future animal farm operators, and local boards of health should recommend them if they've been receiving complaints about CAFOs.

Policy Development: Boards of health in many states can adopt health-based regulations about CAFOs, however, they may be met with some resistance. Humbolt County, Iowa, adopted four health-based ordinances concerning CAFOs that became models for regulations in other states, but the Iowa Supreme Court ruled the ordinances were irreconcilable with state laws. Boards of health that choose to regulate CAFOs can also be subject to pressure from outside forces, including possible lawsuits or withdrawal of funding. Boards of health should also consider working with other local officials to institute regulations on CAFOs, such as zoning ordinances.

Assurance: Boards of health can execute the assurance function by advocating for or educating about better environmental practices with CAFOs. Board members may receive complaints from the public about CAFOs, and boards can hold public meetings to receive complaints and hear public testimony about farms. If boards of health are not capable of regulating industrial farms in their communities, they can still try to collaborate with other local agencies that have jurisdiction. Board of health members can educate other local agencies and public officials about CAFOs and spread awareness about the environmental and health hazards. They can request a public hearing with the permitting agency of the

CAFO to express their concerns about the potential health effects. They can also work with agricultural and farm representatives to teach better environmental practices and pollution reduction techniques.

In many states, boards of health are empowered to adopt more stringent rules than the state law if it is necessary to protect public health. Board of health members should examine their state laws before they take any action regarding CAFOs to determine the most appropriate course of action. Any process should include an investigative period to gather evidence, public hearings, and a time for public review of draft policies.

Board of Health Case Studies

Tewksbury Board of Health, Massachusetts

Locals have complained about Krochmal Farms, a pig farm, for many years, but complaints have increased recently. The addition of a hog finishing facility to the farm coincided with the time that community member complaints grew. Most complaints are centered on the odor coming from the farm. The complaints were originally just logged when phone calls were received; however, the health department added a data tracking system as the number of complaints increased. After a complaint is received, the sanitarian or health director does a site visit to investigate.

The health director in Tewksbury filed an order of prohibition against the farm, which is allowed under Massachusetts law 111, section 143, for anything that threatens public health. The order of prohibition was appealed and the matter was taken to the board of health for a grievance hearing. The board of health hearing included months of testimony about the pig farm. The board of health is also doing a site assignment, which determines if a location is appropriate for treating, storing, or disposing of waste, including agricultural waste. The site assignment process includes both the Department of Environmental Protection (DEP) and the local board of health. The board of health holds a public hearing process, while the DEP reviews the site assignment application. The board of health grants the site assignment only if it is concurrently approved by the DEP.

The health director in Tewksbury points out that the only laws the board of health is able to regulate the farm under are nuisance laws. There have been efforts by the community to do a home rule petition to address the air quality and pest management complaints. The home rule petition is currently working its way through the Massachusetts state house. The status of the petition is unknown.

The board of health has tried to work directly with the pig farm to manage complaints. The farm contains manure composting facilities and the health district has requested advance notice to warn the community before manure is treated or applied to the soil. The farm has adopted a new manure management system. This system uses Rapp technology to control odors and reduce ammonia and hydrogen sulfide levels. However, questions still remain as to whether this addition will fully solve the odor issue. Typically, systems using Rapp technology include an oil cap that floats on manure holding pools and helps seal odors inside. These techniques have been researched and proven to reduce odors. However, the Tewksbury farm did not install the oil cap, and it is unknown whether the exclusion of the cap will hinder the technology's ability to reduce odors.

The complaints about the farm primarily concern the odor that emanates from the farm. The complaints do include mention of health side effects, including nausea and burning eyes. The health director has also heard concerns about potential environmental effects from the pig manure. Community members are

worried the manure runoff is entering and contaminating Sutton Brook, since there has been flooding in that area. There has been no confirmation of this occurring. The board of health is aware that the farm has a nutrient management plan, but they are not allowed to request and find out what is incorporated in that plan.

The Tewksbury piggery is technically not classified as a CAFO, though it is believed to be the largest pig farm in the commonwealth of Massachusetts. The area around it has become densely populated and the community members state that they just want to live peacefully with the farm. The board of health has submitted multiple grant applications to study the health effects associated with the farm. After the site assignment process is complete, the board of health will decide how it will regulate the farm. At the beginning of 2010, the board of health was still working on drafting regulations for the pig farms.

Wood County Board of Health, Ohio

Wood County, Ohio, contains two existing large dairy farms, both of which were proposed in 2001 to be expanded to over 1500 cows each. It is also the site for three other proposed dairy farms. There is a large community effort that supports restricting the operation and expansion of these farms, mainly represented by the community group Wood County Citizens Opposed to Factory Farms. The Wood County Board of Health became involved in investigating these dairy farms through this community group and other local officials. The Trustees of Liberty Township requested assistance from the Wood County Board of Health in supporting a moratorium on factory farm operations until local regulations were in effect. The trustees believed that manure runoff from the farms could contaminate local waterways, lower the ground water table, increase the presence of insect vectors, and devalue local properties.

The Wood County Health Director, in cooperation with the board of health, contacted nearby counties to determine what actions they had taken against farms in their communities. While the health director and board of health investigated action in the form of a nuisance regulation against the farms, they were advised that nuisance lawsuits filed against farms in Ohio were held to a tough standard, and they would be forced to demonstrate with scientific proof that the farms have a substantial adverse effect on health. They found that no other board of health in Ohio had opted to regulate farming operations and relied on the enforcement of existing state laws.

The board of health held a public forum to hear public opinion regarding the industrial farms. Ultimately, the Wood County Board of Health took actions other than regulations to help protect the health and environment of its community. They helped community members protect the safety of their water wells by offering free and low cost water well testing and inspections. They tested area ditch and water ways for fecal coliform bacteria, phosphorous, and nitrates to monitor the impact of farm runoff. They also purchased fly traps to monitor and count fly types to determine if the farms have caused an increase in insect vectors. Board of health members also met with state officials from the Ohio EPA in an effort to facilitate cooperation regarding the factory farms. While the Wood County Board of Health and Health Department chose not to institute any local regulations, they continue to monitor the situation and respond to community complaints.

Cerro Gordo County Board of Health, Iowa

Officials in Cerro Gordo County, Iowa, began looking into regulating animal feeding operations after the number of hog farms in Iowa started to grow. Floods in North Carolina and new regulations in Colorado meant that many hog farms began relocating to Iowa. Many citizens had concerns over the effects of

CAFOs, and the Iowa State Association of Counties wanted to review air quality issues. Officials in Cerro Gordo County originally began working on a regulation that required inspections and was based on public health concerns, since farms were already exempt from any regulations related to zoning. However, Iowa state senators soon introduced legislation that passed and prevented any animal feeding operations from being regulated from a public health angle as well.

As Iowans were now prevented from regulating animal feeding operations in terms of zoning or public health, officials in Cerro Gordo County decided to place a moratorium on the construction of new animal feeding operations in that county. They wanted to temporarily stop the growth of animal feeding operations until they could get better science about their effects. Cerro Gordo County Ordinance #40, the "Animal Confinement Moratorium Ordinance," went into effect on May 14, 2002. Since the moratorium did not address public health or zoning, officials were able to get around the rules and still have a way to temporarily control animal feeding operation growth in their county. The ordinance placed "a 1-year moratorium on any new construction, expansion, or activity occurring on land used for the production, care, feeding, or housing of animals." The ordinance also afforded "local public health officials adequate time to appropriately assess health and environmental concerns that may be related to confined animal feeding operations and concentration of animals; establish objective measurable standards of enforcement; exercise the Board of Health's responsibility to protect and improve the health of the public; refrain from impacting farm operators unfairly; and provide penalties for violations of the provisions hereof pursuant to Chapter 137, Code of Iowa" (Cerro Gordo County, 2002).

The moratorium was first adopted by the Cerro Gordo County Board of Health. It was then presented to the county board of supervisors by the health director on behalf of the board of health. Before the board of health adopted the moratorium, they held an investigative meeting in which representatives from the Iowa Farm Bureau and other industry spokespeople exchanged opinions on the issue of animal feeding operations. The moratorium was created through a collaboration between local and county officials—health department staff, the board of health, and the board of supervisors. The moratorium did not receive any help or backing from state officials, who were concerned about the political nature of the ordinance. However it did receive backing from a *Globe Gazette* editorial.

The moratorium was immediately met with resistance from state officials. The Cerro Gordo County Board of Supervisors was contacted by a local legislator, and the Iowa Farm Bureau stated they would challenge the county budget. The Iowa Farm Bureau threatened to take the county to court. There were concerns over the cost of a court trial, which was estimated to be as high as $60,000. The county attorney doubted the legality of the moratorium and ultimately recommended removing it. The moratorium was in effect until June of 2005, when it was repealed by the county board of supervisors.

Since the moratorium was repealed there have been a few hog farms built in Cerro Gordo County, but the decline in pork prices has prevented any large growth of hog farms. Health officials believe that if the county had not implemented the animal confinement moratorium, there would have been many more farms built in their county, since many hog farms were built in counties south of Cerro Gordo County. There is now a process for siting new animal confinement operations in Iowa that uses a Master Matrix scoring system. The Cerro Gordo County Board of Supervisors tracks the Master Matrix system, but so far no animal feeding operations in Iowa who have applied using this system have been denied the right to build.

Conclusion

Concentrated animal feeding operations or large industrial animal farms can cause a myriad of environmental and public health problems. While they can be maintained and operated properly, it is important to ensure that they are routinely monitored to avoid harm to the surrounding community. While states have differing abilities to regulate CAFOs, there are still actions that boards of health can and should take. These actions can be as complex as passing ordinances or regulations directed at CAFOs or can be simply increasing water and air quality testing in the areas surrounding CAFOs. Since CAFOs have such an impact locally, boards of health are an appropriate means for action. Boards of health should take an active role with CAFOs, including collaboration with other state and local agencies, to mitigate the impact that CAFOs or large industrial farms have on the public health of their communities.

Appendix A: Regulatory Definitions of Large CAFOs, Medium CAFOs, and Small CAFOs

Animal Sector	Size Thresholds (number of animals)		
	Large CAFOs	Medium CAFOs[1]	Small CAFOs[2]
Cattle or cow/calf pairs	1,000 or more	300-999	Less than 300
Mature dairy cattle	700 or more	200-699	Less than 200
Veal calves	1,000 or more	300-999	Less than 300
Swine (over 55 pounds)	2,500 or more	750-2,500	Less than 750
Swine (under 55 pounds)	10,000 or more	3,000-9,999	Less than 3,000
Horses	500 or more	150-499	Less than 150
Sheep or lambs	10,000 or more	3,000-9,999	Less than 3,000
Turkeys	55,000 or more	16,500-54,999	Less than 16,500
Laying hens or broilers[3]	30,000 or more	9,000-29,999	Less than 9,000
Chickens other than laying hens[4]	125,000 or more	37.500-124,999	Less than 37,500
Laying hens[4]	82,000 or more	25,000-81,999	Less than 25,000
Ducks[4]	30,000 or more	10,000-29,999	Less than 10,000
Ducks[3]	5,000 or more	1,500-4,999	Less than 1,500

Data: Environmental Protection Agency

1 Must also meet one of two "method of discharge" criteria to be defined as a CAFO or must be designated.

2 Never a CAFO by regulatory definition, but may be designated as a CAFO on a case-by-case basis.

3 Liquid manure handling system

4 Other than a liquid manure handling system

Appendix B: Additional Resources

American Public Health Association. *Precautionary moratorium on new concentrated animal feed operations*. http://www.apha.org/advocacy/policy/policysearch/default.htm?id=1243

Center for a Livable Future. http://www.livablefutureblog.com/

Environmental Health Sciences Research Center. *Iowa concentrated animal feeding operation air quality study*. http://www.public-health.uiowa.edu/ehsrc/CAFOstudy.htm

Environmental Protection Agency. *Animal feeding operations*. http://cfpub.epa.gov/npdes/home.cfm?program_id=7

Food and Water Watch. http://www.foodandwaterwatch.org/

Impacts of CAFOs on Rural Communities. http://web.missouri.edu/ikerdj/papers/Indiana%20--%20CAFOs%20%20Communities.htm#_ftn1

Land Stewardship Project. http://www.landstewardshipproject.org/index.html

Midwest Environmental Advocates. http://www.midwestadvocates.org/

National Agriculture Law Center. *Animal feeding operations reading room*. http://www.nationalaglawcenter.org/readingrooms/afos

National Association of Local Boards of Health. *Vector control strategies for local boards of health*. http://www.nalboh.org/publications.htm

Pew Charitable Trusts. *Human health and industrial farming*. http://www.saveantibiotics.org/index.html

Pew Commission on Industrial Animal Farm Production. http://www.ncifap.org/

Purdue Extension. *Concentrated animal feeding operations*. http://www.ansc.purdue.edu/CAFO/

State Environmental Resource Center. http://serconline.org

References

Barrett, J.R. (2006). Hogging the air: CAFO emissions reach into schools. *Environmental Health Perspectives 114*(4), A241. Retrieved from http://ehp03.niehs.nih.gov/article/info%3Adoi%2F10.1289%2Fehp.114-a241a

Batt, A.L., Snow, D.D., & Aga, D.S. (2006). Occurrence of sulfonamide antimicrobials in private water wells in Washington County, Idaho, USA. *Chemosphere, 64*(11), 1963–1971. Retrieved from http://digitalcommons.unl.edu/cgi/viewcontent.cgi?article=1017&context=watercenterpubs

Bowman, A., Mueller, K., & Smith, M. (2000). *Increased animal waste production from concentrated animal feeding operations (CAFOs): Potential implications for public and environmental health*. Nebraska Center for Rural Health Research. Retrieved from http://www.unmc.edu/rural/documents/cafo-report.pdf

Burkholder, J., Libra, B., Weyer, P., Heathcote, S., Kolpin, D., Thorne, P., et al. (2007). Impacts of waste from concentrated animal feeding operations on water quality. *Environmental Health Perspectives, 11*(2), 308–312. Retrieved from http://www.ncbi.nlm.nih.gov/pmc/articles/PMC1817674/pdf/ehp0115-000308.pdf

Burns, R., Xin, H., Gates, R., Li, H., Hoff, S., Moody, L., et al. (2007). *Tyson broiler ammonia emission monitoring project: Final report*. Retrieved from http://www.sierraclub.org/environmentallaw/lawsuits/docs/ky-tysonreport.pdf

Center for Livable Future. (2009). *Flies may spread drug-resistant bacteria from poultry operations*. Retrieved from http://www.livablefutureblog.com/2009/03/flies-may-spread-drug-resistant-bacteria-from-poultry-operations/

Cerro Gordo County, Iowa. (2002). *Ordinance #40: Animal confinement moratorium ordinance*. Retrieved from http://www.cghealth.net/pdf/AnimalConfinementMoratoriumOrdinance.pdf

Congressional Research Service. (2008). *Animal waste and water quality: EPA regulation of concentrated animal feeding operations (CAFOs)*. Retrieved from http://www.nationalaglawcenter.org/assets/crs/RL31851.pdf

Dakota Rural Action. (2006). *CAFO economic impact*. Retrieved from http://www.dakotarural.org/index.php?option=com_content&view=article&id=17&Itemid=30

Donham, K.J., Wing, S., Osterberg, D., Flora, J.L., Hodne, C., Thu, K.M., et al. (2007). Community health and socioeconomic issues surrounding CAFOs. *Environmental Health Perspectives 115*(2), 317–320. Retrieved from http://www.ncbi.nlm.nih.gov/pmc/articles/PMC1817697/pdf/ehp0115-000317.pdf

Environmental Protection Agency. (1998). *Environmental impacts of animal feeding operations*. Retrieved from http://www.epa.gov/waterscience/guide/feedlots/envimpct.pdf

Environmental Protection Agency. (2001). *Environmental assessment of proposed revisions to the national pollutant discharge elimination system regulation and the effluent guidelines for concentrated animal feeding operations*. Available from http://cfpub.epa.gov/npdes/docs.cfm?view=archivedprog&program_id=7&sort=name

Environmental Protection Agency. (2004). *Water on tap: A consumer's guide to the nation's drinking water*. Retrieved from http://permanent.access.gpo.gov/lps21800/www.epa.gov/safewater/wot/wheredoes.html

Environmental Protection Agency. (2005). *Detecting and mitigating the environmental impact of fecal pathogens originating from confined animal feeding operations: Review*. Retrieved from http://www.farmweb.org/Articles/Detecting%20and%20Mitigating%20the%20Environmental%20Impact%20of%20Fecal%20Pathogens%20Originating%20from%20Confined%20Animal%20Feeding%20Operations.pdf

Environmental Protection Agency. (2009). *Animal feeding operations*. Retrieved from http://cfpub.epa.gov/npdes/home.cfm?program_id=7

Environmental Protection Agency. (2009). *Inventory of U.S. greenhouse gas emissions and sinks: 1990-2007*. Retrieved from http://epa.gov/climatechange/emissions/usinventoryreport.html

Government Accountability Office. (2008). *Concentrated animal feeding operations: EPA needs more information and a clearly defined strategy to protect air and water quality from pollutants of concern*. Retrieved from http://www.gao.gov/new.items/d08944.pdf

Heederik, D., Sigsgaard, T., Thorne, P.S., Kline, J.N., Avery, R., Bønløkke, et al. (2007). Health effects of airborne exposures from concentrated animal feeding operations. *Environmental Health Perspectives, 115*(2), 298–302. Retrieved from http://www.ncbi.nlm.nih.gov/pmc/articles/PMC1817709/pdf/ehp0115-000298.pdf

Herriges, J.A., Secchi, S., & Babcock, B.A. (2005). Living with hogs in Iowa: The impact of livestock facilities on rural residential property values. *Land Economics*, 81, 530–545.

Horrigan, L., Lawrence, R.S., & Walker, P. (2002). How sustainable agriculture can address the environmental and human health harms of industrial agriculture. *Environmental Health Perspectives, 110*(5), 445–456. Retrieved from http://ehpnet1.niehs.nih.gov/members/2002/110p445-456horrigan/EHP110p445PDF.PDF

Kaufman, M. (2000). Worries rise over effect of antibiotics in animal feed; Humans seen vulnerable to drug-resistant germs. *Washington Post*, p. A01. Retrieved from http://www.upc-online.org/000317wpost_animal_feed.html

Kleinman, M. (2000). *The health effects of air pollution on children*. Retrieved from http://www.aqmd.gov/forstudents/health_effects_on_children.pdf

MacDonald, J.M. and McBride, W.D. (2009). *The transformation of U.S. livestock agriculture: Scale, efficiency, and risks*. United States Department of Agriculture. Retrieved from http://www.ers.usda.gov/Publications/EIB43/EIB43.pdf

Massey, R. and Ulmer, A. (2008). *Agriculture and greenhouse gas emission*. University of Missouri Extension. Retrieved from http://extension.missouri.edu/publications/DisplayPub.aspx?P=G310

Merkel, M. (2002). *Raising a stink: Air emissions from factory farms*. Environmental Integrity Project. Retrieved from http://www.environmentalintegrity.org/pdf/publications/CAFOAirEmissions_white_paper.pdf

Michigan Department of Environmental Quality (MDEQ) Toxics Steering Group (TSG). (2006). *Concentrated animal feedlot operations (CAFOs) chemicals associated with air emissions*. Retrieved from http://www.michigan.gov/documents/CAFOs Chemicals_Associated_with_Air_Emissions_5-10-06_158862_7.pdf

Michigan State University Extension. (n.d.) *Air emission reporting under EPCRA for CAFOs*. Retrieved from http://www.animalagteam.msu.edu/Portals/0/MSUE%20EPCRA%20REPORTING%20FACT%20SHEET.pdf

Mirabelli, M.C., Wing, S., Marshall, S.W., & Wilcosky, T.C. (2006). Race, poverty, and potential exposure of middle-school students to air emissions from confined swine feeding operations. *Environmental Health Perspectives, 114*(4), 591–596. Retrieved from http://ehp.niehs.nih.gov/realfiles/members/2005/8586/8586.pdf

Pew Charitable Trusts. (n.d.) *Antibiotic-resistant bacteria in animals and unnecessary human health risks*. Retrieved from http://www.saveantibiotics.org/resources/PewHumanHealthEvidencefactsheet7-14FINAL.pdf

Pew Commission on Industrial Animal Farm Production. (2009). *Putting meat on the table: Industrial farm animal production in America*. Retrieved from http://www.ncifap.org/_images/PCIFAPFin.pdf

Purdue Extension. (2007). *Contained animal feeding operations—Insect considerations*. Retrieved from http://www.ces.purdue.edu/extmedia/ID/cafo/ID-353.pdf

Purdue Extension. (2008). *Community impacts of CAFOs: Property value*. Retrieved from http://www.ces.purdue.edu/extmedia/ID/ID-363-W.pdf

Schmalzried, H.D. & Fallon, L.F., Jr. (2007). Large-scale dairy operations: Assessing concerns of neighbors about quality-of-life issues. *Journal of Dairy Science, 90*(4), 2047-2051. Retrieved from http://jds.fass.org/cgi/reprint/90/4/2047?maxtoshow=&hits=10&RESULTFORMAT=&fulltext=large-scale&searchid=1&FIRSTINDEX=0&volume=90&issue=4&resourcetype=HWCIT

Schmalzried, H.D. & Fallon, L.F., Jr. (2008). A proactive approach for local public health districts to address concerns about proposed large-scale dairy operations. *Ohio Journal of Environmental Health, Fall/Winter 2008*, 20-25.

Science Daily. (n.d.) *Algal bloom*. Retrieved from http://www.sciencedaily.com/articles/a/algal_bloom.htm

Sierra Club Michigan Chapter. (n.d.) *Glossary of CAFO terms*. Retrieved from http://michigan.sierraclub.org/issues/greatlakes/articles/cafoglossary.html#E

Sigurdarson,S.T. & Kline, J.N. (2006). School proximity to concentrated animal feeding operations and prevelance of asthma in students. *Chest, 129*, 1486–1491. Retrieved from http://chestjournal.chestpubs.org/content/129/6/1486.full.pdf

Spellman, F.R. & Whiting, N.E. (2007). *Environmental management of concentrated animal feeding operations (CAFOs)*. Boca Raton, FL: CRC Press.

State Environmental Resource Center. (2004). *Issue: Regulating air emissions from CAFOs*. Retrieved from http://www.serconline.org/cafoAirEmissions.html

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CH_4 AND N_2O EMISSIONS FROM LIVESTOCK MANURE

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ABSTRACT

Livestock are produced throughout the world and are a significant contributor to global methane (CH_4) emissions. Methane, a greenhouse gas, is produced from the decomposition of livestock manure under anaerobic conditions. These conditions often occur when large numbers of animals are managed in a confined area (e.g., dairy farms, beef feedlots, and swine and poultry farms) where manure is typically stored in large piles or disposed of in lagoons. Nitrous oxide, also a greenhouse gas, is produced during the nitrification-denitrification of nitrogen contained in livestock waste.

The *Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories* (*IPCC Guidelines*) provide a general guide to estimating methane emissions from livestock manure. Two approaches may be used to estimate emissions: the Tier 1 approach relies on default emission factors drawn from previous studies, while the more complex Tier 2 approach requires country-specific information on livestock manure characteristics and manure management practices. The Tier 2 approach is recommended when the data used to develop the default values does not correspond well with the country's livestock and manure management conditions or when a country has large dairy and swine populations.

To prepare methane estimates, livestock population data characterized by subgroup are required. For Tier 1 estimates, necessary population data should be readily obtainable within the country or from the Food and Agricultural Organization (FAO). The Tier 2 estimates require additional data on manure characteristics and manure management practices, for which country-specific data should be used. These data should be obtained through data collection activities. If necessary, IPCC default values can be used for some of the factors in the Tier 2 calculation.

Nitrous oxide estimates also require livestock population and manure management practice data. The value and source of these data should correspond with that used for estimating methane emissions.

Reporting of emission estimates for both methane and nitrous oxide is clearly described in the *IPCC Guidelines.* With few exceptions, confidentiality is not expected to pose a challenge.

Ensuring the quality of the inventory will be an important activity, particularly where Tier 2 methods are used. The most important aspect of QA/QC (quality assurance/quality control) is thorough and transparent documentation of the emissions calculation steps, including all activity data and emission factor values.

1 INTRODUCTION

1.1 Nature, magnitude, and distribution of source

1.1.1 Overview

Methane Generation

The principal factors affecting methane emission from livestock manure are the amount of manure that is produced and the portion of the manure that decomposes anaerobically. The total amount of manure produced can be estimated using an average amount of manure produced per animal and the number of animals. The type of manure management system used and the climate (primarily temperature) are the primary factors that determine the extent of anaerobic decomposition that takes place.

Some livestock producers reduce the amount of methane that escapes into the atmosphere by constructing lids or caps for lagoons or tanks where manure is kept. This recovered methane is often flared or used as a fuel in a boiler, heater, or an engine-generator.

Nitrous Oxide Generation

Production of N_2O during storage and treatment of animal wastes can occur via combined nitrification-denitrification of nitrogen contained in the wastes. The amount of N_2O released depends on the system and duration of waste management. Because N_2O production requires an initial aerobic reaction and then an anaerobic process, it is theorized that dry, aerobic management systems may provide an environment more conducive for N_2O production.

1.1.2 Process description

Methane

Livestock manure is primarily composed of organic material and water. Under anaerobic conditions, the organic material is decomposed by anaerobic and facultative bacteria. The end products of anaerobic decomposition are methane, carbon dioxide, and stabilized organic material. The methane production potential of manure depends on the specific composition of the manure, which in turn depends on the composition and digestibility of the animal diet.

The amount of methane produced during decomposition is influenced by the climate and the manner in which the manure is managed. The management system determines key factors that affect methane production, including contact with oxygen, water content, pH levels, and nutrient availability. Climate factors include temperature and rainfall. Optimal conditions for methane production include an anaerobic, water-based environment, a high level of nutrients for bacterial growth, a neutral pH (close to 7.0), and warm temperatures.

The key factors affecting methane production from livestock manure are the quantity of manure produced, manure characteristics, the manure management system, and climate.

Quantity of Manure Production

Manure production varies by animal type and is proportional to the animal's weight and feed intake.

Manure Characteristics

The portion of manure that can generate methane is the volatile solids portion (VS)[1]. The VS portion depends on livestock type and diet, which also affect the quantity of methane that can be produced per kilogram of volatile solids (VS) in the manure.

Manure Management System

Methane production depends on the type of manure management system, which can be broadly divided into "liquid" and "dry" systems. Dry systems include solid storage, dry feedlots, deep pit stacks, and daily spreading of the manure. In addition, unmanaged manure from animals grazing on pasture falls into this category. Liquid

[1] Volatile solids (VS) are the organic fraction of total solids in manure that will oxidize and be driven off as gas at a temperature of 600°C.

management systems often use water to facilitate manure handling. These systems include tanks and lagoons which store manure until it is applied to cropland. Liquid systems create the ideal anaerobic environment for methane production. Detailed descriptions of these systems are provided in Table 10 in Annex 2.

Climate

Manure decomposes more rapidly when the climate encourages bacterial growth. For liquid manure systems, warm temperatures increase methane generation. For solid systems, rainfall can affect methane production, with wet climates having higher emissions than arid climates. In either case, emissions from solid systems tend to be very low.

Nitrous Oxide

Nitrous oxide is produced from the combined nitrification-denitrification process that occurs on the nitrogen in manure. The majority of nitrogen in manure is in ammonia (NH_3) form. Nitrification occurs aerobically and converts this ammonia into nitrate, while denitrification occurs anaerobically, and converts the nitrate to N_2O. Temperature, pH, biochemical oxygen demand (BOD), and nitrogen concentration affect N_2O generation. BOD is the amount of dissolved oxygen used by aerobic microorganisms to completely consume the available organic matter.

Increasing aeration initiates the nitrification-denitrification reactions, and hence makes release of N_2O possible. Therefore, as fresh dung and slurry is highly anoxic and well-buffered with near neutral pH, N_2O production is expected to increase with increasing aeration. However, the denitrification process that produces N_2O requires an anaerobic environment. Currently, there is not enough quantitative data to derive a relationship between the degree of aeration and N_2O emissions. This makes N_2O emissions estimates from this source highly uncertain.

2 METHODOLOGICAL ISSUES

2.1 Selection of good practice methods

The *IPCC Guidelines* provides a general approach to estimate methane emissions from livestock. The three main steps used to estimate methane emissions from livestock manure are as follows: a) collect activity data for livestock population groups and subgroups; b) estimate emissions factors for each subgroup or use default emission factors; and c) multiply the emission factor by the population to obtain total methane emission estimate for the population. The total emissions estimates should be reported in gigagrams (Gg). Because the emission factors are reported in kilograms per head per year, the total emissions in Gg is estimated as follows:

Emission Factor (kg/head/yr) • Population (head) / (10^6 kg/Gg) = Emissions Gg/yr.

To execute this process in the most efficient manner, the *IPCC Guidelines* recommends two approaches to estimate methane emissions from livestock manure.

The **Tier 1** approach is simplified so that only readily available animal population data are needed to estimate emissions. Default emission factors are presented for each of the recommended population subgroups.

The **Tier2** approach provides a more detailed method for estimating methane emissions from manure management systems. This approach is recommended for countries with large livestock populations managed under confined conditions because the Tier 1 method will not accurately account for the higher level of emissions that are generally produced in confined facilities. This method requires detailed information on animal characteristics and the manner in which manure is managed. Using this additional information, emission factors specific to the conditions of the country are estimated and the default emission factors from Tier 1 are not used.

Countries are encouraged to carry out emissions inventory calculations at a finer level of detail beyond Tier 2 if possible. This can include conducting regional analyses of emissions to account for differences in livestock and manure characteristics, climate, and manure management practices across specified regions.

For N_2O, the *IPCC Guidelines* recommends an approach similar to the Tier 2 methane approach. Information on how manure is managed is used to identify default emission factors. These are used with nitrogen excretion estimates for each livestock group based on animal population data to estimate N_2O emissions.

N_2O emissions from all waste management systems are reported under this emissions source category with three exceptions:

- Manure that is applied to agricultural soils (e.g., daily spread);
- Manure deposited by grazing animals on fields (pasture range and paddock), and

- Manure used for fuel.

N_2O emissions from manure that is managed in these systems are instead accounted for in the methodology for estimating direct emissions from agricultural soils, direct soil emissions of N_2O from animal production, and manure used as fuel, respectively. The class "used for fuel" is not included here as a source of N_2O because it is considered an energy-related emission. Currently, this class incorrectly includes manure managed in anaerobic digesters.

2.2 Emissions factors

Methane

Emission factors are estimates of methane produced in kilograms per animal. Emission factors help to standardize emissions across many different livestock groups so that relatively correct total emission estimates can be made.

Tier 1 In this step, emission factors that are most appropriate for the country's livestock characteristics are selected. The *IPCC Guidelines* include default emission factors, which have been drawn from previous studies and are organized by region (Tables 4.5 and 4.6 from the *IPCC Guidelines* are included in Annex 1).

The Tier 1 emission factors incorporate assumptions about manure composition, climate, and manure system usage for developed and developing countries, as described in the Tier 2 discussion below.

The climate data collected as part of the activity data is used to select the appropriate emission factors. If a country manages livestock in more than one climate zone, a weighted average emission factor for each animal type should be computed by multiplying the percentages of the animal populations in each climate region by the emission factor for each climate region.

Weighted Emission Factor = Percentage of Animal Population in Climate • Climate Emission Factor

Tier 2 The Tier 2 emission factors are calculated based on country-specific data on manure composition, manure methane producing capacity, climate, and waste system usage. The major components of the emission factor calculation are as follows:

- *Volatile Solids (VS)* is the portion of the manure that produces methane. Often, data on average daily VS excretion are not available. Therefore, the VS values may need to be estimated from feed intake levels and characteristics. Feed intake data for cattle should be determined by selecting a representative animal from each animal type. The IPCC's suggested methodology for estimating VS using feed data is shown in Annex 2, which reprints Equation 15 from the *IPCC Guidelines.*
- *Methane Producing Potential (B_O)* is the maximum amount of methane that can be produced from a given quantity of manure. The methane producing potential varies by animal type and diet. The *IPCC Guidelines* provide default values for each major global region. The values determined for US livestock are used for all of the developed country regions, and a slightly modified value is used for some categories in the developing country regions. Using country-specific B_O factors based on recent measurement data or research should improve the reliability of the resulting emissions factor.
- *Methane Conversion Factor (MCF)* defines the portion of the methane producing potential (B_O) that is achieved. The MCF varies with the manner in which the manure is managed and the climate, and can theoretically range from 0 to 100 percent. Manure managed as a liquid under warm conditions has a high MCF of 65 to 90 percent. Manure managed as dry material in cold climates has a low MCF at 1 percent. Default MCFs by manure system have been developed from previous studies; the IPCC's recommended MCF's are shown in Annex 2, in Table 11, which was taken from the *IPCC Guidelines.* Incorporating additional research on methane production under various management scenarios may improve the accuracy of these factors.
- *Fraction of Manure in Management System (MS%)* describes the portion of each livestock group's manure that is handled by a specific manure management technique. This factor is collected as activity data, discussed in Section 2.3.

These four variables are used in the equation to calculate emission factors as follows:

EQUATION 1

$$EF_i = VS_i \bullet 365 \text{ days/yr} \bullet B_{oi} \bullet 0.67 \text{ kg/m}^3 \bullet \sum_{jk} MCF_{jk} \bullet MS\%_{ijk}$$

Where:

EF_i: annual emission factor (kg) for animal type i (e.g., dairy cows);

VS_i: daily VS excreted (kg) for animal type i;

B_{oi}: maximum methane producing capacity (m^3/kg of VS) for manure produced by animal type i;

MCF_{jk}: methane conversion factors for each manure management system j by climate region k; and

$MS\%_{ijk}$: fraction of animal type i's manure handled using manure system j in climate region k.

Nitrous Oxide

Nitrous oxide emission factors are estimates of kilogram of nitrous oxide nitrogen produced per kilogram of nitrogen excreted. These factors vary by waste management system, as shown in Table 1

TABLE 1

TENTATIVE DEFAULT VALUES FOR N_2O EMISSION FACTORS FROM ANIMAL WASTE PER ANIMAL WASTE MANAGEMENT SYSTEM (KG N_2O - N/KG NITROGEN EXCRETED)

Animal Waste Management System	Emission Factor EF
Anaerobic lagoons	0.001 (<0.002)
Liquid systems	0.001 (<0.001)
Daily spread[a]	0.0 (no range)
Solid storage and drylot[a]	0.02 (0.005-0.03)
Pasture range and paddock (grazing)[b]	0.02 (0.005-0.03)
Used as fuel[c]	Not Applicable
Other systems[b]	0.005

[a] Considered to be a part of direct soil emissions from agricultural fields after spreading.

[b] Considered to be a part of direct soil emissions from animal production.

[c] Considered to be a part of emissions from energy.

Source: IPCC, 1996.

2.3 Activity data

Activity data include data on livestock population, and manure management system usage. The Tier 1 methodology for methane emissions requires data on livestock population by livestock group. Both the Tier 2 methodology for methane and the nitrous oxide methodology require livestock population data and data on manure system usage.

Methane

Tier 1: The *IPCC Guidelines* recommend collecting the average annual population of livestock listed in Table 2. It is recommended that countries collect their own population data. The number of animals recorded depends on the time at which the census is taken. For example, a census taken before most calves are born yields a lower number of animals than a census taken after most calves are born. Data should represent an average estimate for the entire year. If population data cannot be collected, it can be obtained from an outside source such as the Food and Agriculture Organization (FAO) or similar country-specific livestock census reports.

TABLE 2 DOMESTIC LIVESTOCK INCLUDED IN THE TIER 1 METHODOLOGY
Livestock
Dairy Cattle
Non-Dairy Cattle
Buffalo
Sheep
Goats
Camels
Horses
Mules and Asses
Swine
Poultry

As shown in Table 2, IPCC recommends recording data on dairy cattle separate from other cattle. Dairy cattle are defined as mature cows producing milk in commercial quantities for human consumption, and are managed differently from non-dairy cattle. This generally results in differences in composition and methane production potential between dairy and non-dairy cattle manure. Additionally, dairy cattle manure is often managed differently from cattle manure.

In some countries, there are two types of dairy cows: high-producing, “improved” breeds in commercial operations and low-producing breeds managed with traditional methods. If possible, countries can separate the dairy cow population into two groups. The dairy cow group does not include cows used mainly for producing calves or for draft power. These cows are accounted for in non-dairy cattle data.

In addition, livestock populations must be described in terms of warm or cool temperature climates for purposes of estimating livestock manure emissions. Data on the annual average temperature of the regions where livestock are managed should be used as follows:

- Areas with annual average temperatures less than 15° C are defined as cool;
- Areas with annual average temperatures from 15° C to 25° C inclusive are defined as temperate, and
- Areas with annual average temperatures greater than 25° C are defined as warm.

The fraction of each livestock population should be estimated for each climate. This data can be developed from country-specific climate maps and livestock census reports. To the extent possible, the temperature data should reflect the locations where the livestock are managed.

Tier 2: In addition to the livestock population data described for Tier 1, the Tier 2 approach also requires data on the percentage of manure managed with each management system. Data should be collected for each management system. Table 12 in Annex 2 summarizes the main types of manure management systems, which can be broadly divided into "wet" and "dry" systems. If specific management system data does not exist, there should be at least a division of manure production into wet and dry systems. The IPCC provides default manure management practice data for major regions based on Safley, et al. (1992). If country-specific data exists or can be collected, it should be used. Additionally, if the current data predates known changes in manure management practices, they should be updated to reflect the current practices.

Nitrous Oxide

In addition to livestock population and manure management system data (described above), the nitrous oxide emissions estimation approach also requires nitrogen excretion data by animal type. It is recommended that country-specific data be collected and used. This may require manure composition analysis, which should be coordinated with any research to determine volatile solids content. If this is not feasible, regional default values can be used. These are provided in Table 3.

TABLE 3

TENTATIVE DEFAULT VALUES FOR NITROGEN EXCRETION PER HEAD OF ANIMAL PER REGION (KG/ANIMAL/YR)

Region	Type of Animal					
	Non-Dairy Cattle	Dairy Cattle	Poultry	Sheep	Swine	Other Animals
North America	70	100	0.6	16	20	25
Western Europe	70	100	0.6	20	20	25
Eastern Europe	50	70	0.6	16	20	25
Oceania	60	80	0.6	20	16	25
Latin America	40	70	0.6	12	16	40
Africa	40	60	0.6	12	16	40
Near East & Mediterranean	50	70	0.6	12	16	40
Asia & Far East	40	60	0.6	12	16	40

Source: IPCC, 1996.

2.4 Uncertainty

Parallel to the IPCC sector-specific meetings on good practice guidance, the IPCC is completing a programme of work on emissions inventory uncertainty. This work will result in recommendations to the United Nations Framework Convention on Climate Change (UNFCCC) on approaches to assessing and managing uncertainty. During the IPCC Inventory Experts Group Meeting in Paris (October 1998), technical experts in the uncertainty programme came up with a series of questions to be answered in the sector meetings. Specifically, the sector meetings should provide answers to these questions in the individual source context. The questions are listed in the general background paper.

Methane

Tier 1: Given that the emissions factors for Tier 1 are not based on country-specific data, they do not represent accurately the manure management system characteristics for any given country. The emissions factors are highly uncertain as a result. Emission factors should be updated for regions that have experienced significant changes in manure management practices.

Tier 2: One source of uncertainty in the Tier 2 emissions factors is the manure system usage data. The level of confidence in this data depends on the methods used to collect the data for each country. Additionally, there is uncertainty in the MCFs used to estimate the portion of the methane production potential that is realized in each manure management system. Conditions can vary significantly, particularly in liquid systems. The default MCFs may not account for all of the variability in methane production that can exist within systems. A secondary source of uncertainty lies in the equations used to calculate the emissions factor (presented in Annex 2). Generally, uncertainty in the equations is low compared to the uncertainty in the manure system usage data. Consequently, efforts undertaken to reduce uncertainty should focus first on improving this data.

Nitrous Oxide

In addition to the uncertainty in the manure system usage data, there is also uncertainty in the nitrogen excretion data. Similar to manure system usage, the level of uncertainty in nitrogen excretion data depends on the methods used to collect the data. As discussed before, there is also a high level of uncertainty in the emission factors that arises from a lack of data on N_2O production from manure.

2.5 Completeness

Given that the different livestock species are distinct and population data are generally available, each country is expected to create a complete inventory comprised of emissions estimates for each required livestock species. If population data are unavailable, countries can use data collected by FAO (FAO, 1999).

2.6 Other important issues

2.6.1 Baseline

An emission baseline is an important component of an inventory programme. Below is a description of issues related to creating a baseline for the methane and nitrous oxide methods recommended by the IPCC.

Methane

Tier 1: Developing a baseline for Tier 1 requires collecting and compiling animal population data during the baseline period. For the Tier 1 methodology, difficulties arise when

- Animal population data are not available for the baseline period;
- Animal population data during the baseline period are not broken down into the animal groups recommended by IPCC, and
- Changes in manure management practices over time affect methane emissions.

Approaches to overcoming these difficulties include collecting aggregate historical data from FAO and using current data to break out historical population data into the animal groups. If changes in manure management practices affect methane emissions significantly, the Tier 1 method is unreliable, and the Tier 2 method should be used.

Tier 2: Developing a baseline for Tier 2 requires the collection and compilation of manure management system usage data during or following the baseline period. In addition to the issues related to animal population data described for Tier 1, difficulties arise in the Tier 2 methodology when:

- Manure management system data are not available for the baseline period;
- Manure management system data during the baseline period are not broken down into the systems recommended by IPCC, and
- The Tier 2 methodology was not used throughout the baseline period.

Approaches to overcoming a lack of substantial management system data include applying a sample area or region's manure management practice trends to the entire country. If emission estimation methodologies have changed, historical data that are required by the current methodology should be collected and used to re-estimate emissions for that period. If these data do not exist, it may be appropriate to create a trend with recent data and use the trend to back-estimate management practices for the baseline period. Among other sources, publications, industry and university experts can be used to estimate trends for the livestock and feed characteristics.

Nitrous Oxide

The issues related to animal population and manure management practices described for methane also apply to emissions from nitrous oxide.

2.6.2 Accurate detection of mitigation measures

Efforts to reduce methane emissions through improved productivity, and thus declining livestock populations, would be reflected in the livestock population data. This decline would directly affect manure and volatile solids production, as well as nitrogen production. All other factors kept constant, decreases in volatile solids and nitrogen production would reduce methane and nitrous oxide emissions.

Shifts in manure management practices towards dry systems would have a similar affect on methane emissions. On a weight basis, manure in dry systems produces significantly less methane than liquid systems. Even with increased manure production, shifts toward dry systems could decrease methane emissions dramatically. Based on default emission factors, such shifts would presumably have an opposite effect on nitrous oxide emissions. However, the high uncertainty associated with these factors may diminish any effects of such changes.

The current methodology accounts for manure handled in anaerobic digesters. The IPCC default MCF for these digesters is 5-15%, which is much lower than the MCF values for anaerobic lagoons (90%) and liquid/slurry systems (10-65%). Thus, increased handling of manure in such systems could significantly decrease methane emissions.

2.6.3 Consistency with inventory for livestock digestive systems

The livestock characterization used to estimate methane and nitrous oxide emissions from livestock manure should be consistent with the characterization used for methane emissions from livestock digestive systems. If there are conflicts or inconsistencies, these should be resolved as soon as possible.

3 REPORTING AND DOCUMENTATION

A recent report from the UNFCCC Secretariat "Methodological Issues Identified While Processing Second National Communications" (UNFCCC/SBSTA/1998/7) noted that almost all countries reported methane emissions from manure, and all countries, with the exception of two countries, reported emissions from manure separately from enteric fermentation emissions. Specifically, Belgium included emissions from manure with emissions from enteric fermentation and Estonia reported methane emissions from all agriculture rather than separating each agricultural source (Estonia, 1998).

In reporting emissions, countries should include all activity data, and document the source of the data. Countries using the methane Tier 2 approach should also explicitly show the emission factor calculation method. This includes the calculation method and steps to determine the respective emission factors that are weighted and aggregated across manure management systems to produce a single factor for each livestock category.

3.1 Current IPCC reporting guidelines

The *IPCC Guidelines* are used to guide countries in the preparation and submissions of annual greenhouse gas emissions inventories to the UNFCCC Secretariat. The Guidelines establish:

- Standard tables, definitions, units, and time intervals for reporting all types of emissions;
- Necessary documentation to enable comparison of national inventories, including worksheets, major assumptions, methodological descriptions, and enough data to allow a third party to reconstruct the inventory from national activity data and assumptions, and
- An uncertainty assessment.

Both methane and nitrous oxide emissions from livestock manure are reported in Table 4, Volume 2 of the *IPCC Guidelines* - Sectoral Report for Agriculture. This table requires recording emissions from each livestock source, and also across the major manure management systems.

3.2 Confidential business information

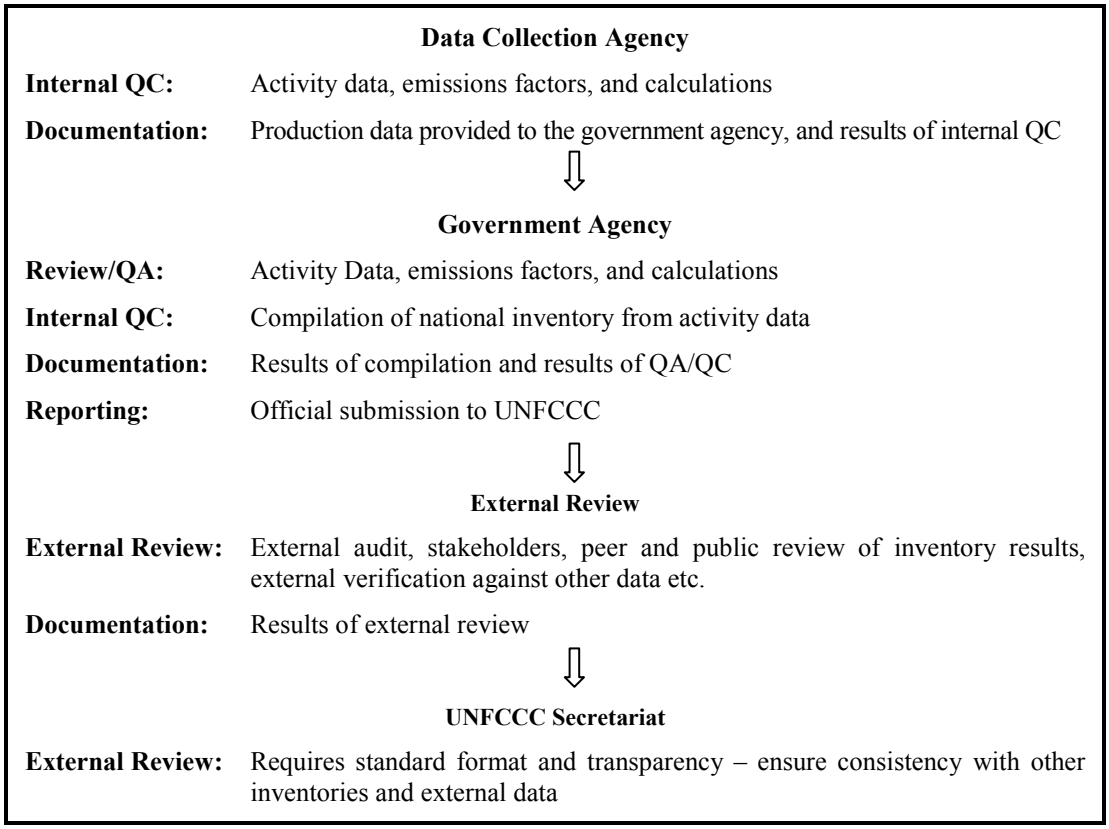
In isolated cases, reporting population data and information on management practices may be a problem in regions with a small number of large, commercial operations. Confidentiality is not expected to be a significant issue for this source.

4 INVENTORY QUALITY

4.1 Introduction

Inventory quality assurance and quality control (QA/QC) is a process integral to the development of a credible inventory. A well-developed and well-implemented quality assurance programme fosters confidence in the final inventory results regardless of the purpose and goal of the inventory. A successful quality assurance programme requires internal quality control procedures and an unbiased, external review and audit. The internal QC activities are designed to ensure accuracy, documentation, and transparency. The external review process is designed to minimize errors that occur in the preparation of emissions inventories, and reduce or eliminate potential inherent bias. Figure 1 outlines the flow of information and processes followed at each step.

Figure 1 Inventory QA/QC Process



4.2 Internal inventory QA/QC systems

4.2.1 Emissions factors

Emissions Factors QC

Methane

Tier 1: The emissions factors are based on default data. QC procedures include reviewing the available default values and documenting the rationale for selecting specific values. Other QC procedures are not required.

Tier 2: QC procedures for the Tier 2 emissions factors involve checking the equations and calculations used to calculate the emissions factor. The Tier 2 emissions factors are based on country-specific information on animal and feed characteristics. QC procedures on these data are described below in the Activity Data section.

Nitrous Oxide

The emissions factors are based on default data. QC procedures include reviewing the available default values and documenting the rationale for selecting specific values. Other QC procedures are not required.

Emissions Factors Documentation

Documentation is a crucial component of the review process because it enables reviewers to identify mistakes and suggest improvements. Among other elements, a detailed description of the equations used to estimate emissions factors is needed. In addition, a standardized reporting form is recommended to provide transparent information on the steps taken to calculate the emissions factors. Each step should contain the numbers used in each calculation, including the source of any data collected.

4.2.2 Activity data

Activity Data QC

Tier 1 and Tier 2 ***Livestock Population Data:*** The annual livestock population data are generally collected by a country's ministry of agriculture or a similar organization focused on the agriculture sector. The personnel that

collect data are responsible for reviewing the data collection methods, checking the data to ensure they were collected and aggregated correctly, and cross-checking the data with previous years to ensure the data are reasonable. The basis for the estimates, whether statistical surveys or "desk estimates," must be reviewed and described as part of the QC effort.

Tier 2 ***Manure Management Practices Data:*** There are generally two approaches to collecting manure management system usage data: a) a government agency or related body collects the data by surveying farms; or b) the agency or related body interviews industry and university experts. The QC activities for the two approaches are described below:

- *Farm Survey*: Government agencies, such as the ministry of agriculture or a related body, collect the animal and feed characteristics data required for the inventory. The personnel collecting the data are responsible for reviewing the collection methods, checking to ensure the data were collected and aggregated correctly, and comparing data with data from previous years to ensure the data are reasonable.
- *Industry and University Experts*: Manure system usage data may be obtained by surveying and interviewing industry and university experts. The personnel collecting the data are responsible for reviewing surveys used to collect the data to make sure the survey is appropriate for the data needs. Questions used in interviews should also be reviewed.

Activity Data Documentation

Documentation is a crucial component of the review process, because it enables reviewers to identify mistakes and suggest improvements. Among other information, the following is needed for the reviewing/auditing agency:

- A highly detailed description of the methods used to collect the activity data, and
- A discussion of potential areas of bias in the data, including a discussion of whether the manure management practices are representative of the country.

4.2.3 Inventory agency level activities

Inventory Agency Review of Activity Data QA

Before accepting the activity data, the inventory agency should assess them, including all data on the animal population and manure management practices. This review involves close cooperation with the personnel responsible for collecting, compiling, and analyzing the data. The assessment should include a review of the detailed methods used to collect the data, including a review of any surveys and interviews performed to collect the data. In addition, the assessment should include a comparison of the activity data with historical data, a discussion of the potential for bias, and recommendations for improvement.

Inventory Agency QC on Compiling National Emissions

In addition to a thorough quality assessment of data discussed above, the inventory agency should ensure that the process of aggregating data to develop the national inventory undergoes quality control. This should include, among other things:

- Cross-referencing the aggregated population data with the national totals;
- Back-calculating national and regional emissions factors from the Tier 2 management system usage data (if using Tier 2);
- Ensuring that the manure management practices are representative of the country (if using Tier 2);
- Ensuring that all farms are included in the population data, and
- Comparing with national trends to look for anomalies.

Inventory Agency Documentation on Compiling National Emissions

For the CH_4 emission inventory for enteric fermentation, a QA/QC management plan should address the specific items needed to perform audits and reviews. Examples of the types of information needed for documentation and external audit include:

- A detailed description of the inventory methodology;
- Identification of the input parameters that are needed and how the input parameters are obtained, and
- Frequency of data collection and estimation and results of determinations of accuracy and precision.

4.3 External inventory QA/QC systems

External QA activities include a planned system of review and audit procedures conducted by personnel not actively involved in the inventory development process. The key concept is an independent, objective review to assess the effectiveness of the internal QC programme, the quality of the inventory, and to reduce or eliminate any inherent bias in the inventory processes. Several types of external reviews, or audits, may be appropriate for the inventory of CH_4 and N_2O emissions from livestock manure.

- **Third party audit by an accredited organization, expert, independent third party:** An audit of the documentation and calculations ensures that each number is traceable to its origin.
- **Expert (peer) review:** Although a detailed peer review would be appropriate when a procedure for determining CH_4 emissions is first adopted or revised; it would not be needed on an annual basis. Such a review is designed to ensure that the methodology is rigorous, accurate, and that the data and assumptions reflect the best available information.
- **Stakeholder review:** Review by industrial organizations and government can provide a forum for review of the methods used.
- **Public review:** Some countries make their entire inventory available for public review and comment. This process may result in a range of comments and issues broader than those from other review processes.

Confidential Business Information Issues

Confidentiality is not a major issue when private parties review the data. However, in areas with several large, commercial producers, there may be opposition to releasing the activity data to the public.

5 UPDATES TO ESTIMATION METHODS

At the IPCC workshop on Good Practices in Inventory Methods held in the Netherlands on February 24-26, 1999, participants recommended updates to the Tier 2 method used to estimate methane emissions from livestock manure. These updates included the following:

- Modifications to the maximum methane producing capacity of cattle, poultry, and swine based on recent research;
- New MCF values for liquid/slurry and pit storage manure management systems;
- Revised definitions for several management systems, and
- The addition of new manure management systems into the IPCC list of systems.

Recent work by Zeeman and Gerbens (1999) showed that B_o values for swine manure may be lower than the IPCC default value. The latter would suggest an unrealistic high biodegradability of 92% (Zeeman and Gerbens, 1999), in contradiction to the observed biodegradability of 70% (Zeeman, 1994). Therefore it is proposed that the estimated B_o (Zeeman and Gerbens, 1999) values should be used as the default values in the *IPCC Guidelines*. A comparison of these values is shown in Table 4.

TABLE 4

RANGE IN B_O VALUES REPORTED BY SAFLEY ET AL.(1992) AND ESTIMATED B_O VALUES FOR DEVELOPED AND DEVELOPING COUNTRIES (ZEEMAN AND GERBENS,1999) IN COMPARISON TO IPCC DEFAULT VALUES (M^3 CH_4/KG VS)

	IPCC (1996) Developed Countries	IPCC (1996) Developing Countries	Safley et al. (1992)	Zeeman and Gerbens (1999) Developed	Zeeman and Gerbens (1999) Developing
	Default	Default	range	estimated	estimated
Non-dairy	0.17	0.10	0.17-0.33		
Dairy	0.24	0.13	0.10-0.24	0.25	0.14[1]
Poultry	0.32	0.24	0.24-0.39		
Swine	0.45	0.29	0.32-0.52	0.34	0.22[1]

Estimated B_o values for developing countries (Zeeman and Gerbens, 1999) are proportionally lower and similar to the IPCC estimate for B_o values for developinged regions.

The participants also proposed using revised MCF values based on values observed by Zeeman(1994) shown in Table 5.

TABLE 5

COMPARISON BETWEEN IPCC DEFAULT MCF VALUES AND PROPOSED MCF VALUES

Manure management Strategy	Climatic condition	MCF (%) (IPCC, 1995)	MCF (%) (Zeeman and Gerbens, 1999)
Liquid/slurry	Cool	10	39
	Temperate	35	45
	Warm	65	72
Pit < 1 month	Cool	5	0
	Temperate warm	18 33	0 30
Pit > 1 month	Cool	10	39
	Temperate	35	45
	Warm	65	72

In addition, it was recommended that digesters and anaerobic lagoons be subdivided to account for recovery, flaring and use of the biogas including the gas produced/emitted during manure storage after digestion. The proposed revisions to the manure management system definitions and MCF values are shown in Table 6. The proposed additional management systems are shown in Table 7.

TABLE 6

MANURE MANAGEMENT SYSTEMS (BLANK MEANS NO CHANGE FROM CURRENT IPCC DEFINITIONS/MCFS)

System	Definition	MCFs by Climate			Comments
		Cool	Temperate	Warm	
Pasture/Range/ Paddock					
DailySpread	Dung and urine is collected by some means such as scraping. The collected waste is applied to fields.				
Solid Storage	Dung and urine are excreted in a stall. The solids (with or without litter) are collected and stored in bulk for a long time (months) before disposal, with or without liquid runoff into a pit system.				
Drylot					
Liquid/Slurry	Dung and urine are collected and transported in liquid state to tanks for storage. Liquid may be stored for a long time (months). To facilitate handling water maybe added.	39%	45%	72%	When slurry tanks are used as fed-batch storage/digesters, MCF should be calculated according to formula 1.
Anaerobic Lagoon		0-100%	0-100%	0-100%	Should be subdivided in different categories, considering percentage recovery of the biogas and flaring of the biogas.
Pit Storage Below Animal Confinements	Combined storage of dung and urine below animal confinements <1 month >1 month	0-39%	0-45%	30%-72%	When pits are used as fed-batch storage/digesters, MCF should be calculated according to formula 1. The stable temperature, not the ambient temperature, is to be used for determining the climatic conditions.

TABLE 6 (CONTINUED)

MANURE MANAGEMENT SYSTEMS (BLANK MEANS NO CHANGE FROM CURRENT IPCC DEFINITIONS/MCFS)

System	Definition	MCFs by Climate			Comments
		Cool	Temperate	Warm	
Drylot					
Anaerobic Digester	The dung and urine in liquid/slurry is collected and anaerobically digested. Methane may be burned flared or vented.	0-100%	0-100%	0-100%	Should be subdivided in different categories, considering amount of recovery of the biogas, flaring of the biogas and storage after digestion .
Burned for Fuel	The dung and urine are excreted on fields. The sun dried dung cakes are burned for fuel.				

TABLE 7

PROPOSED NEW MANURE MANAGEMENT SYSTEMS

Recommended Additional Systems	Definition	MCFs by Climate			Comments
		Cool	Temperate	Warm	
Cattle Deep Litter	Cattle dung and urine is excreted on stall floor. The accumulated waste is removed after a long time.	10%	35%	65%	MCF's are similar to liquid/slurry; temperature dependant.
Composting – Intensive	Dung and urine is collected and placed in a vessel or tunnel, there is forced aeration of the waste.	0.5%	0.5%	0.5%	MCF's are less than half of solid storage. Not temperature dependant.
Composting – Extensive	Dung and urine collected, stacked and regularly turned for aeration.	0.5%	1%	1.5%	MCF's are slightly less than solid storage. Less temperature dependant.
Poultry manure with bedding	Manure is excreted on floor with bedding. Birds walk on waste.	1.5%	1.5%	1.5%	MCF's are similar to solid storage but with generally constant warm temperatures.
Poultry manure without bedding	Manure is excreted on floor without bedding. Birds do not walk on waste.	1.5%	1.5%	1.5%	MCF's are similar to dry lot at a warm climate.
Aerobic Treatment	Dung and manure is collected as a liquid. The waste undergoes forced aeration, or treated in aerobic pond or wetland systems to provide nitrification and denitrification.	0.1%	0.1%	0.1%	MCF's are near zero.

6 CONCLUSIONS

The key issues for estimating emissions from manure management relate to the actual methodology as well as to the creation of a baseline for methane and nitrous oxide emissions. Major issues concerning the Tier 1 methodology include lack of animal population data by animal groups. Approaches to overcoming this difficulty include collecting aggregate historical data from FAO and using current data to break out historical population data into the animal groups. For the Tier 2 methodology, the key issue is obtaining an accurate representation of manure management systems for any particular additional country. Approaches to overcoming this issue include applying a sample area or region's manure management practice trends to the entire country.

Issues to be addressed when developing a baseline include lack of available data, historic data not having been organized as recommended by IPCC, and changes in manure management practices over time that affect emissions results. The approaches for resolving issues include re-examination of historical data by means of the current methodology, the application of data from a representative region to the entire country as well as the creation of a trend with recent data and back-estimating historic data using this trend.

Updates to the Tier 2 method recommended at the IPCC Workshop in *Good Practices* in Inventory Methods held on February 24-26, 1999 in the Netherlands included the results of recent research such as modifications to the maximum methane producing capacity of livestock (B_o values), new MCF values for liquid slurry and pit storage as well as the revision and incorporation of the additional manure management systems currently being used (i.e. daily spread, solid storage, drylot, and anaerobic lagoon were revised; pit storage is a new system that has been incorporated).

REFERENCES

Estonia. 1998. *Second National Report under the United Nation's Framework Convention on Climate Change*.

Food and Agriculture Organization (FAO). 1999. Statistical Database. << http://apps.fao.org/lim500/nph-wrap.pl?Production.Livestock.Stocks&Domain=SUA&servlet=1 >>

Hashimoto, A. and J. Steed (1993), *Methane Emissions from Typical U.S. Livestock Manure Management Systems*. Draft report prepared for ICF Incorporated under contract to the Global Change Division of the Office of Air and Radiation, US Environmental Protection Agency, Washington D.C., U.S.A.

International Panel on Climate Change (IPCC). 1996. *Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories, Reference Manual (Revised)*. v.3.

International Panel on Climate Change (IPCC). 1995. *IPCC Guidelines for National Greenhouse Gas Inventory*.

Lichtman, R.J. (1983), *Biogas Systems in India*, Volunteers In Technical Assistance (VITA), Arlington, Virginia, U.S.A.

Safely, L.M., M.E. Casada, J.W. Woodbury, and K.F. Roos (1992), *Global Methane Emissions from Livestock and Poultry Manure*. US Environmental Protection Agency, Global Change Division, Washington D.C., February 1992, EPA/400/1091/048.

Safley, L.M. Jr. and P.W. Westerman, (1992), "Performance of a low temperature lagoon digester," *Bioresource Technology* 41:167-175.

Stuckey, D.C. (1984), "Biogas: a global perspective." In: *Biogas Technology, Transfer and Diffusion*, M.M. El-Halwagi (ed.), Elsevier, New York, U.S.A., pp. 18-44.

Woodbury, J.W. and A. Hashimoto (1993), "Methane Emissions from Livestock Manure." In *International Methane Emissions*, US Environmental Protection Agency, Climate Change Division, Washington D.C., U.S.A.

Yancun, C., H. Cong and Liang Pusen (1985), "Development of a new energy village - Xinbu, China." In: *Integrated Rural Energy Planning*, Y. El Mahgary and A.K. Biswas (eds.), Butterworths Publishing, Guildford, England, pp. 99-108.

Zeeman, G. (1994). "Methane production/emission in storage's for animal manure," *Fertilizer Research* 37: 207-211.

Zeeman, G. and Gerbens, S. (1999) *Expert group meeting on good practice in inventory preparation. Workgroup 2: "Methane emission from animal manure,* Background paper for IPCC Workshop, February 24-26 1999, Wageningen, The Netherlands

ANNEX 1 TIER 1 EMISSION FACTORS

TABLE 8

MANURE MANAGEMENT EMISSION FACTORS (KG PER HEAD PER YR.)

	Developed Countries			Developing Countries		
Livestock	Cool	Temp.[a]	Warm	Cool	Temp.[a]	Warm
Sheep	0.19	0.28	0.37	0.10	0.16	0.21
Goats	0.12	0.18	0.23	0.11	0.17	0..22
Camels	1.6	2.4	3.2	1.3	1..9	2.6
Horses	1.4	2.1	2.8	1.1	1..6	2.2
Mules and Asses	0.76	1.14	1.51	0.60	0.90	1.2
Poultry[b]	0.078	0.117	0.157	0.012	0.018	0.023

The range of estimates reflects cool to warm climates. Climate regions are defined in terms of annual average temperature as follows: Cool = less than 15° C; Temperate = 15° C to 25° C inclusive; and Warm = greater than 25° C. The Cool, Temperate, and Warm regions are estimated using MCFs of 1% and 2%, respectively.

[a] Temp. = Temperate climate region.

[b] Chickens, ducks, and turkeys.

All estimates are ±20%.

Sources: Emission factors developed from: feed intake values and feed digestibilities used to develop the enteric fermentation emission factors; MCF, and B_O values reported in Woodbury and Hashimoto (1993). All manure is assumed to be managed in dry systems, which is consistent with the manure management system usage reported in Woodbury and Hashimoto (1993).

Source: IPCC, 1996 (Chapter 4, Table 4.5).

TABLE 9

TIER 1 MANURE MANAGEMENT EMISSION FACTORS FOR CATTLE, SWINE, AND BUFFALO

Regional Characteristics	Livestock Type	Emission Factor by Climate Region (kg/head/yr)		
		Cool	Temperate	Warm
North America: Liquid-based systems are commonly used for dairy and swine manure. Non-dairy manure is usually managed as a solid and deposited on pastures or ranges.	Dairy Cattle	36	54	76
	Non-dairy Cattle	1	2	3
	Swine	10	14	18
	Buffalo			
Western Europe: Liquid/slurry and pit storage systems are commonly used for cattle and swine manure. Limited cropland is available for spreading.	Dairy Cattle	14	44	81
	Non-dairy Cattle	6	20	38
	Swine	3	10	19
	Buffalo	3	8	17
Eastern Europe: Solid based systems are used for the majority of manure. About one-third of livestock manure is managed in liquid-based systems.	Dairy Cattle	6	19	33
	Non-dairy Cattle	4	13	23
	Swine	4	7	11
	Buffalo	3	9	16
Oceania: Virtually all livestock manure is managed as a solid on pastures and ranges. About half of the swine manure is managed in anaerobic lagoons.	Dairy Cattle	31	32	33
	Non-dairy Cattle	5	6	7
	Swine	20	20	20
	Buffalo			

TABLE 9 (CONTINUED)

TIER 1 MANURE MANAGEMENT EMISSION FACTORS FOR CATTLE, SWINE, AND BUFFALO

Regional Characteristics	Livestock Type	Emission Factor by Climate Region (kg/head/yr)		
		Cool	Temperate	Warm
Latin America: Almost all livestock manure is managed as a solid on pastures and ranges. Buffalo manure is deposited on pastures and ranges.	Dairy Cattle	0	1	2
	Non-dairy Cattle	1	2	1
	Swine	0	1	2
	Buffalo	1	1	2
Africa: Almost all livestock manure is managed as a solid on pastures and ranges.	Dairy Cattle	1	1	1
	Non-dairy Cattle	0	1	1
	Swine	0	1	2
	Buffalo			
Middle East: Over two-thirds of cattle manure is deposited on pastures and ranges. About one-third of swine manure is managed in liquid-based systems. Buffalo manure is burned for fuel or managed as a solid.	Dairy Cattle	1	2	2
	Non-dairy Cattle	1	1	1
	Swine	1	3	6
	Buffalo	4	5	5
Asia: About half of cattle manure is used for fuel with the remainder managed in dry systems. Almost 40% of swine manure is managed as a liquid. Buffalo manure is managed in drylots and deposited in pastures and ranges.	Dairy Cattle	7	16	27
	Non-dairy Cattle	1	1	2
	Swine	1	4	7
	Buffalo	1	2	3
Indian Subcontinent: About half of cattle and buffalo manure is used for fuel with the remainder managed in dry systems. About one-third of swine manure is managed as a liquid.	Dairy Cattle	5	5	6
	Non-dairy Cattle	2	2	2
	Swine	3	4	6
	Buffalo	4	5	5

The range of estimates reflects cool to warm climates. Climate regions are defined in terms of annual average temperature as follows: Cool = less than 15° C; Temperate = 15° C to 25° C inclusive; and Warm = greater than 25° C. All climate categories are not necessarily represented within every region. For example, there are no significant warm areas in Eastern or Western Europe.

Note: Significant buffalo populations do not exist in North America, Oceania, or Africa.

Source: IPCC, 1996 (Chapter 4, Table 4.6).

ANNEX 2 TIER 2 EMISSION FACTORS

IPCC VS Excretion Rate Equation (Equation 15 in the IPCC Guidelines)

EQUATION 15

$$VS\ (kg\ dm/day) = Intake\ (MJ/day) \bullet (1kg\ dm / 18.45\ MJ) \bullet (1 - DE\% / 100) \bullet (1 - ASH\% / 100)$$

Where:

VS: VS excretion per day on a dry weight basis;

dm: dry matter;

Intake: the estimated daily average feed intake in MJ/day;

DE%: the digestibility of the feed in percent;

ASH%: the ash content of the manure in percent.

TABLE 10

MANURE MANAGEMENT SYSTEMS AND METHANE CONVERSION FACTORS (MCFS)

System		MCF by Climate			Source
		Cool	Temperate	Warm	
Pasture/Range/Paddock: the manure from pasture and range grazing animals is allowed to lie as is, and is not managed.		1%	1.5%	2%	b
Daily Spread: manure is collected in solid form by some means such as scraping. The collected manure is applied to fields regularly (usually daily).		0.1%	0.5%	1%	b
Solid Storage: manure is collected as in the daily spread system, but is stored in bulk for a long period of time (months) before any disposal.		1%	1.5%	2%	b
Drylot: in dry climates animals may be kept on unpaved feedlots where the manure is allowed to dry until it is periodically removed. Upon removal, the manure may be spread on fields.		1%	1.5%	5%	b
Liquid/Slurry: these systems are characterized by large concrete-lined tanks built into the ground. Manure is stored in the tank for six or more months until it can be applied to fields. To facilitate handling as a liquid, water may be added to the manure.		10%	35%	65%	b
Anaerobic Lagoon: anaerobic lagoon systems are characterized by flush systems that use water to transport manure to lagoons. The manure resided in the lagoon for periods from 30 days to over 200 days. The water from the lagoon may be recycled as flush water or used to irrigate and fertilize fields.		90%	90%	90%	c
Pit Storage: liquid swine manure may be stored in a pit while awaiting final disposal. The length of storage time varies, and for this analysis is divided into two categories: less than one month or greater than one month.	<1 month	5%	18%	33%	b
	> 1 month	10%	35%	65%	b
Anaerobic Digester: the manure, in liquid or slurry form, is anaerobically digested to produce methane gas for energy. Emissions are from leakage and vary with the type of digester.		5-15%	5-15%	5-15%	d
Burned for Fuel: manure is collected and dried in cakes and burned for heating or cooking. Emissions occur while the manure is stored before it is burned. Methane emissions associated with the combustion of the manure are not considered here. Combustion-related emissions are estimated in the *Traditional Biomass Fuels* Section of the *Energy* chapter.		5-10%	5-10%	5-10%	e

a The range of estimates reflects cool to warm climates. Climate regions are defined in terms of annual average temperature as follows: Cool = less than 15° C; Temperate = 15° C to 25° C inclusive; and Warm = greater than 25° C.

b Hashimoto and Steed (1993).

c Safley et al., (1992) and Safley and Westerman (1992).

d Yancun et al. (1985), Stuckey (1984) and Lichtman (1983).

e Safely et al., (1992).

Source: IPCC, 1996.

Greenhouse gas emissions from ruminant supply chains

A global life cycle assessment



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A report prepared by:

FOOD AND AGRICULTURE ORGANIZATION OF THE UNITED NATIONS
Animal Production and Health Division

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Greenhouse gas emissions from ruminant supply chains
A global life cycle assessment

This report presents results from a broad assessment carried out to improve the understanding of greenhouse gas (GHG) emissions along livestock supply chains. The analysis was conducted at the Animal Production and Health Division of FAO and co-financed by the Mitigation of Climate Change in Agriculture (MICCA) programme. The following persons and institutions contributed to this work:

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Abbreviations

ABP	animal products and by-products
AEZ	agro-ecological zone
BFM	bone-free meat
Bo	manure maximum CH_4 producing capacity
CF	carbon footprint
CGIAR	Consortium of International Agricultural Research Centers
CH_4	methane
CO_2	carbon dioxide
CO_2-eq	carbon dioxide equivalent
CW	carcass weight
DM	dry matter
DMI	dry matter intake
DOM	dead organic matter
FCR	feed conversion ratio
EF	emission factor
EI	emission intensity
FPCM	fat and protein corrected milk
GHG	greenhouse gas
GLEAM	Global Livestock Environmental Assessment Model
GIS	Geographical Information System
GPP	gross primary production
GWP	global warming potential
HCFC	hydrochlorofluoro carbon
IFPRI	International Food Policy Research Institute
IPCC	Intergovernmental Panel on Climate Change
ISO	International Organization for Standardization
kg CO_2-eq	kilograms of CO_2 equivalent
LAC	Latin America and the Caribbean
LCA	life cycle assessment
LCI	life cycle inventory
LPS	livestock production system
LUC	land-use change
LULUCF	land use, land-use change and forestry
LW	live weight
MC	Monte Carlo Simulation
MCF	methane conversion factor
MMS	manure management system
N	nitrogen
NENA	Near East & North Africa
NH_3	ammonia
NIR	national inventory report
NO_X	nitrogen oxide air pollutants NO and NO_2 (nitric oxide and nitro gen dioxide)

N_2O	nitrous oxide
OECD	Organisation for Economic Cooperation and Development
PDF	probability distribution frequency
RCC	Rank Correlation Coefficient
SD	standard deviation
SSA	Sub-Saharan Africa
SOC	soil organic carbon
SPAM	Spatial Production Allocation Model
SRM	specified risk material
t CO_2-eq	tonnes of CO_2 equivalent
UNFCCC	United Nations Framework Convention for Climate Change
USDA	United States Department of Agriculture

Definitions of commonly-used terms

Anaerobic	In the absence of oxygen, i.e. conditions conducive to the conversion of organic carbon into methane (CH_4) rather than carbon dioxide (CO_2).
Breeding overhead	Animals that are kept to maintain the herd/flock size, rather than to produce food.
By-product	Material produced during the processing including slaughtering of a crop or livestock product that is not the primary objective of production (e.g. meals and brans, offal or skins).
Carbon footprint	The total amount of GHG emissions associated with a product along its supply-chain, and sometimes includes emissions from consumption, end-of-life recovery and disposal. Usually expressed in kg or t of carbon dioxide equivalent (CO_2-eq).
CO_2-equivalent emission	The amount of CO_2 emissions that would cause the same time-integrated irradiative forcing, over a given time horizon, as an emitted amount of a mixture of GHGs. It is obtained by multiplying the emission of a GHG by its Global Warming Potential (GWP) for the given time horizon. The CO_2 equivalent emission is a standard metric for comparing emissions of different GHGs (IPCC, 4 AR 2007).
Coefficient of variation	The standard deviation expressed as a percentage of the mean.
Cohort	Class of animals within a herd defined by their age and sex (e.g. adult females, replacement females, males for fattening, etc.).
Co-product	Material generated by a production activity that generates more than one output (e.g. meat, eggs and manure are co-products of chicken production).
Crop residue	Materials left in an agricultural field after the crop has been harvested (e.g. straw or stover).

Dairy herd	For the purposes of this assessment, includes milking animals, replacement stock and surplus calves that are fattened for meat production.
Direct energy	Energy used on-farm for livestock production, e.g. for lighting, heating and cooling.
Embedded energy	Energy or emissions arising during the manufacture of farm inputs, such as fertiliser or steel.
Emission factor	Factor that defines that rate at which a greenhouse gas is emitted, e.g. kg CH_4 per animal per year or kg N_2O-N/kg manure N.
Emissions intensity	Mass of emissions per unit of product, e.g. kg CO_2/kg of meat/milk.
Fat and protein corrected milk (FPCM)	Milk corrected for its fat and protein content to a standard of 4.0 percent fat and 3.3 percent protein. This is a standard used for comparing milk with different fat and protein contents. It is a means of evaluating milk production of different dairy animals and breeds on a common basis.
Feed conversion ratio	Measure of the efficiency with which an animal converts feed into tissue, usually expressed in terms of kg of feed per kg of output (e.g. CW, milk or protein).
Feed material	Individual feed type (e.g. maize grain or wheat straw).
Fieldwork	General term for the field operations undertaken during crop cultivation, e.g. ploughing, drilling, spreading, etc.
Geographical Information System	A computerized system organizing data sets through the geographical referencing of all data included in its collections.
Globalwarming potential	Defined by the Intergovernmental Panel on Climate Change (IPCC) as an indicator that reflects the relative effect of a GHG in terms of climate change considering a fixed time period, such as 100 years, compared with the same mass of carbon dioxide.
Grassland-based livestock systems	Livestock production systems in which more than 10 percent of the dry matter fed to animals is farm-produced and in which annual average stocking rates are less than ten livestock units per hectare of agricultural land (FAO, 1996).

Manure N	Nitrogen in manure.
Methane conversion factor	The percentage of the manure's maximum methane producing capacity (Bo) that is achieved during manure management
Mixed farming systems	Livestock production systems in which more than 10 percent of the dry matter fed to livestock comes from crop by-products and/or stubble or more than 10 percent of the value of production comes from non-livestock farming activities (FAO, 1996).
Monte Carlo analysis	Method that uses repeated random sampling for estimating uncertainty in results.
Pixel	The smallest unit of information in GIS raster data, usually square in shape. In GIS dataset, each pixel represents a portion of the earth, and usually has an attribute value associated with it, such as soil type or vegetation class. Pixel is often used synonymously with cell.
Ration	The combination of feed materials constituting the animal's diet.
Synthetic N	Nitrogen in the form of manufactured fertilisers, such as ammonium nitrate.
Tier levels	Defined in IPCC (2006), these correspond to a progression from the use of simple equations with default data (Tier 1 emission factors), to country-specific data in more complex national systems (Tier 2 & 3 emission factors). Tiers implicitly progress from least to greatest levels of certainty as a function of methodological complexity, regional specificity of model parameters, spatial resolution and the availability of activity data.

Executive summary

BACKGROUND AND PURPOSE

In decades to come, the global demand for livestock products will continue to increase driven by growing populations, incomes and urbanization. As a consequence the sector needs to produce more but in a context of increasing natural resource scarcity and challenges posed by climate change.

In 2010, the ruminant sector contributed about 29 percent to global meat production (equivalent to 81 million tonnes) of which 79 percent is from the cattle sector and the remaining from buffalo and small ruminants. Global milk production in 2010 was 717 million tonnes with milk production from the cattle sector contributing the bulk, about 83 percent of global production.

While ruminants play an important role in providing high quality protein essential for human diets, they are an important source of greenhouse gas (GHG) emissions. The demand for bovine meat, mutton and milk is forecasted to grow at a rate of 1.2 percent, 1.5 percent and 1.1 percent, respectively, during the period 2006-2050. To avoid significant increases in total GHG emissions from the sector, a reduction of the intensity of emissions is required.

This report presents a life cycle analysis of the GHG emissions arising from ruminant supply chains around the year 2005. This first comprehensive and disaggregated global assessment of emissions enables the understanding of emission pathways and hotspots. This is a fundamental and initial step to identify mitigation strategies and inform public debate.

Two similar reports on the emissions from pig and chicken supply chains and on the emissions from the dairy sector are also available. An overall report providing an overview of results and exploring mitigation potential and options is also available.[1]

METHODOLOGY

This assessment is based on a life cycle assessment (LCA) and includes all main sources of emissions along the supply chain starting from land use and the production of feed, through emissions from animal production to emissions related to processing and transportation of products to the retail distribution point.

GHG emissions arising from land-use change (LUC) associated with livestock production were also assessed. Land-use change emissions considered include the transformation of forest to cropland and of forest to pasture in Latin America and the Caribbean. Given the year of reference (2005), latest trends could not be fully reflected (e.g. reduction of deforestation rates in LUC). A sensitivity analysis was conducted, showing that the period of the analysis has an important influence on results.

[1] FAO. 2010. Greenhouse gas emissions from the dairy sector – A life cycle assessment. FAO, Rome.
FAO. 2013a. Tackling climate change through livestock – A global assessment of emissions and mitigation opportunities. FAO, Rome.
FAO. 2013b. Greenhouse gas emissions from pig and chicken supply chains – A global life cycle assessment. FAO, Rome.

Due to the lack of globally validated model and databases, sequestration and losses of soil C arising from pasture management could not be included in the assessment but can be significant. The effect of this was tested in the case of Western Europe; carbon sequestration could mitigate about 5 percent of total ruminant emissions in the region, but with a high degree of uncertainty.

This analysis covers emissions from the three major GHGs in agriculture, namely methane (CH_4), nitrous oxide (N_2O) and carbon dioxide (CO_2), omitting gases of minor importance.

The analysis was undertaken using the Global Livestock Environmental Assessment Model (GLEAM). This model quantifies GHG emissions arising from production of the main livestock commodities: meat and milk from cattle, sheep, goats and buffalo; meat from pigs; and meat and eggs from chickens.

The model calculates total emissions and (commodity) production for a given farming system within a defined area. The emissions per unit of product can be calculated for combinations of different commodities/farming systems/locations at different spatial scales.

In a complex analysis such as this, results are not definitive, but rather the best assessment that could be made and subject to improvement in subsequent revisions. Methodological developments are being developed within the context of the LEAP Partnership (Livestock Environmental Assessment and Performance),[2] to harmonize metrics and approaches used in the assessment of environmental performance of livestock supply chains, including future updates of this report.

KEY FINDINGS

Overall sectoral contribution to global GHG emissions

Globally, ruminant supply chains are estimated to produce 5.7 gigatonnes CO_2-eq *per annum* representing about 80 percent of the livestock sector emissions. Emissions from beef and milk production represent respectively 35 and 30 percent of the livestock sector emissions (equivalent to 4.6 gigatonnes CO_2-eq). Buffalos and small ruminants supply chains have a much lower contribution, representing respectively 8.7 percent and 6.7 percent of sector emissions.

Main emission sources

The largest source of GHG emissions in ruminant production is methane (CH_4) from enteric fermentation, which accounts for about 47 percent of the sector's emissions and more than 90 percent of the total CH_4 emissions. Nitrous oxide (N_2O) emissions originating mainly from feed production and N deposited during grazing represent 24 percent of the sector's GHG emissions.

Emissions from land-use change associated with the expansion of grassland into forest account for 14.8 percent of total emissions related to beef production.

While LUC contributes a significant amount to total emissions; and particularly so in certain regions, these estimates vary greatly depending on the assumptions made, data and approach applied.

[2] http://www.fao.org/ag/againfo/livestock-benchmarking/en/.

Emission intensities (emission of GHG per unit of product) per commodity

Average emission intensity for products from ruminants were estimated at 2.8, 3.4 and 6.5 kg CO_2-eq/kg fat and protein corrected milk (FPCM) for cow milk, buffalo and small ruminant milk, respectively, and 46.2, 53.4, and 23.8 kg CO_2-eq/kg carcass weight (CW) for beef, buffalo and small ruminant meat, respectively.

EMISSION INTENSITIES PER PRODUCTION SYSTEMS AND REGIONS

There are variations in emission intensities across regions and production systems for each commodity. These variations are largely driven by differences in production goals (specialized versus non-specialized production) and management practices, including animal husbandry methods, animal health and genetics which influence levels of productivity.

In addition, there is a wide divergence in emission intensity for different commodities produced within the same region under comparable conditions (production systems and climatic zones) pointing to the existence of a considerable emission intensity gap (Section 4.4).

Variation by production systems

Globally, mixed systems provide the bulk of the meat and milk output: about 79 percent of the beef, 85 percent of cow's milk and 70 and 68 percent of small ruminant milk and meat is produced in this system. In addition, mixed systems also supply about 97 and 96 percent of buffaloes' milk and meat, respectively.

On average, mixed systems have slightly lower emission intensities than grassland-based systems. This difference is explained by several factors such as reproductive efficiency (higher fertility rates, lower age at calving,) animal health (lower mortality rates), management (higher slaughter weights, reduced time to slaughter), and better feed quality in mixed farming systems. All these factors combine to result in higher productivity and lower emission intensity.

Variation by region

World regions show highly diverse emission intensities which are to large extent explained by their contribution to production, their production systems and management practices.

Cattle

Regional emission intensity of milk ranges from 1.6 kg CO_2-eq/kg FPCM to 9.0 kg CO_2-eq/kg FPCM. Generally, milk production in low productive systems has higher emission intensities than in high production systems of most affluent counties where better animal feeding and nutrition results in lower enteric and manure emissions and emission intensity at animal level. Improved genetics and animal health care and animal husbandry combine with better feeding to reduce the breeding overhead (i.e. animals kept to maintain the herd) thus further reducing emission intensity at herd level. In North America, manure management emissions are relatively high due to the use of liquid manure management systems that produce greater quantities of methane emissions.

Emission intensity of beef at regional level show a great deal of diversity; ranging from 14 kg CO_2-eq/kg CW in Eastern Europe and the Russian Federation to 76 kg CO_2-eq/kg CW in South Asia. Beef production has the highest emission intensi-

ties in South Asia, sub-Saharan Africa, Latin America and the Caribbean, and East and Southeast Asia. The quality and type of feed, low reproduction efficiency, poor herd management practices, genetics and animal health (high mortality) explain the higher emission intensities in these regions. In addition, in Latin America and the Caribbean, almost one third of the emissions from beef production are related to pasture expansion into forested areas. This figure is however associated with a high level of uncertainty as a result of methodological uncertainty and data gaps.

Regions with the lowest emission intensity such as Europe, North America and Oceania are not necessarily characterized by similar production systems. For example, in Europe about 80 percent of the beef is produced from dairy surplus calves and culled cows which explains the relatively low emission intensity of beef. In North America and Oceania, production is generally characterized by a high level of specialization and higher productivity, which results in lower emission intensities. However, in these two regions, beef cattle may be reared either intensively or extensively (on grain or grass).

Buffalos

Global buffalo milk and meat production is concentrated in three major world regions: South Asia, Near East & North Africa and East & Southeast Asia. South Asia alone produces as much as 90 percent and 70 percent of the global buffalo milk and meat, respectively. Milk produced in South Asia has lower emission intensity, explained by high milk yields compared to Near East & North Africa and East & Southeast Asia. Emission intensity of buffalo meat production is particularly high in East & Southeast Asia as productivity of the animals is low due to poor feed resources (largely based on low quality feed resources such as crop residues and pasture) and low reproductive efficiency. With the exception of a few countries in the Mediterranean region, buffalo production in industrialized world regions plays a very minor role.

Small ruminants

With the exception of small ruminant milk production in Western Europe and lamb and mutton production in Oceania and Western Europe, meat and milk from small ruminants is generally more important in developing world regions. Emission intensity for small ruminant milk is however highest in developing regions such as NENA and East & Southeast Asia, SSA and South Asia due to poorer production conditions in which animals are for the most part reared for subsistence purposes. In contrast, in industrialized countries where small ruminant milk production is important, emission intensity is low due to the specialization of production.

The contribution to global small ruminant meat production is characterized by a dichotomy between regions; global lamb and mutton production is largely concentrated in Western Europe and Oceania while production of meat from goats takes place in developing regions. Emission intensity for small ruminant meat is lowest in Oceania and Western Europe and highest in developing regions.

This difference in emission intensity of small ruminant meat and milk is due to variations in reproductive efficiency (resulting in a smaller "breeding overhead"), feed quality, and management practices that are generally poorer in developing regions.

FACTORS DRIVING EMISSION INTENSITY LEVELS

Differences in emission intensities are driven by a combination of factors.

- At animal level emission intensity is influenced by: (i) digestibility, quality and composition of the feed ration which influence the level of enteric methane emissions and manure emissions (lower release of nitrogen and volatile solids) per unit of product produced (milk or weight gain); and (ii) improved genetics and animal health contribute to better conversion of feed into animal products further reducing emission intensity at animal level.
- At animal level, emission intensity is influenced by feed quality combined with genetics, animal health, reproduction strategies (replacement, age at first calving) reducing the relative number of unproductive animals in the herd and thus emissions per unit of product generated at herd level.
- Land-use change, i.e. pasture and feed crop expansion, is a major driver of emissions. Feed originating from areas where LUC takes place has higher emission intensities.
- Manure management practices influence the release of methane and nitrous oxide.

CONCLUSIONS

The range of emission intensity within supply chains suggests that there is room for improvement. The areas with mitigation potential are the following:

- Improving feeding practices and digestibility of diets;
- Improving yields through genetics, feeding practices and animal health, and overall management;
- Reducing land-use change arising from feed crop cultivation and pasture expansion;
- Improving manure management – reducing the use of uncovered liquid manure management systems (MMSs), particularly in dairy systems;
- Improving the efficiency of feed crop production, particularly improving fertilization management.

This report focuses on one measure of environmental performance: kg CO_2-eq/kg commodity. When evaluating GHG mitigation measures, attention should also be paid to their potential impacts on other environmental dimensions, for example on water quality, as well as on broader development objectives, such as food security and poverty reduction.

1. Introduction

1.1 BACKGROUND

The global livestock sector is faced with a three-fold challenge: the need to increase production to meet demand, adapt to a changing and increasingly variable economic and natural environment and, at the same time, improve its environmental performance. While positive effects of grazing systems are locally verified on biodiversity and landscapes, major concerns have been raised about the potential consequences associated with livestock sector growth, including increasing natural resource use and degradation, contribution to global warming, water resource depletion, biodiversity erosion and habitat change. These concerns have resulted in a widespread interest from governments, consumers and industry in the assessment of the environmental performance of livestock production.

The evidence of human-induced climate change (IPCC, 2006) and the important contribution of the livestock sector to total anthropogenic emissions highlight the urgent need to better understand the sources of the livestock sector's greenhouse gas (GHG) emissions and related mitigation options. Starting in 2009, the Animal Production and Health Division of FAO has been engaged in a comprehensive assessment of livestock-related GHG emissions aimed at identifying low-emission development pathways for the livestock sector. The undertaking follows two broad objectives: first, to improve and break down the initial estimates of livestock sector's overall emissions provided in *Livestock's long shadow – Environmental issues and options* (FAO, 2006) and, second, to identify the major available mitigation options along livestock supply chains.

This report presents an update of the *Livestock's long shadow* assessment of GHG emissions from ruminant supply chains. It should be understood as a step in a series of assessments to measure and guide progress regarding the sector's GHG emissions.

1.2 SCOPE OF THIS REPORT

Livestock commodities differ in resource use and emission profile. These variations reflect fundamental differences in the underlying biology and modes of production. The reporting structure reflects this by bringing together species with important shared features concerning their emission profile. This report quantifies the main sources of GHG emissions, and estimates GHG emissions for major ruminant products, predominant ruminant production systems, main world regions and agro-ecological zones (AEZs), and major stages in the supply chains.

The assessment takes a supply chain approach in estimating emissions generated during: (a) the production of inputs for the production process; (b) crop and animal production; and (c) subsequent transport and processing of the outputs into basic products. Given the global scope of the assessment and the complexity of livestock supply chains, several hypotheses and generalizations had to be made to keep data requirements of the assessment manageable. They are documented in the report and their impact on results is analysed. Emissions related to the consumer (the purchase, storage and preparation of food) and food losses that take place at retail and consumer level are not included.

This report addresses a technical audience in private and public organizations, academia and LCA practitioners. Policy-makers and the informed general public will find a comprehensive review of results, methods and the mitigation potential in the livestock sector in an overview report published in parallel to this report (FAO, 2013a).

By providing the most accurate information available on a global scale, this assessment helps to identify priority areas for mitigation and technical options that can reduce GHG emissions from the ruminant sector. It also provides a benchmark against which future trends can be measured.

This report focuses on GHG emissions only; other environmental dimensions, such as water resources, land, biodiversity and nutrients, have not been considered. GHG emissions from the livestock sector cannot be taken as an indicator of environmental sustainability in general. There are important synergies and trade-offs among competing environmental criteria that require fuller assessment.

The base year selected for assessment is 2005. This year was chosen because at the start of the assessment, the available spatial data, and in particular information on the predicted livestock densities, were based on 2005 data.

1.3 THE GLOBAL LIVESTOCK ENVIRONMENTAL ASSESSMENT MODEL

This assessment is based on a newly-developed analytical framework: the Global Livestock Environmental Assessment Model (GLEAM). GLEAM intends to pull together the existing knowledge on production practices and emissions pathways and create a framework for disaggregation and comparison of emissions on a global scale. The model is developed for six animal species (cattle, buffalo, sheep, goats, pigs and chicken) and related edible products. It recognizes two farming systems for ruminant species (mixed and grazing), three for pigs (backyard, intermediate and industrial) and three for chicken (backyard, industrial egg and industrial meat). Overall, this amounts to over 14 000 theoretical supply chains, defined here as unique sets of commodity, farming system, country and climatic zone. The physical area corresponding to each of these sets is further decomposed in cells on a map.

Four publications present the results of this work:

- This technical report addressing the world's cattle, buffalo and small ruminant (sheep and goat) sectors.
- A report addressing the world's pig and chicken (meat and eggs) sectors, published in parallel to this report (FAO, 2013b).
- An earlier technical report published in 2010, addressing the world's dairy sector (FAO, 2010).
- An overview report, summarizing the above at the sector level and providing additional cross-cutting analysis of emissions and mitigation potential, published in parallel to this report (FAO, 2013a).

Since the publication of the FAO report on GHG emissions from the dairy sector (FAO, 2010), GLEAM has been improved to include additional GHG emissions sources such as direct on-farm energy use and indirect energy embodied in farm buildings and equipment. In addition, new data (herd parameters, feed rations) has also been made available, so this report presents an update of the results on dairy production presented in 2010.

1.4 OUTLINE OF THIS REPORT

This report consists of six sections (including this introductory section). Section two starts with a brief introduction to the global ruminant sector describing production systems and their contribution to global ruminant milk and meat production.

Section 3 gives an overview of the approach used in the estimation of GHG emissions in this assessment, providing basic information on the LCA approach. The section presents a description of the functional units used, system boundary, allocation to co-products and sources of GHG emissions. The section also provides an overview of ruminant production system typology applied, the tool (GLEAM) and methods as well as broad information on data sources and management. Detailed description of the approach and methods can be found in the appendices.

The results (total emissions and emission intensities) of this assessment are presented in Section 4 followed by a discussion on the main important sources and drivers of emissions from ruminant species as well as a discussion on uncertainty and assumptions likely to influence the results (Section 5). It also presents the results of a Monte Carlo uncertainty analysis performed in this study.

Section 6 presents the conclusions and recommendations that can be drawn from this work as well as provides direction on areas for improvement.

The appendices in this report provide a detailed description of the GLEAM model, methods applied (on quantifying carbon losses from land-use change, on-farm direct and indirect energy use and post farmgate emissions) and data. The appendices also explore different computation approaches (e.g. for estimating LUC emissions and allocation of emissions to slaughter by-products) presenting their impact on emission intensity.

2. Overview of the global ruminant sector

In this report, the ruminant sector comprises cattle, sheep and goat, and buffalo. The global ruminant population in 2010 was estimated to be 3 612 million (FAOSTAT, 2012), with cattle making up nearly 40 percent, sheep and goat 55 percent, and buffalo the remaining 5 percent. Within the ruminant sector, the cattle sector is by-far the most important: contributing about 64 and 600 million tonnes of meat and milk, respectively; about 79 and 83 percent of total meat and milk production from ruminants. Small ruminant products constitute a relatively small share of globally-produced ruminant meat and milk, about 17 percent and 4 percent, respectively.

Ruminants are mainly reared in either grazing or mixed systems and the relative global importance of mixed systems compared with grazing systems is reflected by the fact that about 73 percent of all ruminants are reared in mixed farming systems. This study estimates that globally about 79 percent of the beef and 85 percent of cattle milk and 70 percent and 68 percent of the small ruminant milk and meat, respectively, is produced in mixed systems. Mixed systems also supply the bulk of products from buffalo; about 97 and 96 percent of milk and meat, respectively. Within these two systems, there is a wide variation in farming practices of which is subject to several factors such as climatic conditions, availability of fodders, market demand, etc.

Agro-ecological conditions are important determinants of the characteristics of ruminant production and estimates of the relative importance of ruminant meat and milk production within the AEZs varies between cattle, buffalo, and small ruminants (see Maps 1, 2, 3, 4 and 5 in Appendix G). In cattle production, temperate zones contribute 50 percent and 38 percent of the milk and beef compared with 21 percent and 33 percent from humid zones and 29 percent and 29 percent from arid zones.

On the other hand, arid zones contribute the bulk of milk and meat production from small ruminants and buffalo; 69 percent and 52 percent of small ruminant milk and meat, and 84 percent and 70 percent of buffalo milk and meat. The humid and temperate zones contribute 12 percent and 18 percent of small ruminant milk and 18 and 29 percent of the meat.

The relative importance of the different species varies enormously – while economic conditions play a key role, factors such as biophysical conditions and cultural values are also important.

Beef production is the most diverse form of all ruminant meat production. It is produced in extremely diverse production systems, ranging from grazing to mixed livestock-crop systems. Beef is either produced in "dedicated" beef herds, where beef is the only main product, or as a co-product from dairy production, i.e. surplus calves from dairy herds are raised for beef and culled cows are used for meat.

Specialized beef production units may take many forms: breeding and growing beef enterprises, breeding and finishing, growing and finishing on pasture or in feedlots, etc. Such forms of production are usually located in the industrialized

world regions and Latin America. However, in many parts of the world, particularly in the developing regions, this distinction between dairy and specialized beef production is subtle especially where cattle are considered multifunctional producing both milk and meat as well as other valuable non-edible products and services such as manure, hides and skin, and are used for draught power.

Despite their small contribution to global milk and meat output, sheep and goat farming plays a larger role in some specific economies. In many marginal rural areas, it plays a significant socio-economic role. An important attribute of small ruminants is that they are able to thrive and produce on unfavourable land and are generally suited to harsh climatic conditions where cattle would perform poorly. Sheep and goats are better converters of low-quality fibrous feed into meat and milk due to their better digestive ability to utilize poor quality roughages. In this regard, about 56 percent of the world's small ruminants are located in arid zones and 27 percent and 21 percent in the temperate and humid zones, respectively. However, these animals also adapt very easily to intensive production systems and can produce meat and milk efficiently.

Milk and meat products from sheep and goats have two purposes: they are used for subsistence at household level or are sold as niche products. Meat and milk from sheep is usually obtained from high yielding animals kept under intensive conditions e.g. dairy intensive systems in the Mediterranean region, lamb production in New Zealand and Australia. In Northern Europe and Oceania (particularly New Zealand), sheep are kept mainly for meat production while in the Mediterranean region almost all sheep and goats belong to dairy breeds where milk is the main output of production and meat considered as a by-product.

Similar to other ruminant species, systems of buffalo production vary widely through the different regions of the world and are determined by several interacting factors that include climate (tropical or temperate, humid or arid), location (rural, peri-urban or urban), cropping systems (rain-fed or irrigated, annual or perennial crops), type of operation (small or large farm, subsistence or commercial), and primary purpose for buffalo production and/or management (milk, meat, draught power or mixed).

In South Asia, North Africa and the Near East, buffalo are mainly kept for milk and meat production. In East & Southeast Asia, draught power and meat are important, while in Europe, buffalo are kept on large commercial farms under modern intensive systems for milk and meat production (Perera, 2011).

Buffalo provide milk, meat, hides and draught power. Among the different products obtained from buffalo, meat and hides are more important, although buffalo play an important role in milk production in Asian countries and few countries in the Mediterranean region. Global milk production is concentrated in two countries, India and Pakistan, which together account for 92 percent of the world's total milk production. Buffalo have an inherent ability to produce milk of high fat contents (ranging from 6 to 8.5 percent) and, because of this, buffalo milk is preferred over cow milk in some regions of the world such as South Asia. In 2010, about 98 percent of the global buffalo meat production was produced in South, East and Southeast Asia with the bulk contributed by India and Pakistan. This is easily explained by the fact that the two countries have 73 percent of the global buffalo population. Besides edible products, ruminants also produce a host of non-edible products such

as manure, hides and skin, and natural fibre (wool, cashmere and mohair). While farm mechanization has resulted in significant reduction in the use of animals for draught power, farmers in many parts of the world still rely on cattle and buffalo as a source of draught power.

3. Methods

3.1 CHOICE OF LIFE CYCLE ASSESSMENT (LCA)

The use of Life Cycle Assessment (LCA) to assess food production is becoming increasingly common. This trend is driven by the need of policy-makers, producers and consumers for reliable and comprehensive environmental information to identify environmentally and economically sustainable agricultural products and practices.

The LCA approach, which is defined in ISO standards 14040 and 14044 (ISO, 2006), is now widely accepted in agriculture and other industries as a method for evaluating the environmental impact of production, and for identifying the resource and emission-intensive processes within a product's life cycle. The main strength of LCA lies in its ability to provide a holistic assessment of production processes in terms of resource use and environmental impacts, as well as to consider multiple parameters (ISO, 2006).

LCA also provides a framework to broadly identify effective approaches to reduce environmental burdens and is recognized for its capacity to evaluate the effect that changes within a production process may have on the overall life-cycle balance of environmental burdens. This enables the identification and exclusion of measures that simply shift environmental problems from one phase of the life cycle to another.

However, LCA also presents significant challenges, particularly when applied to agriculture. First, the data-intensive nature of the method places limitations on the comprehensive assessment of complex food chains and biological processes. Limited data availability can force the practitioner to make simplifications, which can lead to losses of accuracy.

A second difficulty lies in the fact that methodological choices and assumptions such as system boundary delineation, functional units, and allocation techniques may be subjective and affect the results. These complications call for a thorough sensitivity analysis.

3.2 GENERAL PRINCIPLES OF LCA

The LCA method was originally applied to analyse industrial process chains, but is increasingly being used to assess the environmental impacts of agriculture. It involves the systemic analysis of production systems to account for all inputs and outputs associated with a specific product within a defined system boundary. The system boundary largely depends on the goal of the study.

The reference unit that denotes the useful output of the production system is known as the functional unit, and it has a defined quantity and quality. The functional unit can be based on a defined quantity, such as 1 kg of product, or it may be based on an attribute of a product or process, such as 1 kg of fat and protein corrected milk (FPCM) or 1 kg of carcass weight (CW).

The application of LCA to agricultural systems is often complicated by the multiple-output nature of production, because major products are usually accompanied by the joint production of by-products. This requires appropriate partitioning of

environmental impacts to each product from the system according to an allocation rule, which may be based on different criteria such as economic value, mass balances, product properties, etc.

3.3 USE OF LCA IN THIS ASSESSMENT

In the last five years, an increasing number of LCA studies have been carried out for livestock production, mostly in Organisation for Economic Cooperation and Development (OECD) countries (Leip *et al*., 2010; Ledgard *et al.,* 2011; Beauchemin *et al*., 2010; de Vries and de Boer, 2010; Verge *et al*., 2008; Foley *et al*., 2011). Although LCA methods are well defined, the studies vary considerably in their level of detail, their definition of system boundaries, the emission factors (EFs) they use, and other technical aspects such as the allocation techniques and functional units they employ.

This assessment sets out to perform a complete LCA for the global livestock sector, using consistent calculation methods, modelling approaches, data and parameters for each production system within the sector. In contrast to previous LCA studies carried out for the livestock sector, which have primarily concentrated on either farm level or the national level emissions in OECD countries, this study is global in scope and includes both developed and developing countries.

As a consequence of its global scope, the approach developed for this study has had to overcome onerous data requirements by relying on some simplifications that result in a loss of accuracy, particularly for systems at lower levels of aggregation.

This assessment follows the attributional approach, which estimates the environmental burden of the existing situation under current production and market conditions, and allocates impacts to the various co-products of the production system. This differs from the consequential LCA approach, which considers potential consequences of changes in production, and relies on a system expansion analysis to allocate impacts of co-products (Thomassen *et al*., 2008).

The current assessment is based on the methodology for LCA, as specified in the following documents:

- ISO, 2006. *Environmental management – Life Cycle Assessment- Requirements and guidelines* - BS EN ISO 14044.
- British Standards Institute PAS 2050; 2008. Specification for the assessment of the life cycle greenhouse gas emissions of goods and services (BSI, 2008).

3.3.1 Functional unit

Ruminant production systems produce a mix of goods and services:

- Edible products: meat and milk.
- Non-edible products and services including natural fibre (wool, cashmere, mohair), draught power, hides and skin, manure and capital.

In this assessment, the functional units used to report GHG emissions for meat are expressed as a kg of carbon dioxide equivalents (CO_2-eq) per kg of carcass weight (CW) and emissions from milk are reported in CO_2-eq per kg of FPCM. FPCM is a method used to standardize milk produced in different systems with varying qualities. Appendix A provides details of the equations used in the standardization of milk from ruminants.

3.3.2 System boundary

The assessment encompassed the entire livestock production chain, from feed production through to the final processing of product, including transport to the retail distribution point (see Figure 1).

The cradle to retail system boundary is split into two subsystems:

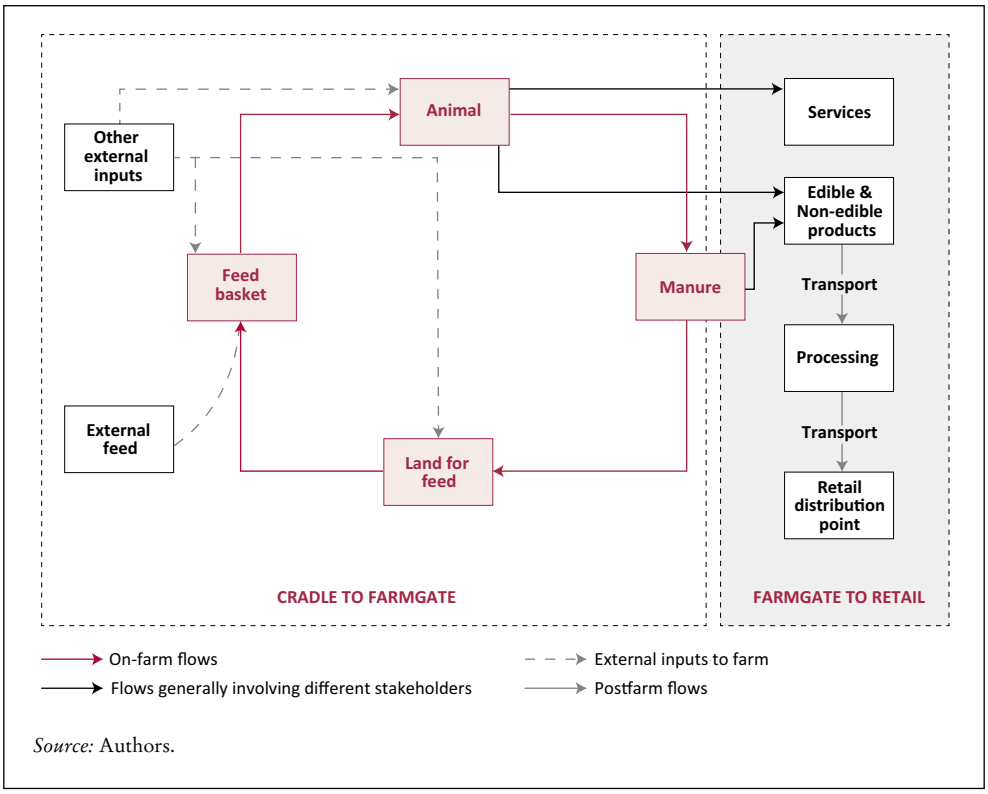
- *Cradle to farmgate* includes all upstream processes in livestock production up to the farmgate where the animals or products leave the farm, i.e. production of farm inputs and on-farm production activities.
- *Farmgate to retail* includes transport of animals and product (milk) to processing plants (dairies and slaughter plants) or directly to market, processing into primary products, refrigeration during transport and processing, production of packaging material, and transport to the retail distributor.

All aspects related to the final consumption of milk and meat products (i.e. consumer transport to purchase product, food storage and preparation, food waste and waste handling of packaging) lie outside the defined system, and are thus excluded from this assessment.

To calculate GHG emissions from cradle to farmgate, a simplified description of livestock production systems (derived from Oenema *et al.*, 2005; Schils *et al.*, 2007; Del Prado and Scholefield, 2008) was developed (Figure 1).

Livestock production is complex, with a number of interacting processes that include crop and pasture production, manure handling, feed processing and transport, animal raising and management, etc. This requires modelling the flow of all

Figure 1.
System boundary as defined for this assessment



Source: Authors.

Table 1. Sources of GHG emissions included and excluded in this assessment

Food chain	Activity	GHG	Included	Excluded
Upstream	Feed production	N_2O	Direct and indirect N_2O from: • Application of synthetic N • Application of manure • Deposition of manure on pasture, ranges • Crop residue management	• N_2O losses related to changes in C stocks • Biomass burning • Biological fixation • Emissions from non-N fertilizers and lime
		CO_2	• Energy use in field operations • Energy use feed transport and processing • Fertilizer manufacture • Feed blending • Land-use change related to deforestation soybean and pasture expansion	• Changes in carbon stocks from land use under constant management practices
	Non-feed production	CO_2	• Indirect (embedded) energy related to the manufacture of on-farm buildings and equipment	• Production of cleaning agents, antibiotics and pharmaceuticals
Animal production unit	Livestock production	CH_4	• Enteric fermentation • Manure management	
		N_2O	• Direct and indirect N_2O from manure management	
		CO_2	• Direct on-farm energy use for milking, cooling, ventilation and heating	
Downstream	Post farmgate	CO_2; CH_4; HFCs	• Transport of live animals and product to slaughter and processing plant • Transport of processed product to retail point • Refrigeration during transport and processing • Primary processing of meat into carcasses or meat cuts and raw milk and dairy products • GHGs related to leakage of refrigerants during transportation • Manufacture of packaging	• On-site waste water treatment • Emissions from animal waste or avoided emissions from on-site energy generation from waste • Emissions related to slaughter by-products e.g. rendering material, offal, hides and skin • Retail and post-retail energy use • Waste disposal at retail and post-retail stages

Source: Authors.

products through internal chains on the farm and also allowing for imports and exports from the farm. The model therefore provides a means of integrating all these processes and linking all components in a manner that adequately captures major interactions among biological and physical processes. The flows are represented as directional lines between compartments in the system.

- "*Land for feed*" is the land used for feed production, on the farm itself or within the vicinity of production site (with negligible emissions related to the transport of feed to the animal rearing site).
- "*External feed*" originates from off-site production and includes by-products from the food industry and feed crops produced and transported over longer distances, e.g. soybeans; in most situations, the external feed is concentrate feed.
- "*Manure*" is shown partly outside the 'cradle-to-farmgate' system boundary in order to illustrate situations where manure is used as a fertilizer on food crops, either on- or off-farm, or where manure is used as fuel.
- "*Other external inputs*" refers to the inputs into production such as energy, fertilizer, pesticides, on-farm machinery, etc.

The connection of the four compartments shown in Figure 1 requires the devel-

opment of specific models (see Appendix A) and attribution techniques (see Section 3.6 and Appendix A) for the allocation of emissions among different processes, uses and outputs. These compartments not only represent different activities in the production process such as animal production, feed production, manure management, etc., but also define the inter-linkages among production processes such as the link between animal performance (genetics, management), animal feed requirements (energy and protein requirements) and the production of outputs such as edible and non-edible products and services, and emissions.

3.3.3 Sources of GHG emissions

This study focuses on emissions of the three major GHGs associated with animal food chains – methane (CH_4), nitrous oxide (N_2O) and carbon dioxide (CO_2) – as well as GHGs related to refrigerants. The following emission sources were included and further grouped into pre- and post farmgate sources, and a number of potential GHG emissions and sinks were excluded from the analysis (Table 1).

Table 1 also illustrates a number of processes and activities in the livestock food chain that have been excluded due to:

- lack of global databases, e.g. on the production of co-products at slaughterhouse, post retail emissions, etc.;
- lack of methodology or consensus on quantification approach, e.g. changes in soil carbon stocks from LU; and
- limited contribution of the processes to the carbon footprint, e.g. use of production of cleaning agents, antibiotics and pharmaceuticals.

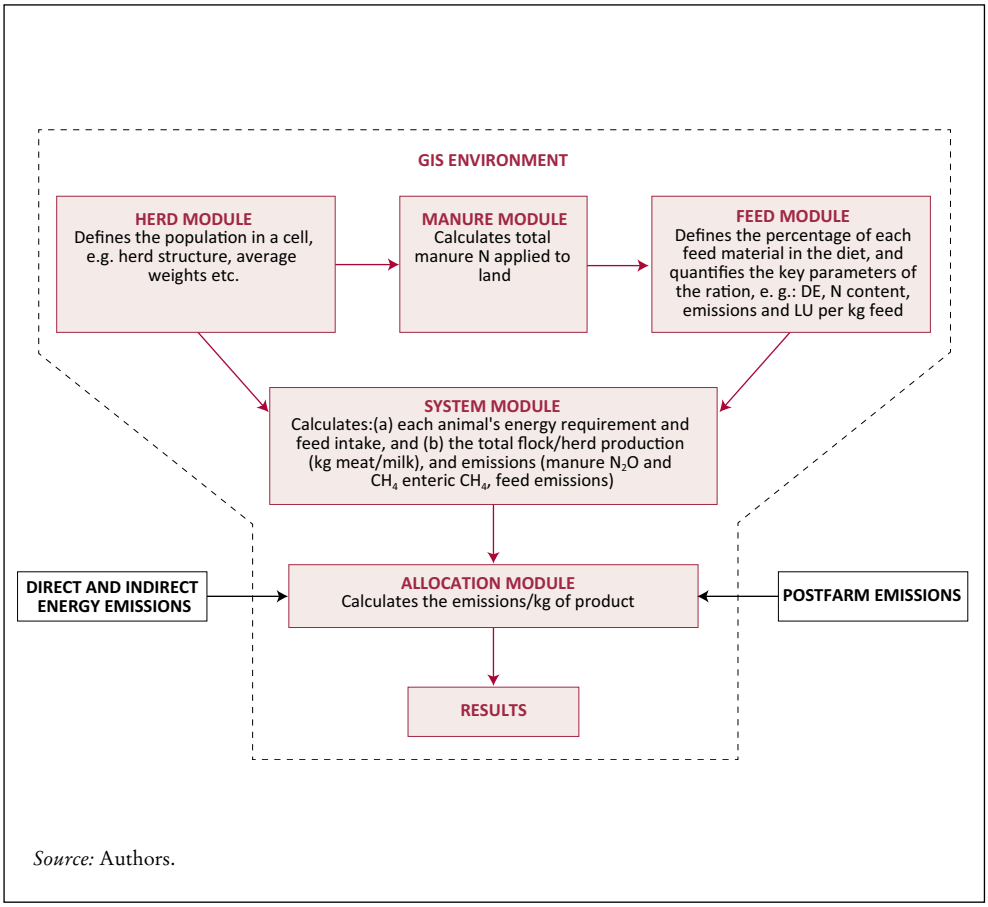
Emission categories and a description of the emissions included in each category are presented in Table 2.

Table 2. Description of emission categories used in this assessment

Category		Description
Feed N_2O		Direct and indirect N_2O emissions from manure deposited on pasture Direct and indirect N_2O emissions from organic and synthetic N applied to crops and pasture
Feed CO_2	blending and transport	CO_2 arising from the production and transportation of compound feed
	fertilizer production	CO_2 from energy use during the manufacture of urea and ammonium nitrate (and small amounts of N_2O)
	processing and transport	CO_2 from energy use during crop processing (e.g. oil extraction) and transportation by land and (in some cases) sea
	field operations	CO_2 arising from the use of energy for field operations (tillage, fertilizer application). Includes emissions arising during both fuel production and use.
Feed LUC CO_2		CO_2 from LUC associated with soybean cultivation and pasture expansion
Indirect (embedded) energy CO_2		CO_2 arising from energy use during the production of the materials used to construct farm buildings and equipment
Manure N_2O		Direct and indirect N_2O emissions arising during manure storage prior to application to land
Manure CH_4		CH_4 emissions arising during manure storage prior to application to land
Enteric CH_4		CH_4 arising from enteric fermentation
Direct energy CO_2		CO_2 arising from energy use on-farm for heating, ventilation etc.
Post farmgate		Energy use in processing and transport

Source: Authors.

Figure 2.
Overview of the GLEAM modules and computation flows



Source: Authors.

3.4 OVERVIEW OF CALCULATION METHOD

A specific model and related databases were developed to carry out this assessment. The Global Livestock Environmental Accounting model (GLEAM) was designed to represent processes and activities from the production of inputs into the production process to the farmgate, the point at which products and animals leave the farm. It consists of five main modules: *herd module, manure module, feed basket module, system module and allocation module* and two additional modules for the calculation of direct and indirect on-farm energy and post farmgate emissions (Figure 2). Appendix A provides a detailed explanation of GLEAM.

3.4.1 Spatial variation and the use of Geographic Information System

A challenge faced in conventional LCA modelling is the complexity and variation in biophysical characteristics (such as soil and climate) as well as production processes. Data on farming activities and farming system parameters were collected at different levels of aggregation: production system, country level, AEZs, or a combination thereof (e.g. information on manure storage in developing countries was available for a combination of production systems and AEZs). Additional data, such as livestock numbers, pasture and availability of feedstuff was available in the form of Geographical Information System (GIS) grids (raster layers), with a spatial resolution not coarser than 5 arc minutes (ca. 10 km x 10 km at the equator). For

the outputs of GLEAM, a spatial resolution of 3 arc minutes (ca. 5 km x 5 km at the equator) was used.

GIS can store observed data for specific locations (e.g. soil types, climate factors), can model new information from these data and can also calculate regional summaries such as total area, emissions, etc. GIS was used to analyse spatially varied data (such as crop yields, livestock species distribution), generate location-specific input data required for LCA modelling (e.g. define the typology of livestock production systems, and calculate location-specific feed-crop availability, classification of dominant soil types in forested areas and location-specific temperature to estimate EFs such as CH_4 conversion factors for MMS) and store numerical model input and output data in a GIS database.

The use of GIS allowed the incorporation of spatial heterogeneity into the modelling process which brought with it the benefit of enhancing the reliability of data used as well as results. Furthermore, it produced a more spatially accurate inventory of emissions, particularly CH_4 emissions which are modelled based on animal cohorts and feed intake. In this way, emissions were estimated at any location of the globe, based on available information, and then aggregated along the desired category, e.g. farming systems, country group, commodity and animal species. This assessment thus demonstrates the potential of coupling GIS technology with LCA for assessing GHG emissions from the livestock food chain.

3.4.2 Emission factors

The GHG EFs applied for the various emission sources in this study are specified in Appendix B of this report. A combination of IPCC (2006) Tier 1 and Tier 2 approaches and EFs were used in the estimation of emissions.

Despite the existence of country-specific EFs, the study applied the same approach to all countries. The use of a unified approach was preferred for the assessment, to ensure consistency and comparability of results across regions and farming systems.

IPCC Tier 2 approaches were used in the characterization of livestock population, to calculate emissions related to enteric fermentation as well as manure management and storage. The Tier 1 method was used where data was generally lacking, e.g. estimation of carbon stocks from LUC and N_2O emissions from feed production.

Global Warming Potentials (GWPs) with a time horizon of 100 years based on the 4th Assessment Report of the IPCC (IPCC, 2007) were used to convert N_2O and CH_4 to CO_2-eq terms. Consequently, GWP of 25 and 298 were used for CH_4 and N_2O, respectively.

3.4.3 Land use and land-use change

Assessment of changes in carbon stocks for agricultural land remaining in the same land use category requires dynamic process models and/or detailed inventory measurements. According to IPCC (2006), these models should be able to represent all relevant management practices and their driving variables compatible with available country data. Their validity should also be reported in empirical assessments. As no models satisfy these criteria and are validated on a global scale, this analysis doesn't incorporate C stock changes under constant land use. Nevertheless, a discussion on the effect of this simplification is provided in Appendix C, in particular about the role of grasslands in C sequestration.

Land-use change (LUC) is a highly complex process. It results from the interaction of drivers which may be direct or indirect[3] and which can involve numerous transitions, such as clearing, grazing, cultivation, abandonment and secondary forest re-growth. The debate surrounding the key drivers of deforestation is a continuing one and the causal links (direct and indirect) are both complex and unclear.

In this assessment, LUC considered are the transformation of forest to cropland and of forest to pasture. The former focuses on deforestation associated with soybean production in Brazil and Argentina. This choice results from the use of 2005 as year of reference and from the following observations of trends in LU transitions and crop expansions:

- In the period 1990-2006,[4] which is used as the reference time period in this study, the main global cropland expansions were for maize and soybean production;
- Maize and soybean expansion occurred in different regions of the world but only in Latin America can it be linked to a decrease in forest area during the same period; and
- Within Latin America, Brazil and Argentina account for 91 percent of the total soybean area. Over the period 1990–2006, 90 percent of the soybean area expansion in Latin America took place in these two countries.

LUC emissions were then attributed to only those countries supplied by Brazil and Argentina for soybean and soybean cake, proportionally to the share on imports from these two countries in their soybean supply. This study also provides an analysis of sensitivity to these assumptions, in particular on the reference time period, the expansion of soybean at the expense of other land types including forestland (arable and perennial cropland and grassland) and the assumption that all traded soybean and soybean cake is associated with LUC (see Appendix C).

The second LU transformation focuses on deforestation associated with pasture expansion in Latin America. This choice results from the observation that, during the period 1990-2006, significant pasture expansions and simultaneous forest area decrease occurred in Latin America and Africa. However, due to the lack of reliable data and information, it is difficult to draw conclusions on the land-use conversion trends in Africa.

LUC emissions associated with the expansion of pasture into forest areas in Latin America are attributed to beef production in those countries in which the conversion occurred. Appendix C provides an elaboration of the approach applied.

3.5 DATA SOURCES AND MANAGEMENT

The availability of data varies considerably within and among key parameters. In general, the OECD countries possess detailed statistics, supported by several scientific and technical publications. In contrast, there is a severe paucity of data in non-OECD countries. Where detailed and accurate data are available, they are often outdated and/or lack supporting metadata. Appendix B presents some of the data utilized in this assessment.

[3] Direct drivers include conversion of forest areas for plantation crops or cattle ranching, rural settlements, mining and logging. Indirect drivers include subsidies for agribusiness, investment in infrastructure, land tenure issues, absence of adequate surveillance by the government and demand for forest products, such as timber.

[4] 1990 is chosen as the initial year because it is the most recent available year with a consistent forest dataset from the FAOSTAT database. This practically discounts 4 years of LUC related emissions, compared to the 20-year timeframe recommended by IPCC (IPCC, 2006).

Table 3. Overview of the data sourced for the preparation of this assessment

Data groups	Data collection approach and sources
Herd (animal parameters)	Literature reviews, reports and surveys (see Appendix B)
Manure management	Literature reviews and reports (see Appendix B)
Feed basket	Literature reviews, reports; IFPRI (GIS based data)
LCI feed components	Literature reviews, reports; IFPRI (GIS based data), LCI databases Sweden and the Netherlands
Yield	Literature reviews and FAOSTAT
Non-edible products	Literature reviews and reports, FAOSTAT
Carbon stocks	Use of model based on Gross Primary Production (GPP)
Deforestation	FAO Forestry statistics, IPCC guidelines, literature and own calculations (see Appendix C)
Animal population characterization	Herd layer data, FAOSTAT and FAO Gridded Livestock of the World
Capital goods	Ecoinvent database and literature reviews

Source: Authors.

During the process of data collection, gaps initially encountered were addressed, to the extent possible, by extensive research of databases, literature sources and expert opinion. Assumptions were made when data could not be obtained. Data collection involved a combination of research, direct communication with experts, and access to public and commercially available life cycle inventory (LCI) packages such as Ecoinvent. The study's main data sources included:

- Gridded Livestock of the World (FAO, 2007).
- National Inventory Reports of Annex I countries (UNFCCC, 2009a).
- National Communications of non-Annex I countries (UNFCCC, 2009b).
- Geo-referenced databases on crop production from the International Food Policy Research Institute (You *et al.*, 2010).
- Above-ground net primary production (NPP) (Haberl *et al.*, 2007)
- Life Cycle Inventory (LCI) data from the Swedish Institute for Food and Biotechnology (Flysjö *et al.*, 2008), and Wageningen University, the Netherlands (I. de Boer, personal communication).
- Reports from the CGIAR research institutes.
- Statistics from FAO (FAOSTAT, 2009).
- Peer-reviewed journals.

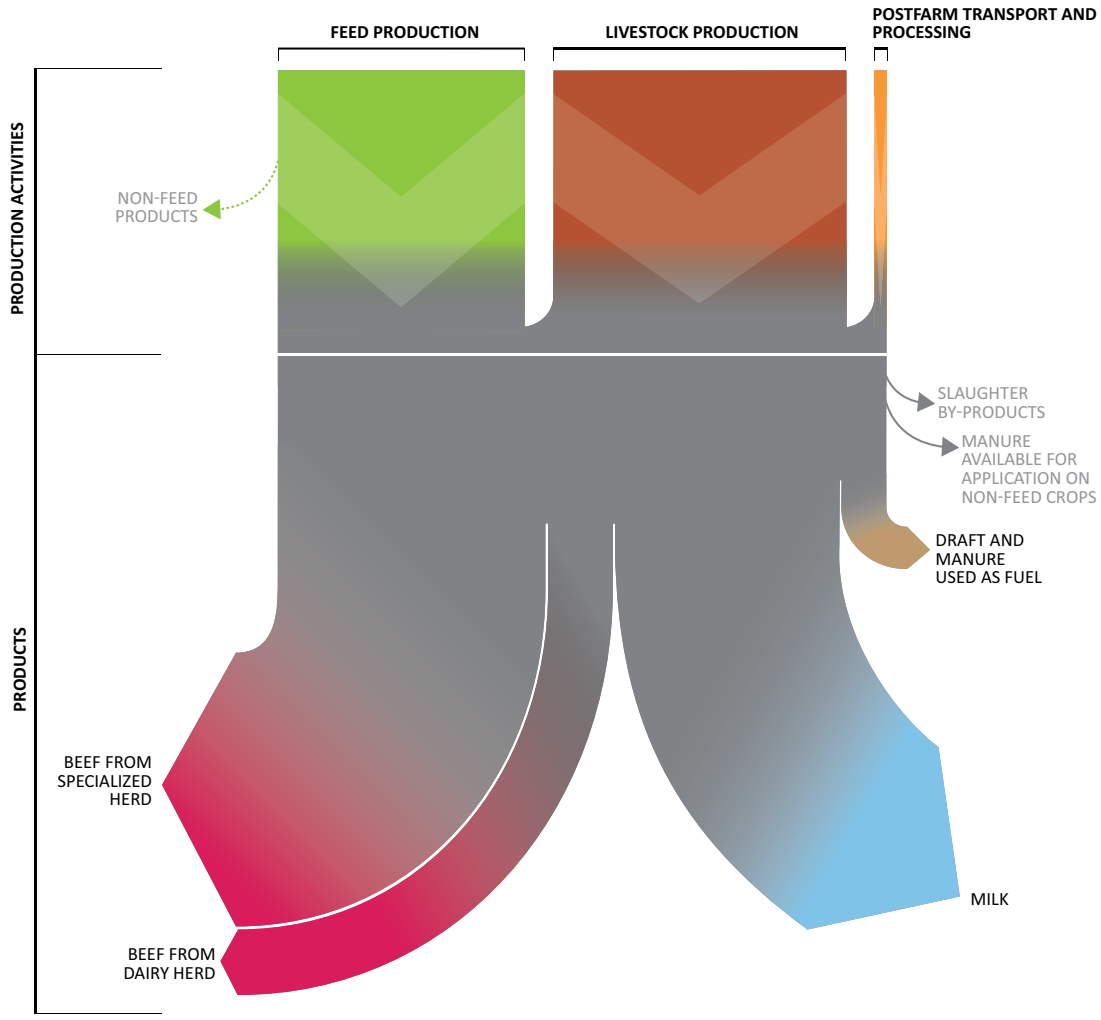
The data have been organized into data groups or "basic data layers". Table 3 summarizes the data collection approach and sources for each main data group.

Further detail on data and data sources is given in Appendix B.

3.6 ALLOCATION OF EMISSIONS BETWEEN PRODUCTS, BY-PRODUCTS AND SERVICES

Livestock produce a mix of goods and services that cannot be disaggregated easily into individual processes. For example, a dairy cow produces milk, manure, draught power and capital services, and eventually meat when it is slaughtered. Given that multiple products are produced from each of the ruminant species, the environmental burden associated with production needs to be allocated for each of the products. In LCA, specific techniques are required to attribute relative shares of

Figure 3.
An illustration of production activities and partitioning of total emissions to products and services from cattle



Source: Authors.

GHG emissions to each of these goods and services. The ISO recommends avoiding allocation by dividing the main process into sub-processes, or by expanding the product system to include additional functions related to the co-products (ISO, 2006). In situations where allocation cannot be avoided (as is often the case in biological processes such as livestock production), GHG emissions can be allocated on the basis of causal and physical relationships.

Where physical relationships alone cannot be established or used as a basis for allocation, emissions should be allocated in a way which reflects other fundamental relationships. In the latter case, the most commonly used approach is economic allocation which, in the context of jointly produced products, allocates emissions to each product according to its share of the products' combined economic value. Other indexes, such as weight or protein content, can also be used (Cederberg and

Figure 4.
Classification of ruminant production systems used in the assessment

HERD TYPE	SYSTEM	CLIMATE	COUNTRY
Dairy herd *(producing milk and meat)*	Mixed[1] Grassland based[2]	Arid Humid Temperate/ tropical highlands	A B ...
Pure meat herd *(producing only meat)*	Mixed[1] Grassland based[2]	Arid Humid Temperate/ tropical highlands	A B ...

[1] Grassland-based livestock systems: Livestock production systems in which more than 10 percent of the dry matter fed to animals is farm-produced and in which annual average stocking rates are less than ten livestock units per hectare of agricultural land (FAO, 1996).
[2] Mixed farming systems: Livestock production systems in which more than 10 percent of the dry matter fed to livestock comes from crop by-products and/or stubble or more than 10 percent of the value of production comes from non-livestock farming activities (FAO, 1996).
Source: Authors.

Stadig, 2003). The allocation techniques used in this assessment to apportion emissions to products and services produced by ruminant systems are summarized below:

- Edible products (e.g. meat and milk): allocation based on protein content.
- Edible and non-edible products (e.g. milk, meat and fibre): allocation based on economic value of outputs.
- Slaughter by-products: no allocation is performed in this assessment. Appendix F explores the impact of allocating emissions to slaughter by-products.
- Manure: allocation based on sub-division of production process.
  - manure storage: emissions from manure management systems (MMS) allocated to livestock sector;
  - manure applied to feed: emissions allocated to livestock sector based on mass harvested and relative economic value;
  - manure applied to non-feed: no allocation to livestock sector; and
  - manure used for fuel: Emissions are deducted from the overall emissions and therefore are not allocation to livestock sector.
- Capital function: no allocation is performed in this assessment.
- Services (e.g. animal draught power): biophysical allocation based on extra-life time gross energy requirements for labour and emissions are deducted from the overall livestock emissions.

A detailed account of the application of the allocation technique is provided in Appendix A. Figure 3 illustrates flows of outputs from the cattle sector.

3.7 PRODUCTION SYSTEM TYPOLOGY

This assessment estimates emissions at global, regional and farming system levels. A farming system typology was thus adapted to provide a framework for examining GHG emission from different dairy farming systems. This typology is based on the classification principles set out by FAO (1996), namely, the feed-base and the agro-ecological conditions of production systems (Figure 4).

The following three AEZs were used:

- *"temperate": temperate regions*, where for at least one or two months a year the temperature falls below 5 ºC; and *tropical highlands*, where the daily mean temperature in the growing season ranges from 5 to 20 ºC.;
- *"arid": arid and semi-arid tropics and subtropics*, with a growing period of less than 75 days and 75-180 days, respectively; and
- *"humid": humid tropics and sub-humid tropics* where the length of the growing period ranges from 181-270 days or exceeds 271 days, respectively.

The widely-used classification approach developed by FAO (1996) that was used here has a number of advantages: it allows researchers to use the multiple databases developed using this structure [e.g. geo-referenced data on animal numbers in each livestock production system (LPS)]; it provides a conceptual framework to make estimates where data are lacking; and it enhances the compatibility of this work with other analyses using similar classification schemes.

4. Results

4.1 CATTLE

This study estimates that in 2005, total emissions from cattle production amount to 4 623 million tonnes CO_2-eq. These emissions include emissions associated with the production of meat and milk, emissions related to land-use change, emissions associated with post farmgate activities, and emissions related to non-edible products and services, draught power and manure used for fuel.

The following sub-sections present the emissions associated with edible products (meat and milk) as well as a disaggregated overview of the contribution of production systems and regions to emissions.

4.1.1 Total production, absolute emissions and emission intensities

In 2005, the global cattle sector produced approximately 508.6 million tonnes of milk and 61.4 million tonnes of beef, of which 56 percent of beef was produced by the specialized beef sector and 44 percent by the dairy herd. Table 4 reports the volume of production, absolute emissions and average GHG emissions per kg of milk and meat for the dairy and beef subsectors.

Globally, about 4 255.9 million tonnes of CO_2-eq were emitted by the global cattle sector in 2005; of this 1 419.1 million tonnes were associated with milk production and 2 836.8 million tonnes with beef production.[5] This is equivalent to 2.8 kg CO_2-eq per kg of fat and protein corrected milk and 46.2 kg CO_2-eq per kg of carcass weight.[6]

Regarding beef production from the cattle sector, there is a distinct difference in emission intensity between beef produced by the dairy herd and the specialized beef herd; the carbon intensity of beef from the specialized beef herds is almost fourfold that produced from the dairy herd (67.8 vs. 18.4 kg CO_2-eq per kg CW) (Table 4). The low emission intensity for dairy meat is caused by the fact that both milk and meat are produced by the dairy herd. Because a large proportion of the

Table 4. Global production, absolute GHG emissions and emission intensities for milk and beef

Cattle herd	Production *(million tonnes)*		Absolute emissions[1] *(million tonnes CO_2-eq)*		Average emission intensity *(kg CO_2-eq/kg product)*	
	Milk[2]	**Meat[2]**	**Milk**	**Meat**	**Milk[2]**	**Meat[2]**
Dairy	508.6	26.8	1419.1	490.9	2.8	18.4
Beef	-	34.6	-	2345.9	-	67.8
Totals	**508.6**	**61.4**	**1419.1**	**2836.8**	**2.8**	**46.2**

[1] Absolute emissions include emissions from production, post farmgate processes and land-use change.

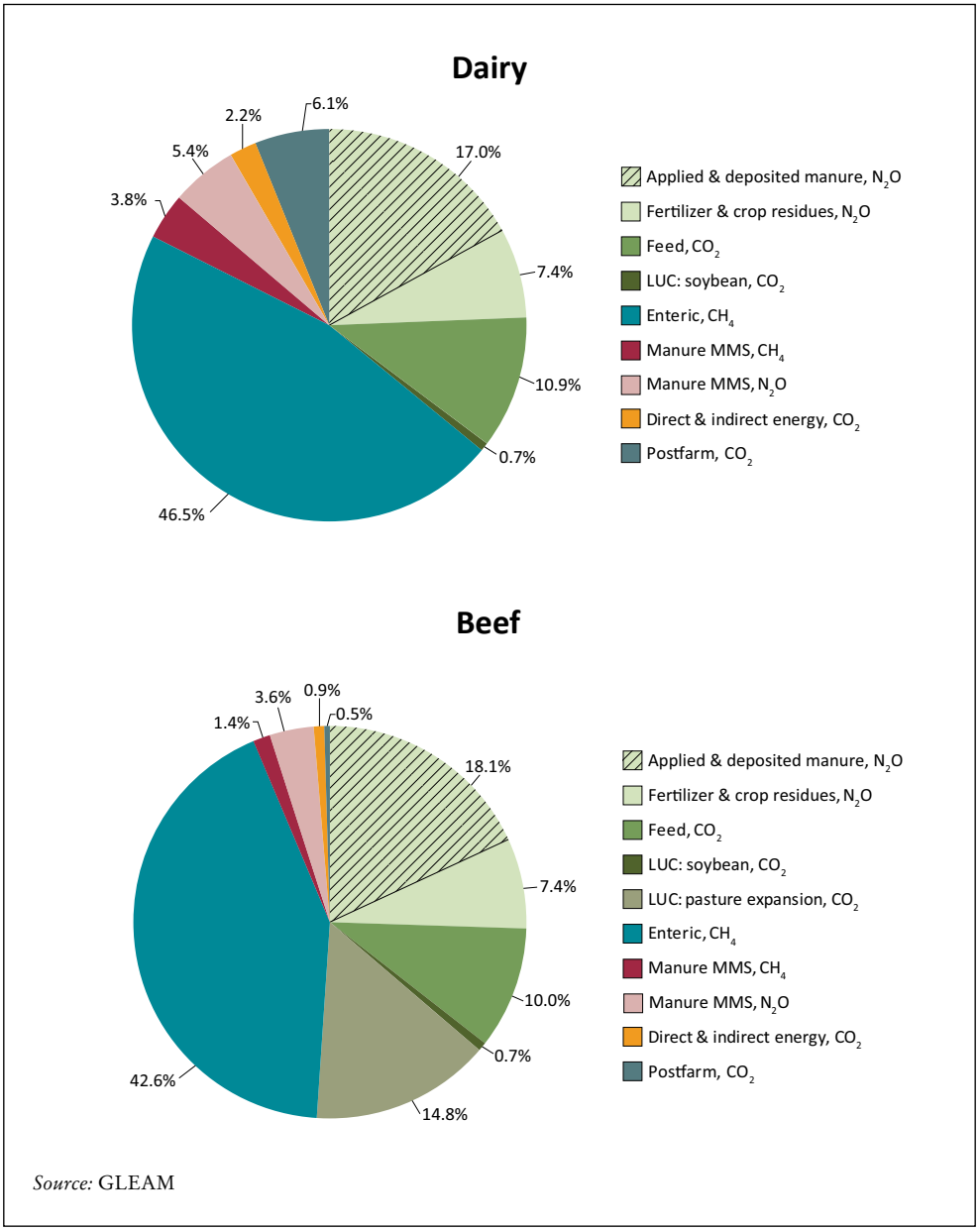
[2] Functional unit for milk and meat defined as fat and protein corrected milk and carcass weight.

Source: GLEAM.

[5] Unless otherwise stated, the term "beef" refers to meat from dairy and specialized beef herds.

[6] Does not include emissions associated to slaughter by-products. See Appendix F for discussion of effects on results.

Figure 5.
Relative contribution of different processes to total GHG emissions from the global cattle sector

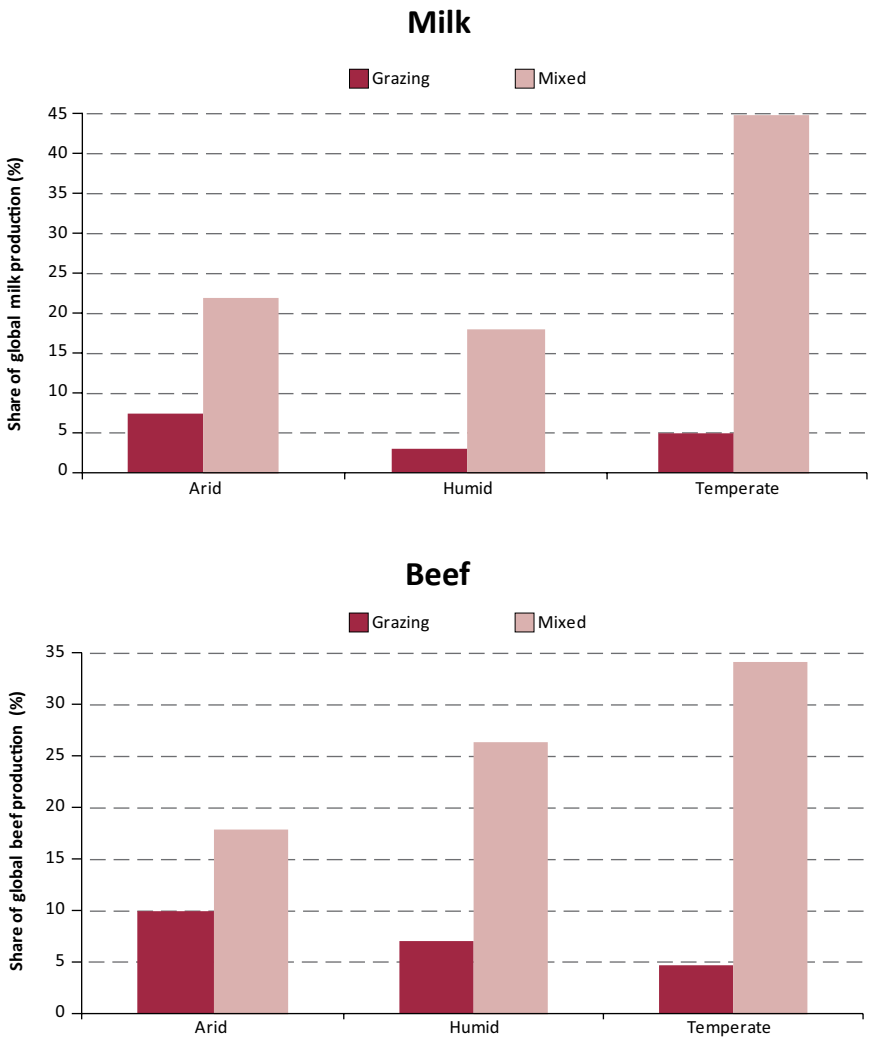


Source: GLEAM

total protein from the dairy herd originates from milk (see Map 6 in Appendix G), a greater proportion of the emissions from dairy herd is attributed to milk. Consequently, this reduces the GHG emissions attributed to meat from culled dairy cows and related meat production from surplus animals.

On the other hand, the specialized beef herd carries the entire burden of emissions because only one product is produced, while the reproductive overhead (cows, bulls and replacement animals) is almost the same. The overhead costs of the cow in dairy-based production systems are largely attributed to milk while in the specialized beef system the full costs are allocated to those animals destined for beef production.

Figure 6.
Contribution to total milk and beef production by production systems and agro-ecological zone[1]



[1] Excluding post farmgate and land-use change emissions (pasture expansion).
Source: GLEAM.

The relative contribution of production processes and gases to the emissions profile for milk and beef at global level is illustrated in Figure 5. A significant share of total GHG emissions is from CH_4 which accounts for 50 percent and 44 percent of the total emissions, with enteric fermentation contributing more than 92 percent and 97 percent of the total CH_4 emissions in dairy and beef production.

In both dairy and beef herds, N_2O emissions amounted to relatively similar proportions of the total carbon footprint – approximately 29 percent of the emissions. Main sources of N_2O emissions include N_2O from manure deposited during grazing and feed production.

On a global scale, CO_2 emissions represent 20 percent and 27 percent of the dairy and beef emission profiles, respectively. The difference in CO_2 emissions between

dairy and beef herds is due to the CO_2 emissions from land-use change associated with the expansion of grassland into forest areas which accounts for 14.8 percent of the total emissions related to beef production and 55 percent of the CO_2 emission.

4.1.2 Emissions by production system and agro-ecological zone

Grass-based systems and mixed livestock production systems contribute 22 and 78 percent of global beef production, and 15 percent and 84 percent of global milk production, respectively (Figure 6).

Average emission intensities for milk and beef produced in grazing and mixed farming systems were estimated at 2.9 and 2.5 kg CO_2-eq/kg FPCM and 42.0 and 38.4 kg CO_2-eq/kg CW, respectively. The variation in emission intensity between the two systems is explained by several factors such as the generally higher slaughter weights, lower age at calving, reduced time to slaughter, and lower mortality rates and better feed quality in mixed farming systems.

Lowest emission intensity in milk and beef production corresponds to the temperate zones in both grassland-based and mixed farming systems (Figures 7 and 8), where productivity is rather high and CH_4 from enteric fermentation is low as a consequence of high digestibility of the feed in these zones. Concomitantly, temperate zones have slightly higher emissions associated with CO_2 feed compared with the humid and arid areas as a result of the high dependency on imported concentrate feed and synthetic fertilizer use in feed production. Lower emission intensity of beef produced in temperate zones is also related to the importance of dairy production in these areas; about 44 percent of the beef from the dairy sector is produced in temperate zones. Beef from the dairy sector as a consequence of the dairy system characteristics comes with discounted emissions because a large share of the emissions related to the meat from culled breeding animals is allocated to milk production.

Enteric CH_4 is the largest source of emissions in all systems; however it is highest in arid and humid zones of both grazing and mixed farming systems where feed, for the most part, is of low quality.

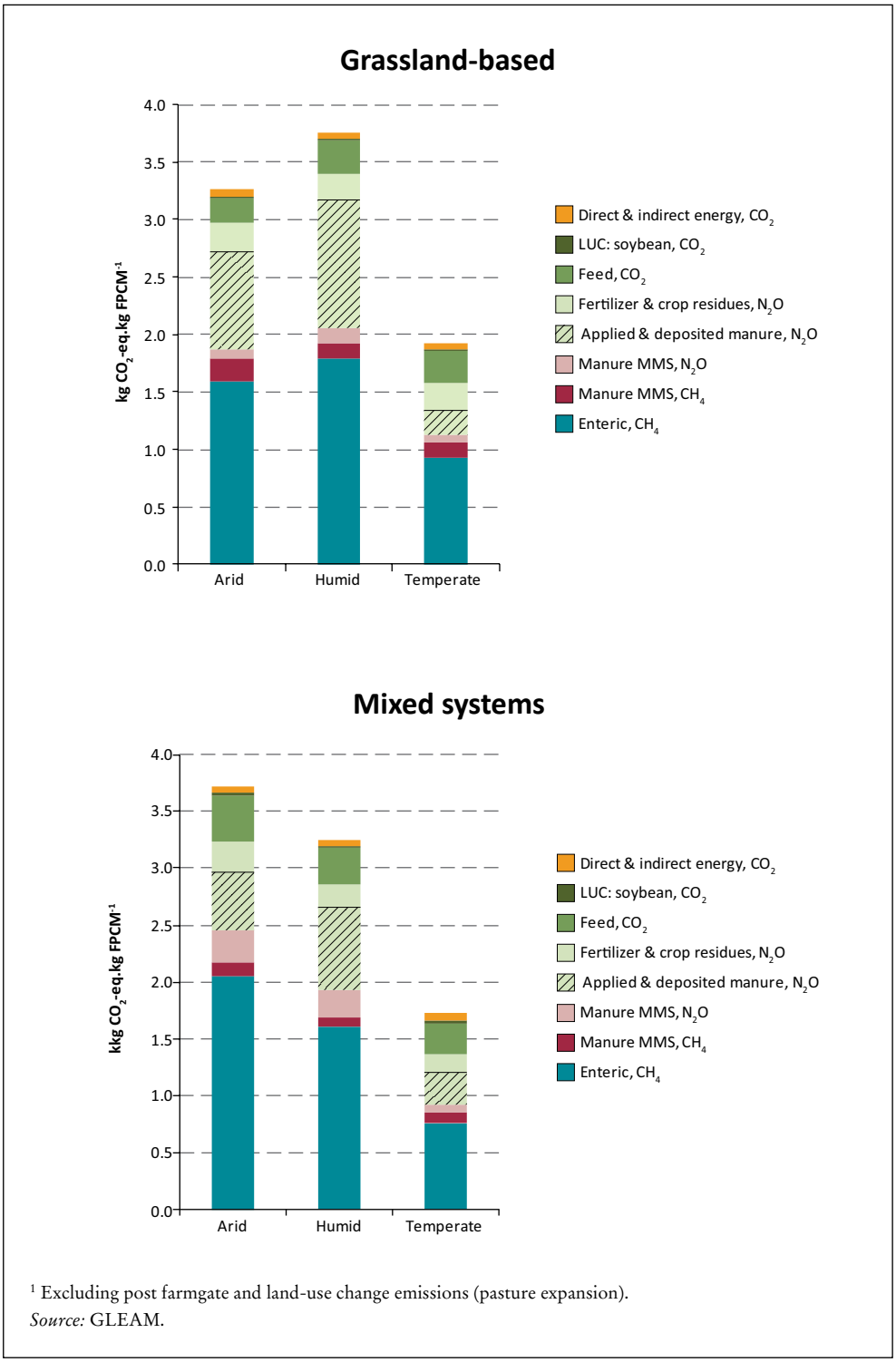
Nitrous oxide emissions from feed production are dominant in both grazing arid and humid zones resulting from manure deposited on pasture during grazing, while in the mixed systems high N_2O emissions are not only associated with manure deposition but also use of synthetic fertilizer in feed production (see Section 5.2).

On the other hand, CH_4 emissions from manure management in both systems are negligible and this is explained by the high proportion of manure that is managed in dry MMS such as drylots or solid systems. Nitrous oxide from manure management is generally low especially in grazing systems because animals are grazing most of the time and manure is mostly deposited on pasture.

4.1.3 Regional emissions, production and emission intensities

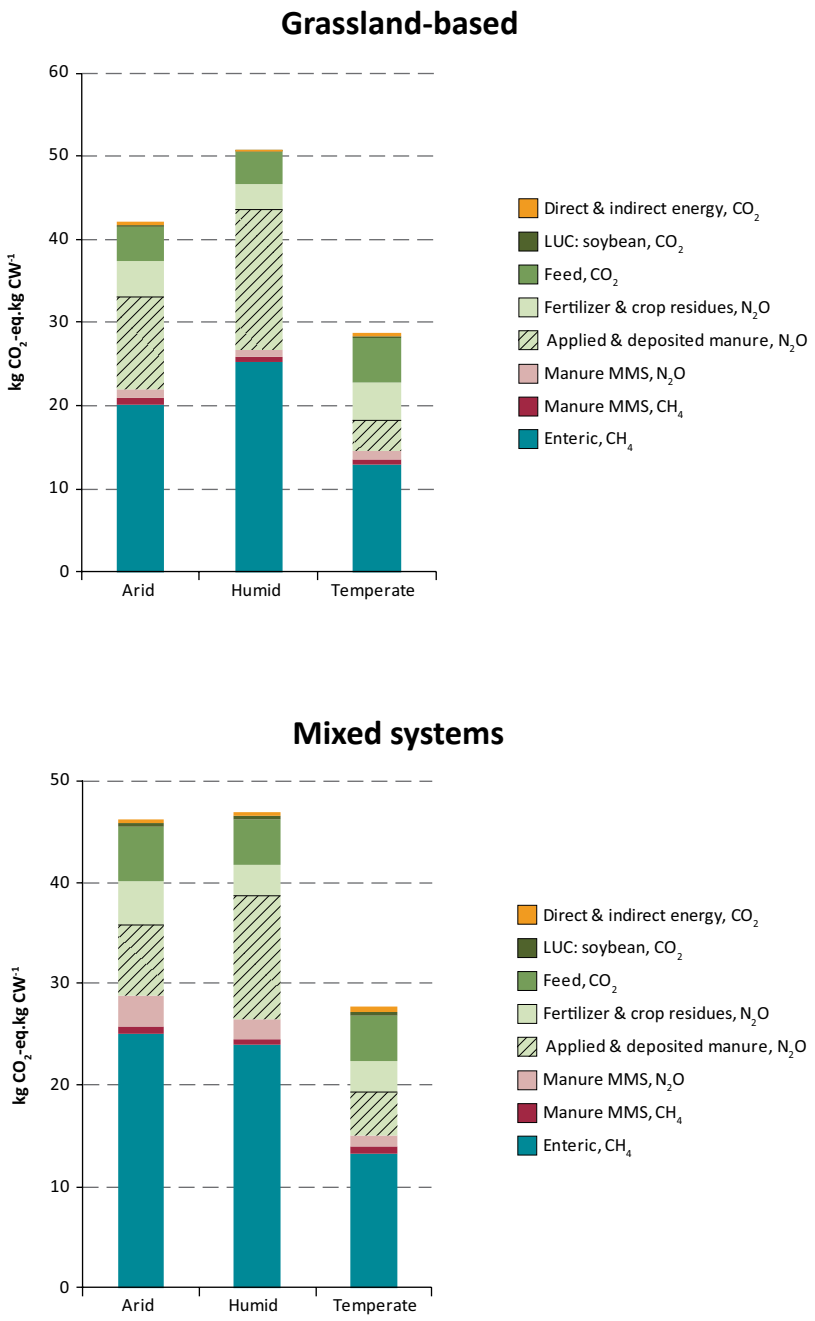
In terms of total production, approximately 67 percent of the total protein from the global cattle sector is from milk. However, this global estimate obscures variations at regional level, where large differences exist both in terms of production and emissions. With the exception of Latin America and the Caribbean, the contribution of milk protein to the total protein from the cattle sector on average ranges from 56 percent in sub-Saharan Africa to 81 percent in Western Europe (Figure 9; Map 6 in Appendix G). In Latin America, meat protein contributes about 54 percent of the

Figure 7.
Emission intensities for milk by production system and agro-ecological zone[1]



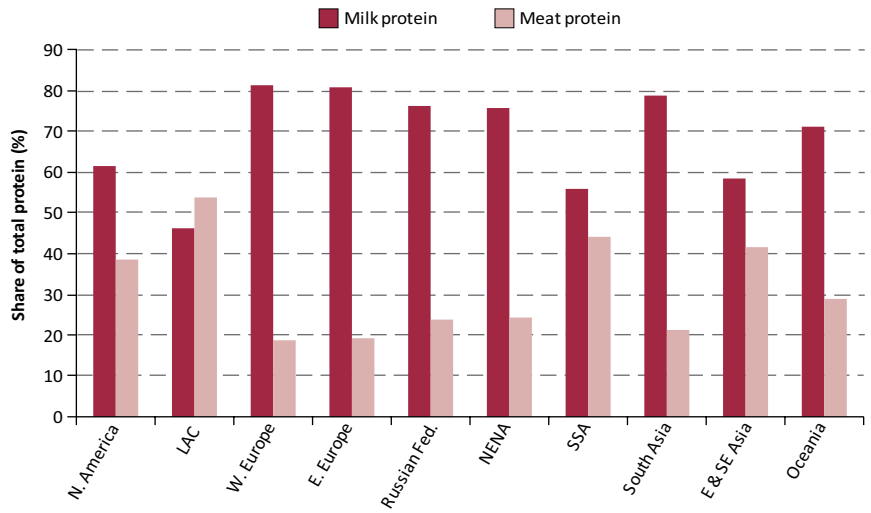
[1] Excluding post farmgate and land-use change emissions (pasture expansion).
Source: GLEAM.

Figure 8.
Emission intensities for beef by production system and agro-ecological zone[1]



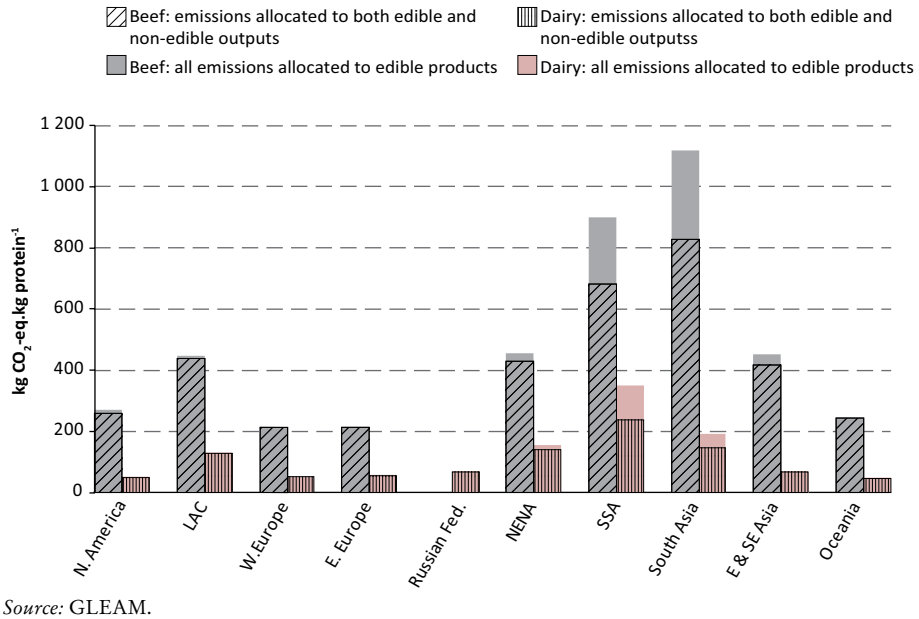
[1] Excluding post farmgate and land-use change emissions (pasture expansion).
Source: GLEAM.

Figure 9.
Regional contribution to milk and meat protein



Source: GLEAM.

Figure 10.
Emissions per kg meat and milk protein, comparing allocation of emissions to different outputs



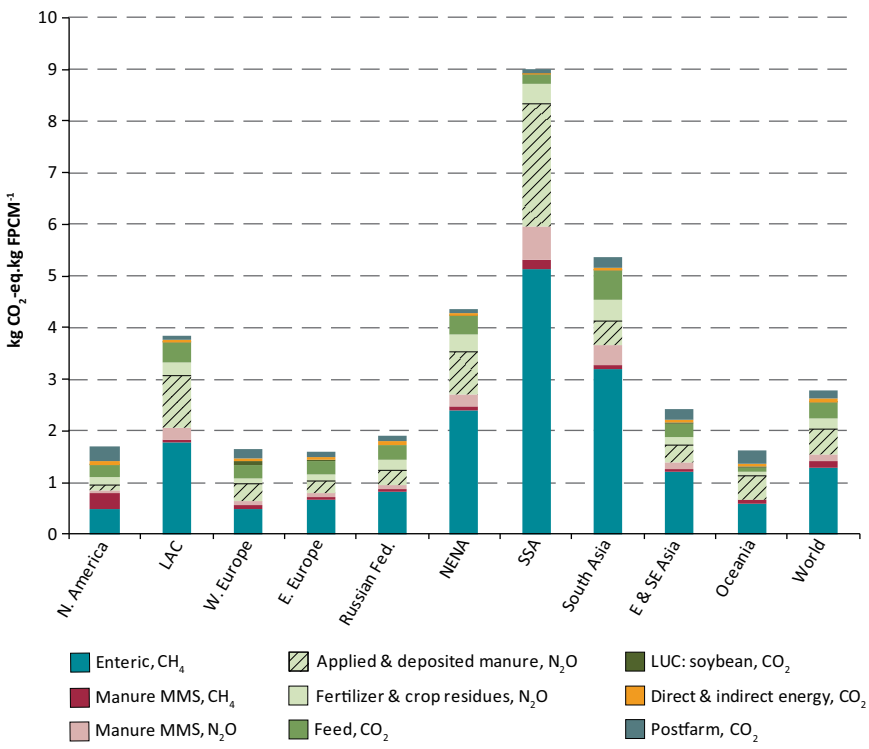
Source: GLEAM.

total protein from cattle, mainly because the emphasis is on beef production rather than dairy. In the other world regions, meat protein ranges between 18 percent in Europe to 44 percent in sub-Saharan Africa.

Figure 10 presents a regional comparison of emission intensities for two computation approaches where (i) all emissions from cattle production are allocated to the main edible outputs from the system, milk and meat; and (ii) emissions related to other functions and processes, e.g. draught power and those related to the use of manure as a source of fuel, are deducted from the overall system emissions.

Figure 10 illustrates the difference in carbon equivalent impact and the extent to which production is specialized, i.e. whether it is meant for milk and meat production or whether animals are kept for other purposes. The starkest difference in emission intensity is shown for sub-Saharan Africa and South Asia where cattle herds are multi-purpose, producing not only edible products but also non-edible products and services that are utilized in other production processes within or outside the livestock sector boundary. In these regions, use of draught power is important as well as the use of manure as a source of fuel, and allocation of emissions to these products and services significantly lowers the emission intensity of edible products in these regions. In contrast, in industrialized regions, production is more specialized with cattle being specifically reared to produce meat and milk products. In these regions, emission intensity is generally lower, because production is more

Figure 11a.
Regional variation in GHG emission intensities for cow milk



Source: GLEAM.

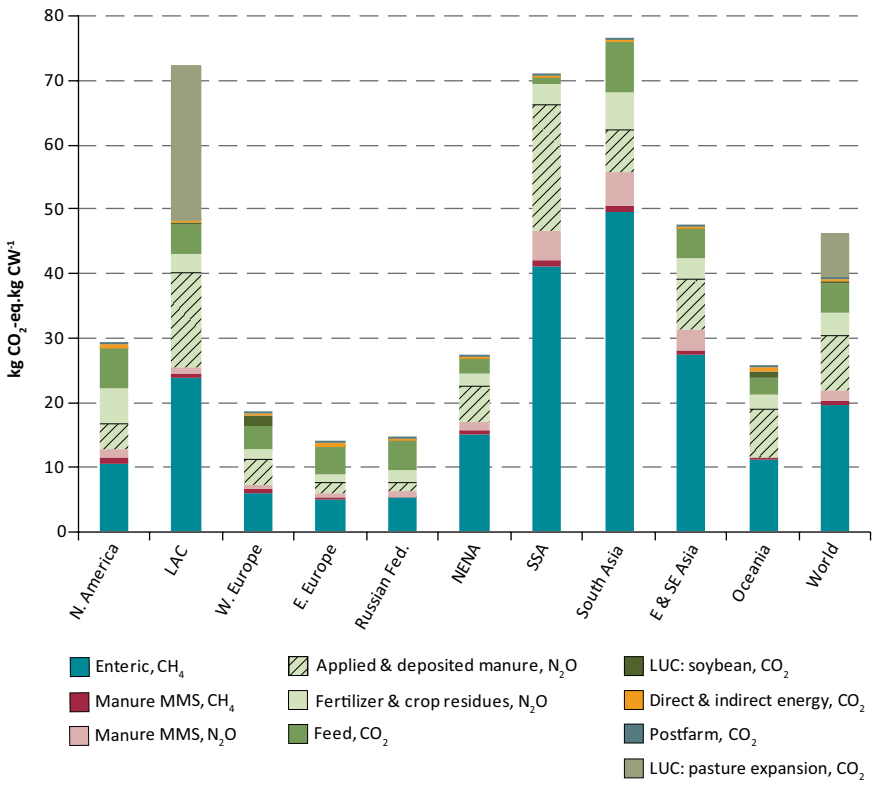
efficient, yields are higher, and animals are not kept for longer periods for other purposes such as draught power.

Figures 11a and 11b present regional variation in emission intensity for milk and meat (after allocation to draught and manure used for fuel) and the contribution of emission categories to the emission profile.

For milk, emission intensities vary from 1.6 kg CO_2-eq/kg FPCM in Eastern and Western Europe to 9 kg CO_2-eq/kg FPCM in sub-Saharan Africa (Figure 11a). Generally, industrialized regions of the world exhibit the lowest emission intensities per kg FPCM ranging between 1.6 and 1.7 kg CO_2-eq/kg FPCM, while in developing regions the range of emission intensity for milk is wider – 2.0 and 9.0 kg CO_2-eq/kg FPCM.

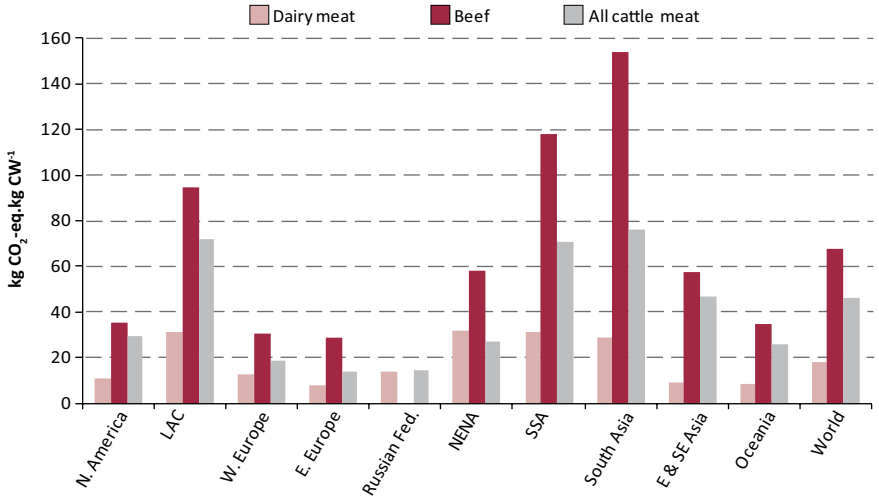
The main contribution to the GHG emission profile of milk in developing regions is enteric fermentation while in industrialized regions dominant emissions are largely related to feed production and processing. With regard to manure management, CH_4 emissions are highest in North America where on average 27 percent of manure from the dairy sector is managed in liquid systems that produce greater quantities of CH_4 emissions (see Section 5.3.1). In contrast, N_2O emissions from manure management are higher in developing regions as a result of the higher proportion of manure managed in dry systems.

Figure 11b.
Regional variation in GHG emission intensities for beef



Source: GLEAM.

Figure 12.
Regional comparison of emission intensity per kilogram of carcass



Source: GLEAM.

Regional variability in emission intensity for beef is presented in Figure 11b, with GHG emissions per kg carcass weight (CW) ranging from 14 kg CO_2-eq/kg CW in Eastern Europe and Russian Federation to 76 kg CO_2-eq/kg CW in South Asia. Highest emission intensities are found in developing regions: South Asia, sub-Saharan Africa, LAC and East and Southeast Asia. A key driver for the high emissions associated with beef is largely related to low feed digestibility, lower slaughter weights and higher age at slaughter. The carbon footprint of beef produced in Latin America comprises emissions related to land-use change from pasture expansion into forested areas. Consequently, land-use change is a major driver of emissions in the region, representing approximately one-third of the footprint (Figure 11b), equivalent to 24 kg CO_2-eq/kg CW. These LUC estimates are however associated with a high level of methodological uncertainty and do not capture recent deforestation trends (the period considered is 1990-2006).

The low emission intensities associated with beef in Europe (Western and Eastern Europe, and the Russian Federation) is explained by the large proportion of the beef produced from the dairy herd.[7] About 80 percent of the beef production in Europe is derived as a co-product from dairy production (from surplus calves and culled cows); in the Russian Federation, all beef is estimated to be produced by the dairy sector. The dairy sector therefore has a much higher impact on beef production in these regions and this is directly linked to the need for their dairy sectors to sustain milk production through production of calves in order to keep cows lactating. Figure 12 compares the regional emission intensity for beef produced by the dairy and beef herd and the average emission intensity of all beef produced by the cattle sector. The low emissions are also an artefact of the production characteristics of dairy herd (dual products) (see discussion on allocation techniques in Appendix A) and hence a large proportion of the emissions attribut-

[7] Table B22, Appendix B presents the contribution of dairy and beef herds to total beef production.

able to dairy cows is allocated to milk, resulting in a lower allocation to beef from the dairy herd.

The emission intensity for beef in Western Europe, North America and Oceania is lower than the global average mainly because these regions are key beef-producing regions characterized by high efficiency in production and high feed digestibility (Map 8 in Appendix G).

Table B13 in Appendix B illustrates average feed digestibility values for the average feed ration used in beef production in different regions. Highest feed digestility is found in industralized countries where feed rations are laregly composed of higher quality roughages and concentrates. The digestibility of average feed rations in developing regions is much lower, particulary in sub-Saharan Africa, South Asia and parts of East and Southeast Asia. Feed rations in this regions are laregly composed of roughages of low quality (grass, crop residues and leaves).

Regarding the contribution of different processes to the emission profile for beef, a distinct difference can be observed between the two broad regional groupings (developing and industrialized).

In developing regions, analogous to the dairy, the overall emission profile for beef is dominated by enteric CH_4 and N_2O emissions related to feed from manure deposited on pasture during grazing. The relatively higher N_2O emissions from manure management in sub-Saharan Africa, South Asia, and East and Southeast Asia reflects the higher share of manure managed in dry systems.

In contrast, enteric CH_4 emissions play a less important role in industrialized regions; however, this is compensated by high CO_2 and N_2O from feed emissions, reflecting a high dependence on feed imports, high fertilizer use in feed production and a higher level of mechanization (see Section 5.2).

4.2 BUFFALO

Milk and meat production from the global buffalo sector contributes an equivalent of 619 million tonnes CO_2-eq consisting of emissions from the production of meat and milk, emissions related to land-use change, emissions associated with post farmgate activities, and emission related to non-edible products and services, i.e. draught power and manure used for fuel.

4.2.1 Total production, absolute emissions, and emission intensities

In 2005, global buffalo milk and meat production amounted to 115.2 and 3.4 million tonnes, respectively, and associated with this, about 390 and 180.2 million tonnes CO_2-eq were emitted from the production of milk and meat from buffaloes, respectively (Table 5). On average, the emission intensity of buffalo milk and meat is estimated at 3.4 kg CO_2-eq/kg FPCM and 53.4 kg CO_2-eq/kg CW, respectively (Table 5). The emission intensity of meat produced by the dairy herd is significantly lower than that produced from the meat herd and the reasons are similar to those outlined in the previous sub-section on the cattle sector.

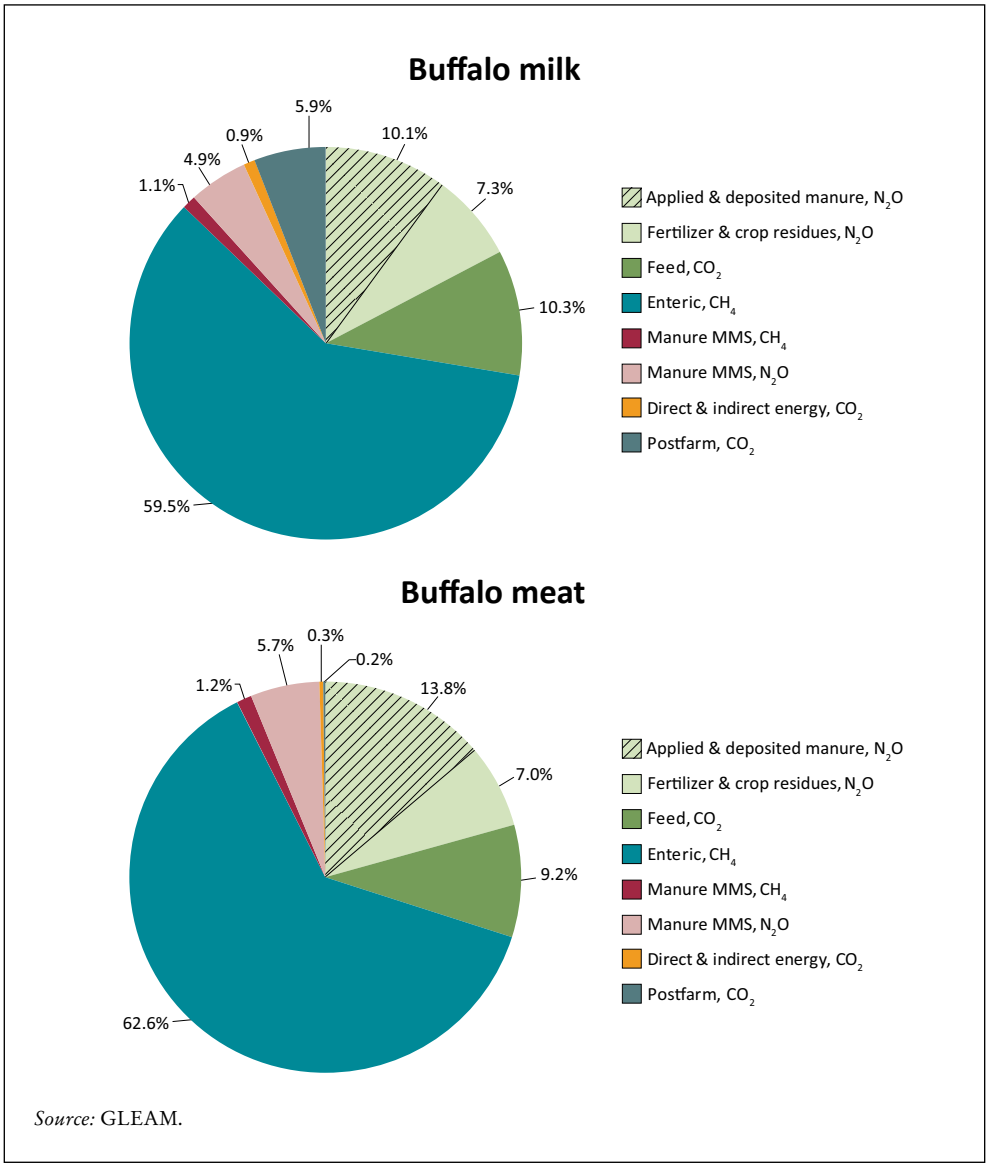
Enteric fermentation is by far the most important source of emissions, contributing over 60 percent of the emissions in both milk and meat production (Figure 13). Other important sources of emissions include emissions from feed production, particularly N_2O emissions from manure deposited largely determined by the long grazing period. Emissions from manure management (N_2O and CH_4 emissions) together contribute 6 percent and 7 percent of the total emissions from dairy and meat herds.

Table 5. Global production, emissions and emission intensity for buffalo milk and meat

Buffalo herd	Production *(million tonnes)*		Absolute emissions[1] *(million tonnes CO_2-eq)*		Average emission intensity *(kg CO_2-eq/kg product)*	
	Milk[2]	Meat[2]	Milk	Meat	Milk[2]	Meat[2]
Milk	115.2	2.4	389.9	40.4	3.4	16.6
Meat	-	0.95		139.9	-	143.9
Totals	**115.2**	**3.4**	**389.9**	**180.2**	**3.4**	**53.4**

[1] Absolute emissions include emissions from production and post farmgate emissions.
[2] Functional unit for milk and meat defined as fat and protein corrected milk and carcass weight.
Source: GLEAM.

Figure 13.
Relative contribution of different processes to GHG emission profile of buffalo milk and meat



Source: GLEAM.

4.2.2 Emissions by production system and agro-ecological zone

Average emission intensity of buffalo milk from grazing and mixed farming systems is estimated at 3.4 and 3.2 kg CO_2-eq/kg FPCM, respectively. On the other hand, the emission intensity of buffalo meat from grazing and mixed farming systems is 36.7 and 54.0 kg CO_2-eq/kg CW, respectively. About 82 percent and 67 percent of milk and meat production from buffalo is produced in the mixed arid zones. Production in the other ecological zones is unimportant.

Lowest emission intensities for milk are found in the grazing temperate and mixed arid production systems (Figure 14).

Lowest emission intensities for buffalo meat are found in the arid zones in both grazing and mixed systems (Figure 15), which contribute 70 percent of all buffalo meat, while humid zones in both systems have highest emission intensities. Important sources of emissions include: enteric fermentation, N_2O from feed production and grazing; and CO_2 emissions from feed production and processing. N_2O from manure and feed is an important source of emissions in the humid zones; these emissions are largely driven by the predominance of dry manure management systems and emissions from the deposition of manure on pasture. The remaining emissions are insignificant in terms of their contribution towards the carbon profile.

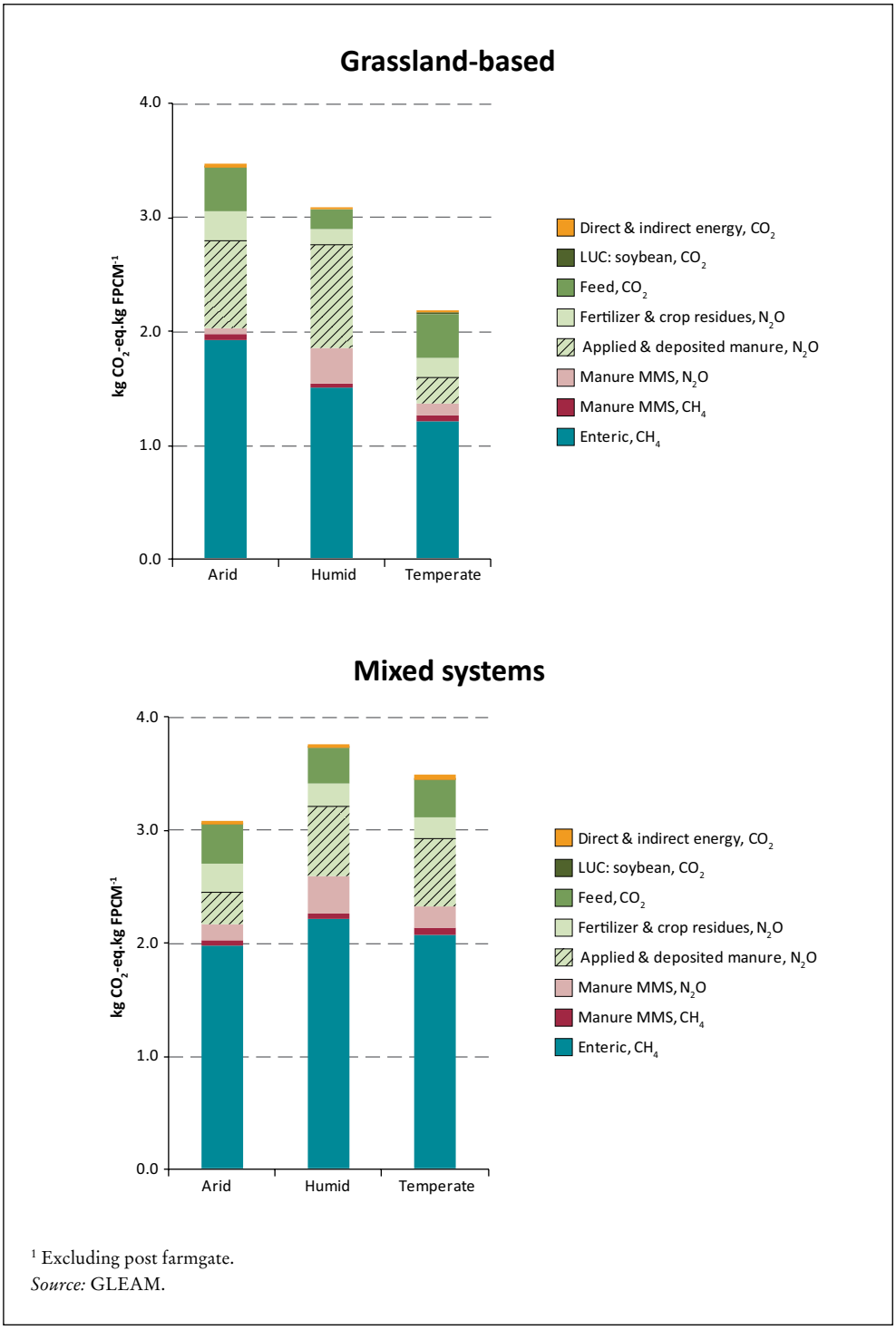
4.2.3 Regional production emissions and emission intensities

Global buffalo milk and meat production is important in three main world regions: South Asia, NENA and East & Southeast Asia; South Asia contributes 90 percent and 70 percent of the global buffalo milk and meat, respectively, and average milk emission intensity ranges from 3.2 to 4.8 kg CO_2-eq/kg FPCM (Figure 16a); milk produced in South Asia has the lowest emission intensity, explained by high yields. Emission intensity in South Asia is similar to the global average, explained by the fact that the bulk of buffalo milk (90 percent) is produced in the region.

On the other hand, the emission intensity of buffalo meat production at regional level ranges from 21 kg CO_2-eq/kg CW in NENA to 70.2 kg CO_2-eq/kg CW in East & Southeast Asia (Figure 16b). Key buffalo meat producing regions include South Asia (producing 70 percent of the global production), East & Southeast Asia (20 percent) and NENA (5 percent).

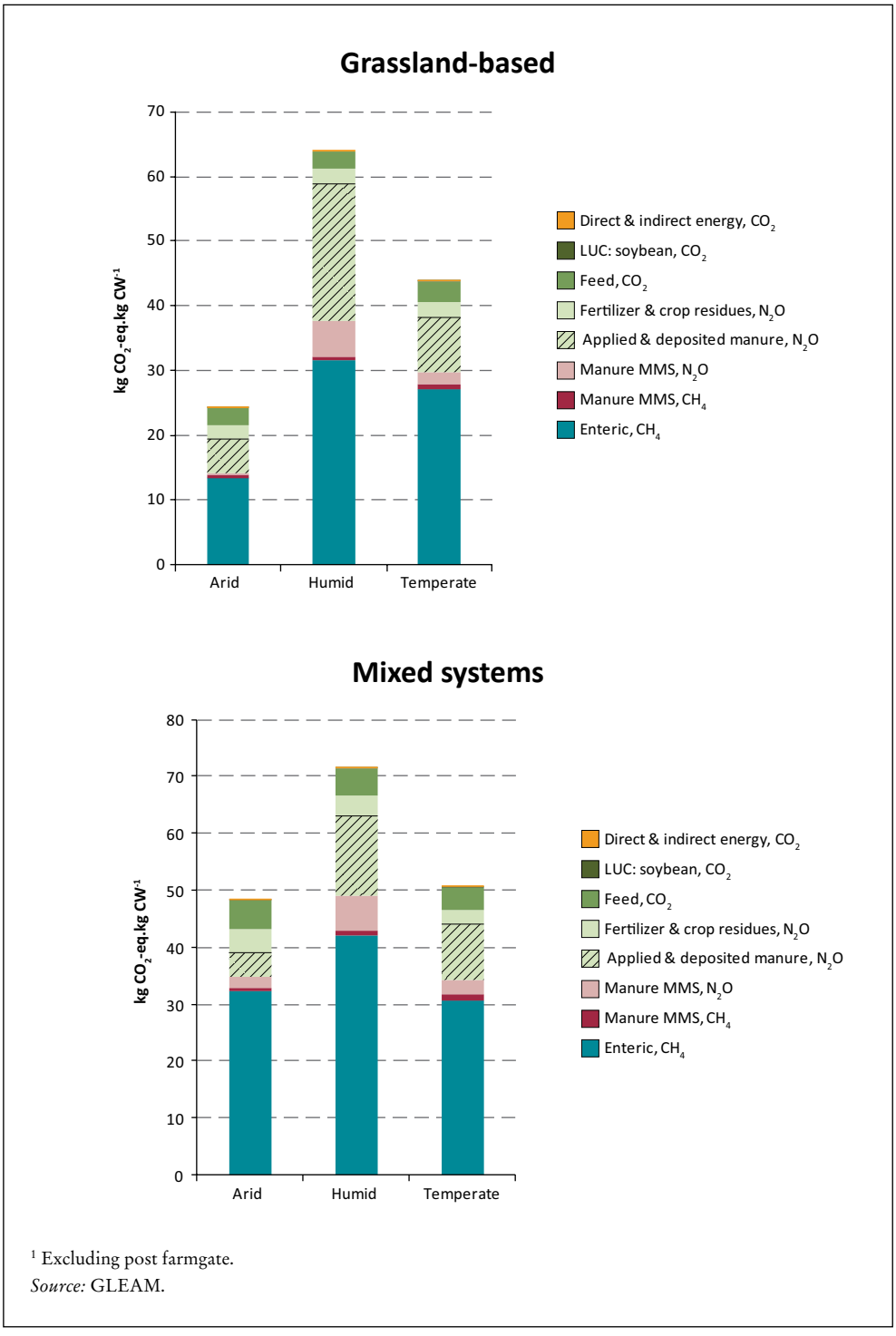
Enteric CH_4 and feed N_2O emissions associated with feed production are the dominant sources of emissions. Key sources of emissions in the buffalo carbon profile comprise CH_4 from enteric fermentation (contributing more than half of the carbon footprint), and CO_2 and N_2O emissions associated with feed production. Nitrous oxide emissions from manure management are significant in East & Southeast Asia, where manure is managed in dry and solid systems.

Figure 14.
Emission intensities for buffalo milk by production system and agro-ecological zone[1]



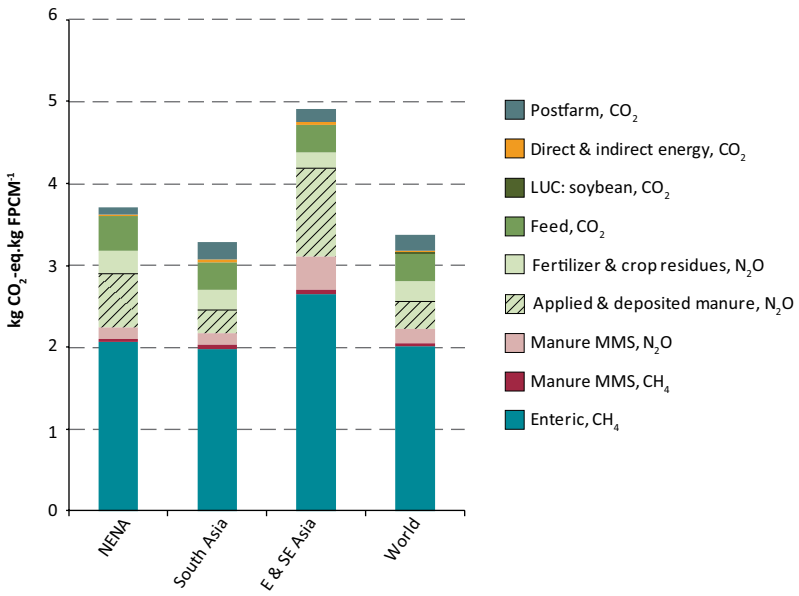
[1] Excluding post farmgate.
Source: GLEAM.

Figure 15.
Emission intensities for buffalo meat by production system and agro-ecological zone[1]



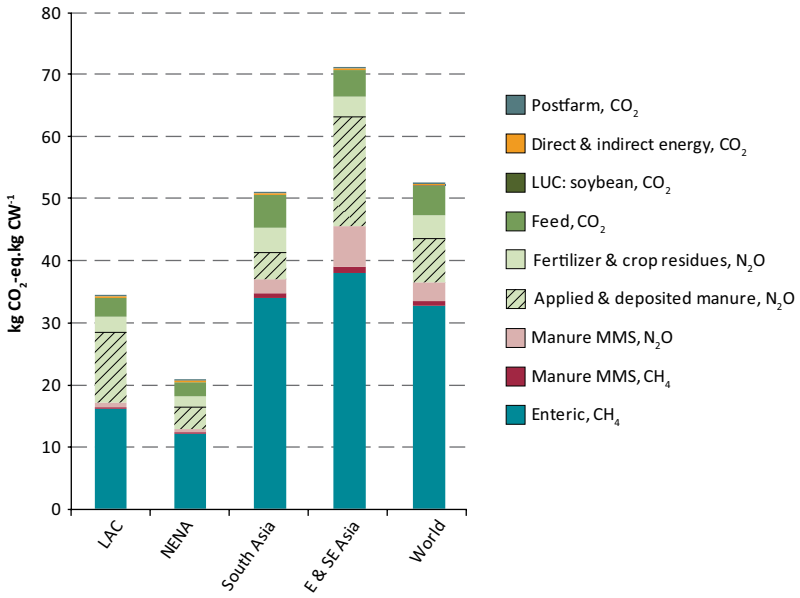
[1] Excluding post farmgate.
Source: GLEAM.

Figure 16a.
Regional variation in GHG emission intensities for buffalo milk[1]



[1] Excludes regions where contribution to global production is less than 2 percent.
Source: GLEAM.

Figure 16b.
Regional variation in GHG emission intensities for buffalo meat[1]



[1] Excludes regions where contribution to global production is less than 2 percent.
Source: GLEAM.

4.3 SMALL RUMINANTS

The contribution of the small ruminant sector to GHG emissions is equivalent to 474 million tonnes CO_2-eq. These total emissions from the sheep and goat production comprise emissions from production of edible (meat and milk) and non-edible products (natural fibre) as well as emissions from post farmgate processes. The discussion in subsequent sections presents total emissions and emission intensities related to small ruminant production at global, farming system and regional grouping levels for edible products.

4.3.1 Total production, absolute emissions, and emission intensities

Globally, small ruminant production of meat and milk is responsible for 428.8 million tonnes CO_2-eq, of which 254.4 million tonnes CO_2-eq (59 percent) are associated with sheep production and 174.5 tonnes CO_2-eq (41 percent) are associated with goat production. Total production from the small ruminant sector amounts to 20.0 and 12.6 million tonnes of milk and meat, respectively. Goats contribute almost 60 percent of the milk produced by small ruminants, while sheep contribute 62 percent of the meat (Table 6).

On average, the emission intensity of small ruminant milk is 6.5 kg CO_2-eq/kg FPCM. In terms of emission intensity, goat's milk has lower emission intensity (5.2 kg CO_2-eq/kg FPCM compared with 8.4 kg CO_2-eq/kg FPCM for milk from sheep) due to higher yields compared with milk from sheep. Average emission intensity for small ruminant meat is 23.8 kg CO_2-eq/kg CW, while emission intensity for sheep and goats meat is quite similar – 24.0 and 23.5 kg CO_2-eq/kg CW, respectively (Table 6).

Similar to cattle and buffalo, CH_4 emissions are important, accounting for half of the total emissions associated with small ruminant production (Figure 17). Enteric fermentation is the single most important emission category in both milk and meat production, contributing 57 percent and 55 percent of the total GHG emissions from milk and meat production, respectively.

Nitrous oxide emissions amount to relatively similar proportions (27 percent and 28 percent) of the total carbon footprint for both milk and meat. Within this, N_2O emissions from manure storage and management are insignificant (4 percent and 2 percent for milk and meat, respectively), mainly because small ruminants are grazing most of the time and consequently a very small proportion of the manure is managed.

Table 6. Global production, emissions and emission intensity for small ruminants

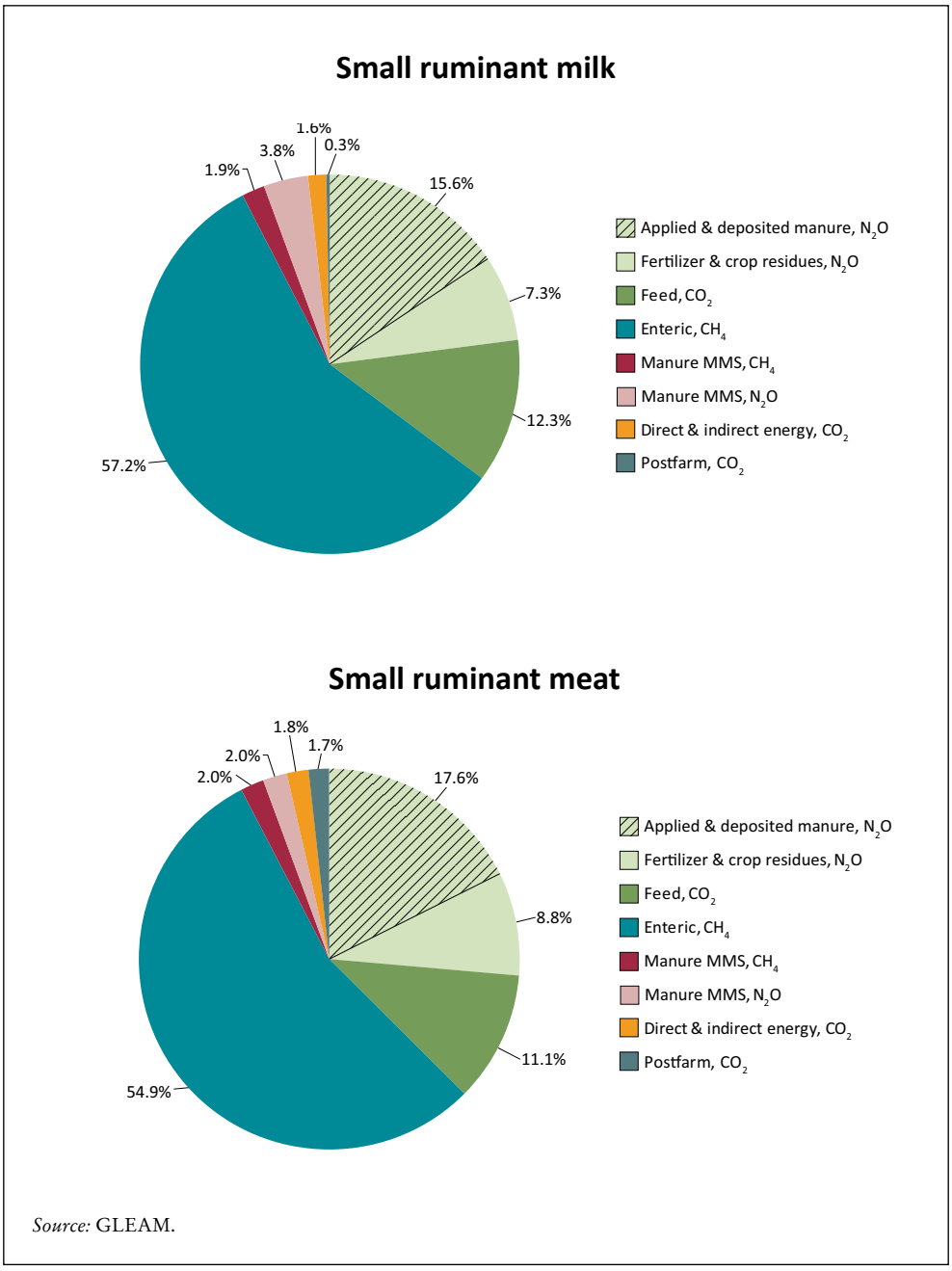
Species	Production *(million tonnes)*		Absolute emissions[1] *(million tonnes CO_2-eq)*		Average emission intensity *(kg CO_2-eq/kg product)*	
	Milk[2]	Meat[2]	Milk	Meat	Milk[2]	Meat[2]
Sheep	8.0	7.8	67.4	186.9	8.4	24.0
Goats	12.0	4.8	62.4	112.5	5.2	23.5
Totals	**20.0**	**12.6**	**129.4**	**299.4**	**6.5**	**23.8**

[1] Absolute emissions include emissions from production and post farmgate emissions.

[2] Functional unit for milk and meat defined as fat and protein corrected milk and carcass weight.

Source: GLEAM.

Figure 17.
Relative contribution of different processes to GHG emission profile of small ruminant milk and meat



Source: GLEAM.

Within the emissions profile, CH_4 from manure management is unimportant because virtually all manure is either deposited on pasture or managed in dry systems such as drylots and solid storage systems (see Table B19, Appendix B). Emissions associated with feed production comprising both N_2O (mainly from manure) and CO_2 emissions amount to 35 percent of the total emissions. Carbon dioxide emissions from on-farm energy use and embedded energy as well as post farmgate activities make a relatively small contribution towards the overall carbon footprint.

4.3.2 Emissions by production system and agro-ecological zone

Emission intensity for milk is higher in grazing systems with an average of 7.6 kg CO_2-eq/kg FPCM compared with 6.6 kg CO_2-eq/kg FPCM in mixed farming systems (Figure 18). A similar trend is found for small ruminant meat; average emission intensity per kg CW is 24.0 and 23.2 kg CO_2-eq/kg CW in grazing and mixed systems, respectively (Figure 19).

In small ruminant milk production in grazing systems, emissions intensity is highest in temperate zones, a trend which contrasts with the emission intensity trends for dairy cattle (see Figure 7). The higher emission intensity for small ruminant milk in grazing temperate zones is explained by a combination of factors: (i) total emissions are dominated by emissions from the temperate areas in regions such as Asia and Africa, where production conditions are poor for the most part; (ii) sheep milk production dominates small ruminant milk in the temperate zones, however milk yields from sheep are much lower compared with goats; and (iii) goats milk, which is characterized by higher yields per animal, mainly occurs in the arid areas.

On the other hand, for small ruminant meat there is no systematic trend across production systems; in grazing systems, highest emission intensity is found in temperate zones, while in mixed systems, meat produced in the arid zones has the highest emission intensity.

The difference in emission intensity of small ruminant meat is explained by a combination of factors: (i) high emission intensity in grazing temperate areas is related to the fact that in temperate zones small ruminants, particularly sheep, are reared for mainly for meat and therefore the carcass bears the whole burden of emissions; (ii) temperate grazing areas are also characterized by low yields, which are closely related to poor production conditions and low feed digestibility, hence the high emission intensity.

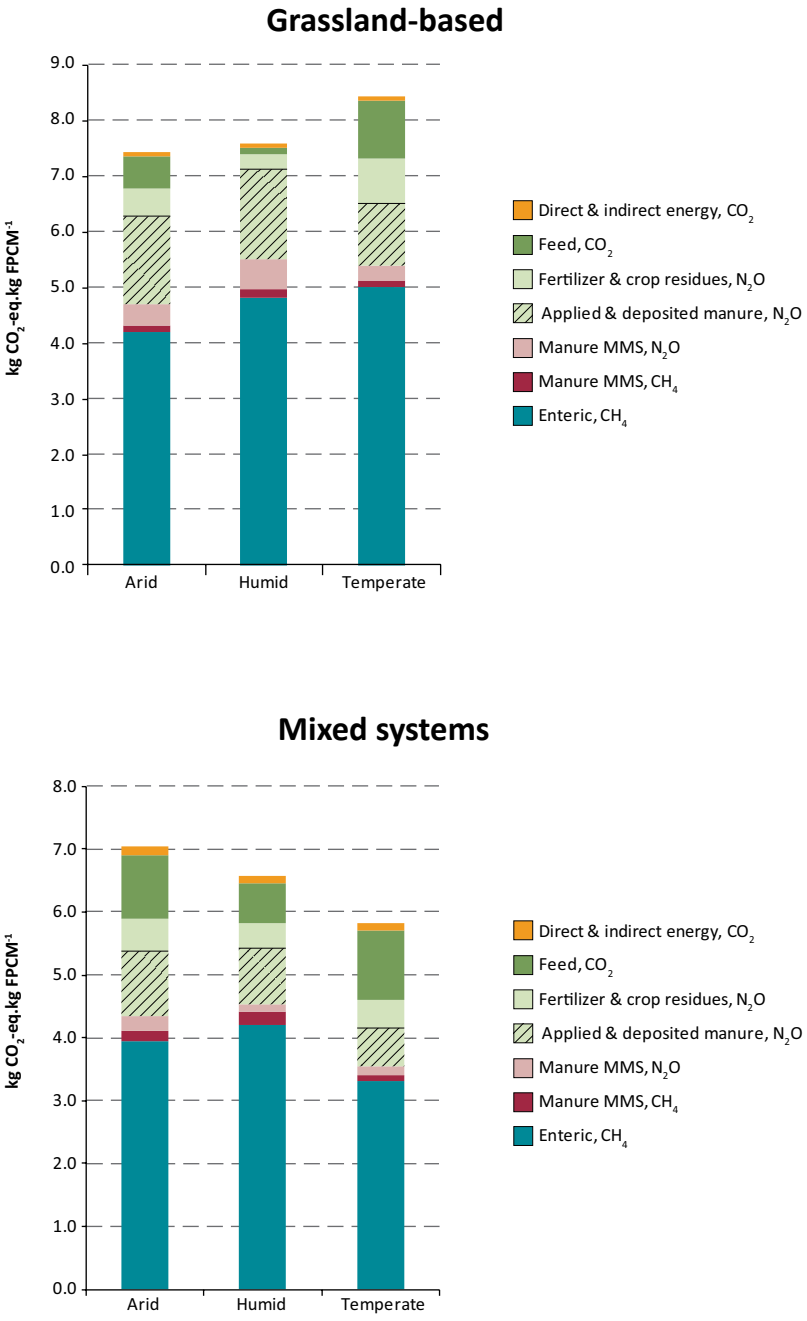
Figure 19, however, masks much of the variation that can be found within similar production systems and climatic conditions. Disaggregated emission intensity at production system level show temperate zones in grassland-based systems with highest emission intensity, about 27.5 kg CO_2-eq/kg CW. However, regions such as Oceania and W. Europe show a contrasting trend, with lowest emission intensities within this production system and AEZ typology (13.7 and 19.8 kg CO_2-eq/kg CW, respectively) as a result of their efficient production systems. Within temperate grassland-based systems, the predominance of other regions such as East & Southeast Asia, NENA and Latin America & Caribbean drive the emission intensities of the system. These high emissions are largely related to poor quality feed, poor performance of animals, and slower growth rates.

Methane emissions from enteric fermentation dominate the emission profile in both systems and across all three AEZs. Nitrous oxide emissions associated with feed production are relatively higher for grassland-based systems and this arises from the deposition of manure on pasture.

The high CH_4 emissions from manure management in the mixed farming systems relative to grazing systems indicate the management of manure in systems other than pasture-based systems.

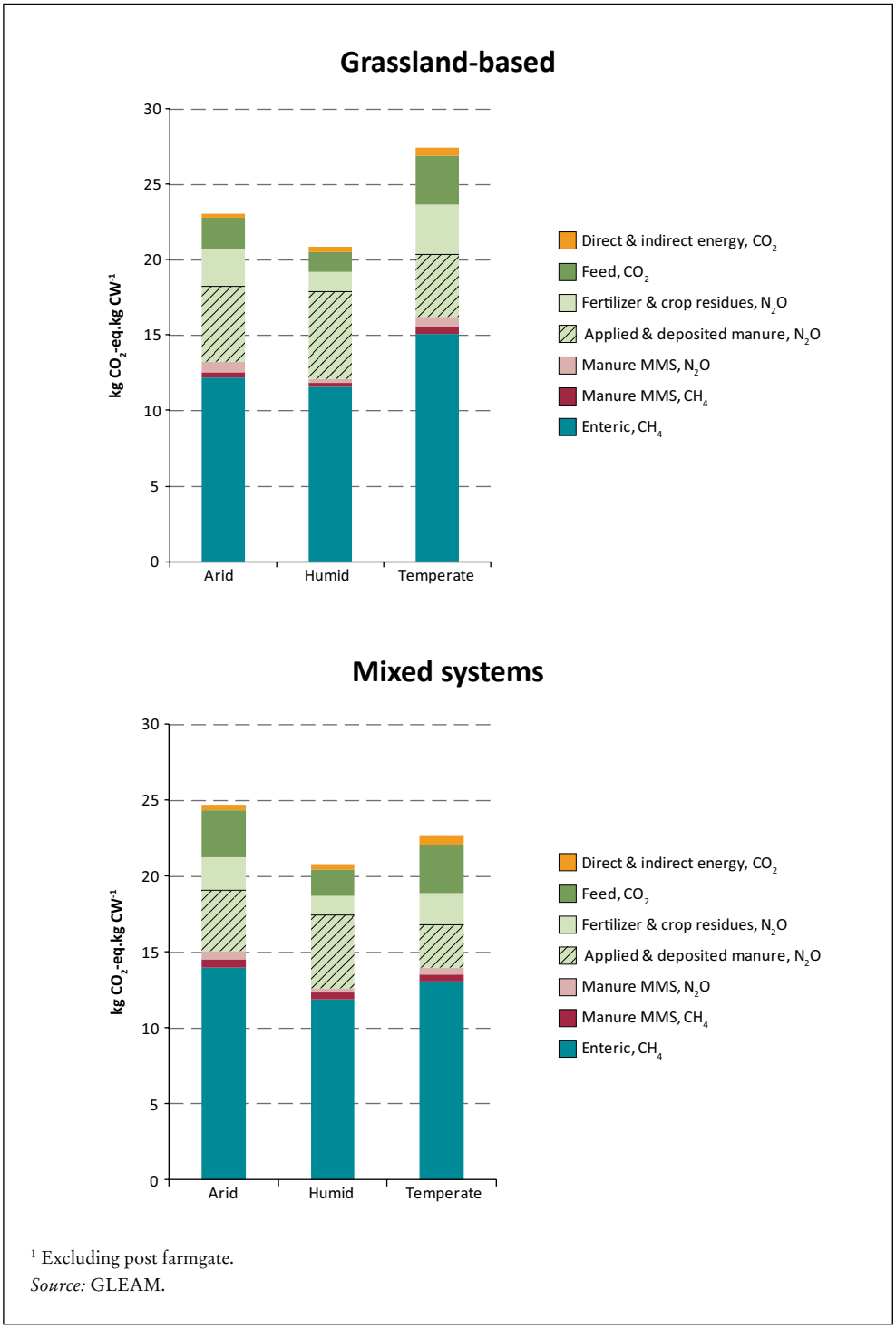
CO_2 emissions related to feed production, transport and processing are important in the temperate areas in both systems, accounting for 12 percent and 19 percent, respectively, and 12 percent and 14 percent, respectively, of the average carbon footprint of small ruminant milk and meat produced in grazing and mixed temperate zones.

Figure 18.
Emission intensities for small ruminant milk by production system and agro-ecological zone[1]



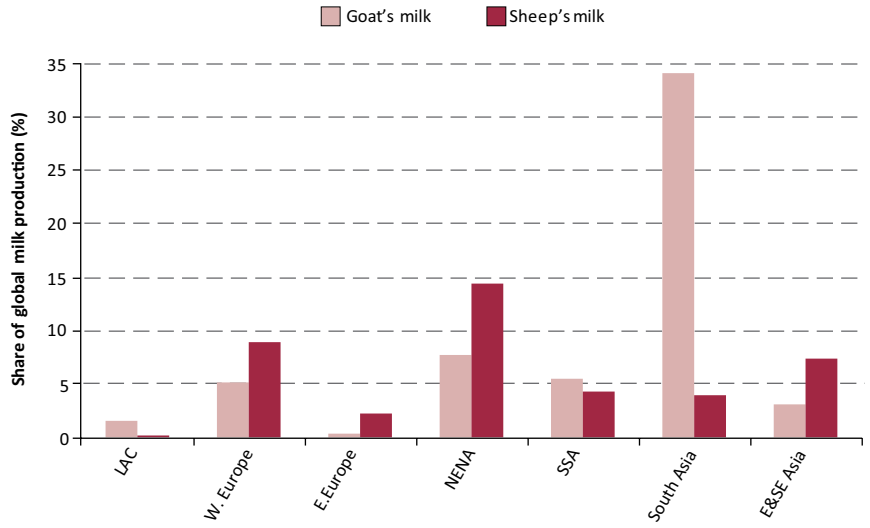
[1] Excluding post farmgate.
Source: GLEAM.

Figure 19.
Emission intensities for small ruminant meat by production system and agro-ecological zone[1]



[1] Excluding post farmgate.
Source: GLEAM.

Figure 20a.
Regional contribution to global small ruminant milk production[1]



[1] Excludes regions where contribution to global production is less than 2 percent.
Source: GLEAM.

4.3.3 Regional production, emissions and emission intensities

The production of small ruminant milk and meat is largely concentrated in developing regions. Figures 20a and 20b illustrate this trend; with the exception of small ruminant milk production in Western Europe and lamb and mutton production in Oceania and Western Europe, small ruminant production is generally more important in developing world regions.

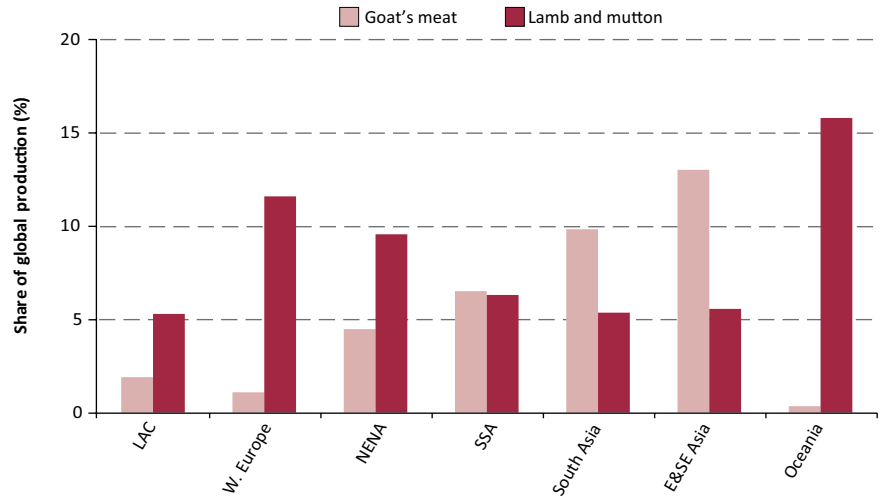
Small ruminants produce not only edible products; other important co-products include natural fibre such as wool, cashmere and mohair. As mentioned in Section 3.6 of this report, we have applied an economic value allocation to partition total GHG emissions between the edible products (meat and milk) and non-edible products (natural fibre). Figure 21 illustrates the impact of allocation to co-products.

Figure 21 illustrates those regions where the natural fibre production is important and has a high economic value compared with edible products, such as North America, Latin America & Caribbean, Oceania, and East & Southeast Asia. In the other regions, natural fibre production is generally not profitable and of low economic value.

At a regional level, emission intensity for small ruminant milk ranges from 4.7 kg CO_2-eq/kg FPCM in Western and Eastern Europe to almost 8.9 kg CO_2-eq/kg FPCM in East & Southeast Asia. Emissions in NENA, sub-Saharan Africa and South Asia are 8.7, 6.9, and 4.9 kg CO_2-eq/kg FPCM, respectively (Figure 22a). Within the developing regions, South Asia has the lowest emissions explained by high milk productivity. Overall, across the regions, goats milk tends to have lower emission intensity mainly because of the higher productivity compared with sheep.

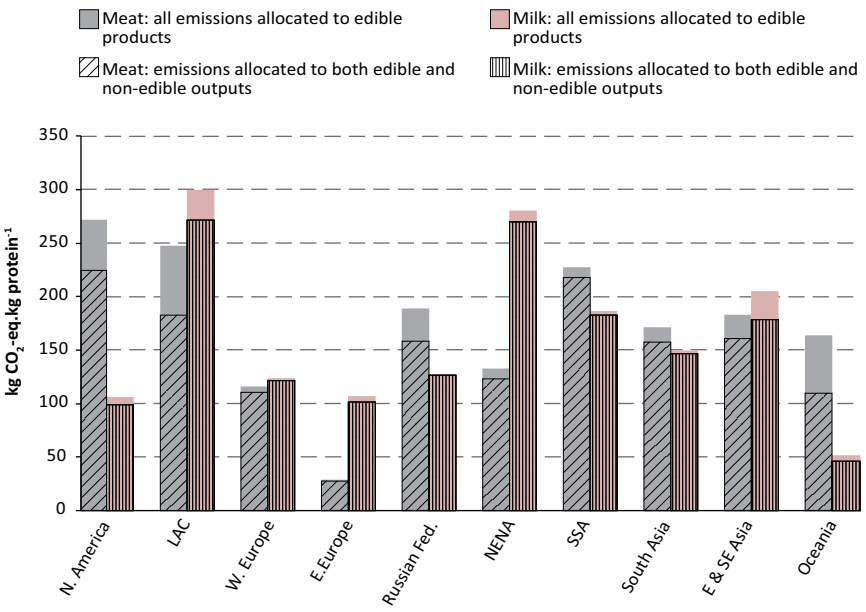
Methane from enteric fermentation is the dominant source of emissions in developing regions, ranging from 60 percent of the GHG emissions profile in South Asia to 69 percent in sub-Saharan Africa. For developing regions, N_2O emission related

Figure 20b.
Regional contribution to global small ruminant meat production[1]



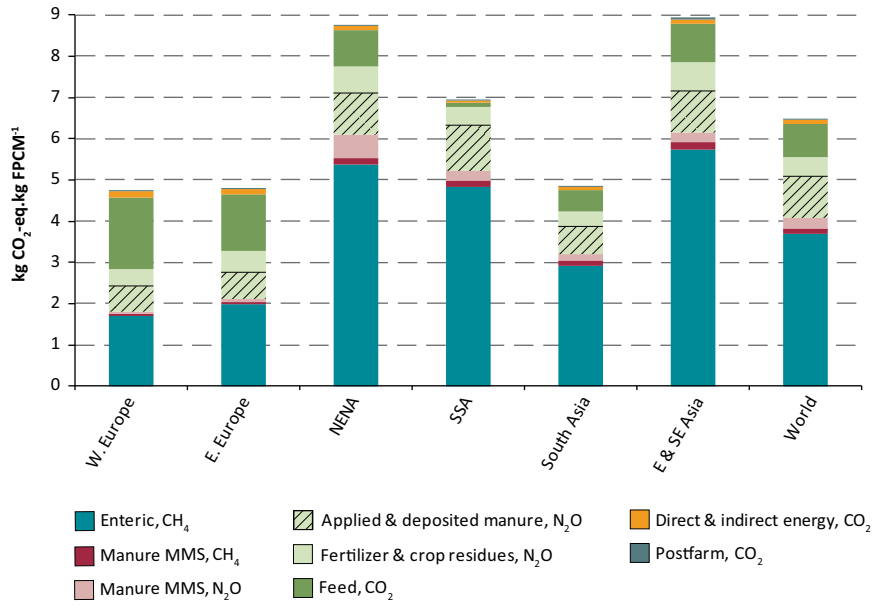
[1] Excludes regions where contribution to global production is less than 2 percent.
Source: GLEAM.

Figure 21.
Emissions per kg meat and milk protein, comparing allocation of emissions to different outputs



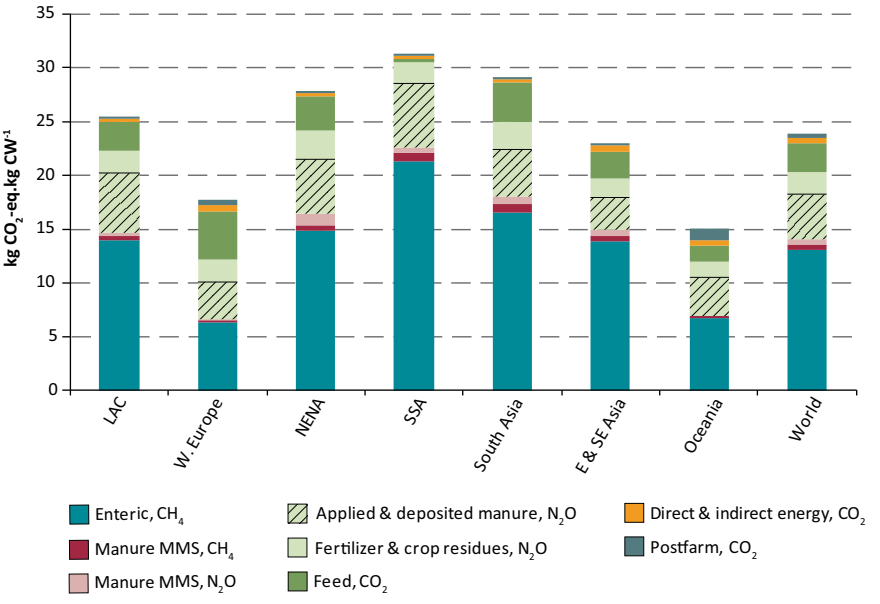
Source: GLEAM.

Figure 22a.
Regional variation in GHG emission intensities for small ruminant milk[1]



[1] Excludes regions where contribution to global production is less than 2 percent.
Source: GLEAM.

Figure 22b.
Regional variation in GHG emission intensities for small ruminant meat[1]



[1] Excludes regions where contribution to global production is less than 2 percent.
Source: GLEAM.

to feed production is a significant source of emissions as a result of the deposition of manure during grazing (see Section 5.3 in Chapter 5). While CH_4 emissions from manure are negligible in most regions because manure is mainly managed in dry systems, in South Asia and East & Southeast Asia, CH_4 emissions from manure are slightly higher as a result of the higher temperatures in warmer climatic zones.

In most regions, N_2O from manure management is also negligible because a large proportion of the manure produced is deposited on pasture and these emissions are captured in feed production (in this analysis, manure deposited on pasture is considered as a fertilizer). However, NENA, sub-Saharan Africa, South Asia and East & Southeast Asia have relatively high N_2O emissions from manure because manure is not only deposited on pasture but also managed in other MMS such as drylot or solid systems which tend to have higher rates of conversion of N excreted to N_2O emissions.

Emissions of meat from small ruminants range from as low as 15 kg CO_2-eq/kg CW in Oceania to 31 kg CO_2-eq/kg CW in sub-Saharan Africa. Very little variation exists within the developing regions; emissions for East & Southeast Asia, Latin America, NENA and South Asia are 23.0, 25.5, 27.9 and 29 kg CO_2-eq/kg CW, respectively (Figure 22b). Contributions of different sources to emission intensity, differences among regions and the underlying reasons are very much the same as described above for milk.

Post farmgate emissions per kg carcass weight in Oceania are significant because of the importance of mutton and lamb exports from Australia and New Zealand. The two countries supply a major portion of global lamb and mutton exports, equivalent to 50 percent and 67 percent of their total production in 2005, respectively.

4.4 SUMMARY OF RESULTS

4.4.1 Comparison between ruminant species

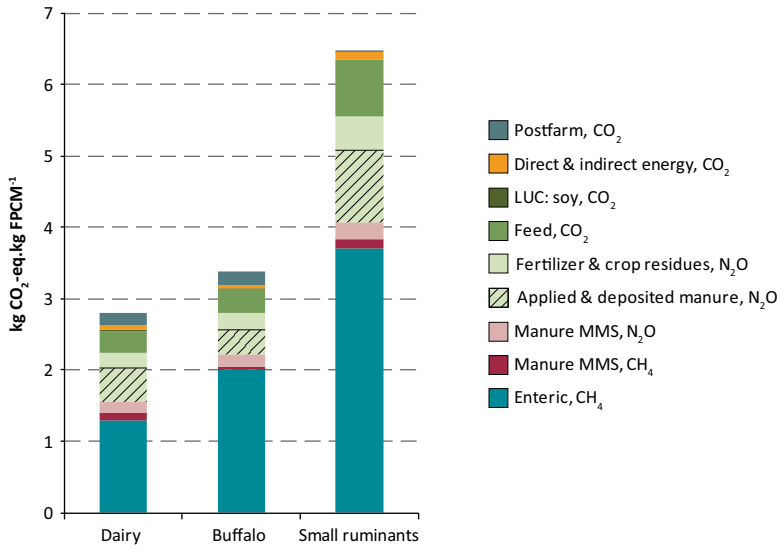
Despite the similarities in emission profiles, there are differences among cattle, buffalo and small ruminant species. The carbon footprint for milk from small ruminants is more than double that of milk from dairy cattle and buffalo: 6.5 kg CO_2-eq/kg FPCM vs. 2.8 and 3.4 kg CO_2-eq/kg FPCM, respectively (Figure 23a). With regard to meat from ruminants, small ruminant meat has a smaller carbon footprint compared with that of beef; 23.8 kg CO_2-eq/kg CW vs. 46.2 and 53.4 kg CO_2-eq/kg CW for beef and buffalo meat, respectively (Figure 23b).

Among the edible commodities produced by ruminant systems, milk generally has the lowest emission intensity compared to meat suggesting that dairy systems are more efficient than pure meat systems. This is because dairy herds produce both milk and meat while beef systems are maintained mainly for calf production.

The difference in emission intensity among ruminant species can be attributed to a number of factors such as:

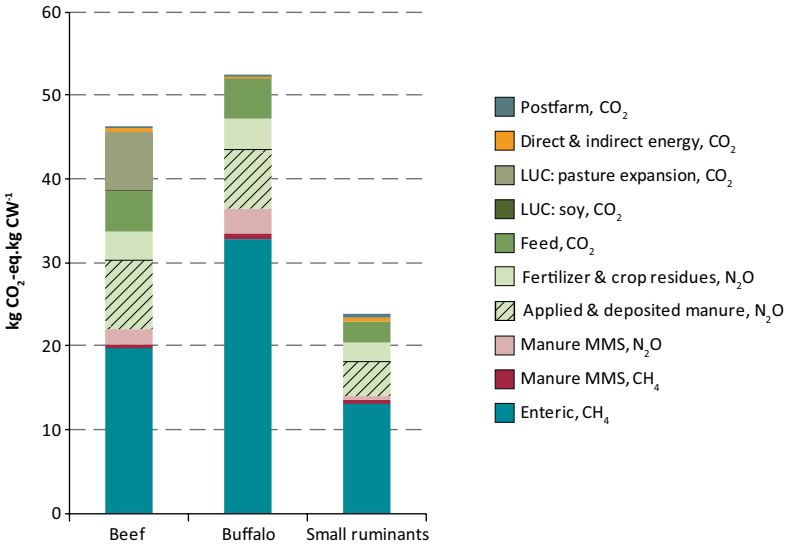
- Higher milk yields from dairy cattle and buffalo as opposed to small ruminants;
- Greater fecundity, and faster reproductive cycles and growth rates in small ruminants;
- Larger supporting breeding herds are required to sustain the production of beef; non-productive animals produce CH_4 and urinary-N without contributing to milk and meat production; and
- Whether LUC is associated with the production process.

Figure 23a.
Average emission intensity for milk from cattle, buffalo and small ruminants



Source: GLEAM.

Figure 23b.
Average emission intensity for meat from cattle, buffalo and small ruminants



Source: GLEAM.

This assessment also found a wide diversity in emission intensity at regional and production system level. These variations are largely driven by differences in production goals (specialized versus non-specialized production) and management practices, including animal husbandry methods, animal health and genetics which influence levels of productivity.

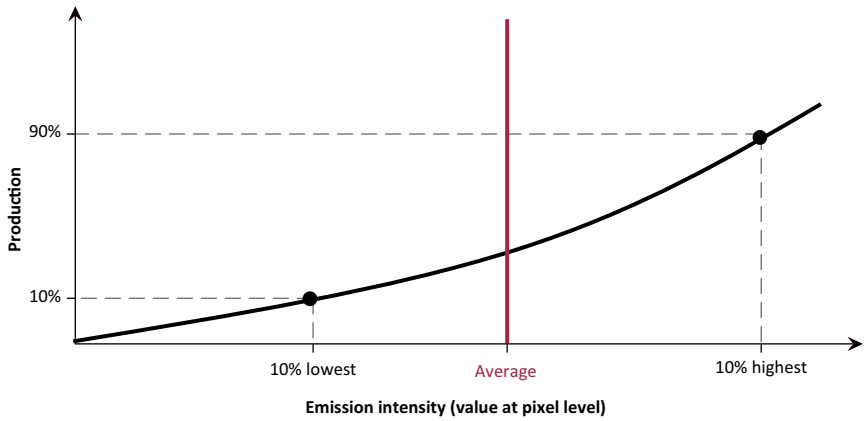
4.4.2 Emission intensity gap within systems, climatic zones and regions

The comparison of emission intensity for ruminant commodities produced within the same region and comparable production conditions (production systems and agro-ecological zones) shows the existence of a considerable emission intensity gap. Average emission intesities within each region for each combination of production system and climatic zone as well as the lowest and highest emission intesity of pixels accounting for 10 percent of the production in the same system-region-AEZ were assessed. Figure 24 is a schematic representation of the analytical approach used to assess the emission intensity gap within regions, production systems and climatic zones.

Tables 7-9 provide an illustration of this variation in emission intensity for cattle (dairy and beef), buffalo milk and small ruminants (milk and meat). The emission intensity gap is particularly substantial in dairy and beef production. For example, in mixed temperate dairy systems in sub-Saharan Africa, the average emission intesity is 7.6 kg CO_2-eq/kg FPCM, compared to 1.6 and 13.3 kg CO_2-eq/kg FPCM in lowest and higher 10 percent, respectively (Table 7).

Within the dairy mixed and grassland-based systems in sub-Saharan Africa, Latin America and the Caribbean, and East and Southeast Asia, the emission intensity of the lowest 10 percent is comparable to other regions with similar production conditions. This is explained by the dominance of high productive countries within these systems and climatic zones. For example, in sub-Saharan Africa, within the dairy mixed and grassland-arid zones, South Africa alone accounts for almost 25 percent

Figure 24.
Schematic representation of emission intensity gap, for a given commodity, within a region, climate zone and farming system



Source: Authors.

Table 7. Variation of cattle emission intensities within regions, systems and agro-ecological zone[1]

	Arid			Temperate			Humid		
	10% lowest	Average	10% highest	10% lowest	Average	10% highest	10% lowest	Average	10% highest
Mixed dairy									
N. America	1.7	1.9	2.0	1.3	1.5	1.7	1.5	1.7	1.9
Russian Fed	1.7	1.8	1.9	1.8	1.9	2.0	1.7	1.8	2.0
W. Europe	1.5	1.6	1.8	1.5	1.6	1.7	1.5	1.7	1.8
E. Europe	1.8	1.8	2.0	1.4	1.6	1.8	1.8	1.9	1.9
NENA	1.9	4.3	9.7	2.6	3.7	5.3	2.3	3.5	9.4
E & SE Asia	2.1	2.7	3.7	1.4	2.3	2.9	1.5	2.6	3.4
Oceania	1.7	1.8	1.9	1.0	1.0	1.8	NA	NA	NA
South Asia	4.0	5.2	6.8	3.4	4.5	6.5	4.1	6.8	8.0
LAC	1.4	3.1	4.9	1.4	3.0	5.0	1.7	4.0	5.4
SSA	1.7	10.0	17.2	1.7	7.6	13.3	5.5	9.7	17.3
Grassland dairy									
N. America	1.7	1.9	1.9	1.3	1.7	1.8	1.7	1.9	2.0
Russian Fed	1.7	1.8	1.8	1.8	1.9	2.0	NA	NA	NA
W. Europe	1.5	1.6	1.8	1.5	1.7	1.8	1.7	1.7	1.9
E. Europe	1.7	1.9	2.0	1.5	1.6	1.7	NA	NA	NA
NENA	1.4	5.9	10.6	2.7	3.2	4.1	10.0	10.1	10.2
E & SE Asia	1.6	1.8	2.0	1.6	2.5	7.3	2.4	7.7	10.1
Oceania	1.7	1.8	1.9	1.5	1.5	1.5	1.5	1.6	1.8
South Asia	2.9	3.8	5.2	2.7	4.1	5.5	3.8	4.1	4.2
LAC	1.7	3.1	6.0	1.8	3.6	5.5	2.2	4.8	6.3
SSA	1.8	9.6	16.6	1.7	3.1	5.6	6.3	10.8	18.9
Mixed beef									
N. America	28.4	32.0	36.1	26.0	28.5	30.3	26.9	28.6	30.5
W. Europe	13.6	19.9	23.0	12.9	17.3	21.9	20.2	24.1	25.7
E. Europe	11.1	12.0	12.7	12.3	13.9	16.3	11.2	11.9	12.6
NENA	17.5	28.4	35.7	16.7	20.4	25.5	18.1	24.4	34.0
E & SE Asia	36.9	46.9	61.3	33.1	43.0	54.0	40.1	54.5	81.0
Oceania	29.1	31.1	33.8	11.7	20.5	31.6	11.0	18.9	31.9
South Asia	25.3	73.0	110.5	20.4	46.8	77.6	58.8	103.0	168.1
LAC	36.5	42.9	48.5	37.4	46.6	59.0	38.2	46.8	53.9
SSA	44.2	75.0	106.6	27.4	56.0	73.0	32.9	59.7	95.3
Grassland beef									
N. America	24.2	31.2	36.6	27.4	29.9	32.9	27.7	28.7	30.1
W. Europe	14.1	20.4	23.0	18.7	21.7	24.7	23.9	23.9	25.6
E. Europe	11.6	12.4	13.2	12.0	12.9	14.6	NA	NA	NA
NENA	19.5	36.6	38.5	15.9	18.6	21.5	35.0	35.3	35.6
E & SE Asia	47.3	55.0	66.7	26.4	47.5	57.5	53.3	62.4	70.1
Oceania	28.9	30.5	33.2	10.3	17.4	29.4	11.2	25.2	31.9
South Asia	22.6	31.6	33.6	21.3	26.9	26.5	71.4	76.9	80.6
LAC	42.8	48.9	57.2	40.8	52.4	72.7	43.8	53.9	64.9
SSA	41.1	76.9	102.6	38.3	43.2	58.8	49.9	93.4	118.8

[1] Regions representing less than 2% of global production within systems are not included.
Note: The 'average' is calculated at regional-climatic zone level. "10% lowest" is the upper bound of lowest emission intensities up to 10% of production.
"10% highest" is the lower bound of highest emission intensities down to 90% of production.
NA: Not Applicable. Some regions may not have data for a combination of system and AEZ or production is insignificant within the system and AEZ.
Source: GLEAM.

Table 8. Variation of buffalo milk emission intensities within regions, systems and agro-ecological zone[1]

	Arid			Temperate			Humid		
	10% lowest	Average	10% highest	10% lowest	Average	10% highest	10% lowest	Average	10% highest
Mixed dairy									
NENA	2.8	3.4	4.8	2.8	3.6	4.3	3.3	3.3	4.0
E & SE Asia	2.6	4.0	5.8	3.7	5.2	6.6	4.2	5.2	6.2
South Asia	2.7	3.3	4.1	2.4	3.0	4.2	2.6	3.5	4.5
Grassland dairy									
NENA	2.7	4.3	5.0	3.5	3.6	3.8	NA	NA	NA
E & SE Asia	2.6	2.7	2.8	2.5	3.0	4.0	3.0	3.3	3.5
South Asia	2.7	3.0	3.3	2.4	2.7	2.9	2.5	2.7	2.8

[1] Regions representing less than 2% of global production within systems are not included.
Note: The 'average' is calculated at regional-climatic zone level. "10% lowest" is the upper bound of lowest emission intensities up to 10% of production. "10% highest" is the lower bound of highest emission intensities down to 90% of production.
NA: Not Applicable. Some regions may not have data for a combination of system and AEZ or production is insignificant within the system and AEZ.
Source: GLEAM.

of production in this regional-system-climatic zone with emission intensity ranging between 1.4 and 1.8 kg CO_2-eq/kg FPCM. Similarly, in mixed and grassland-based systems in temperate zones, South Africa contributes 20 and 70 percent of the regional production, respectively, with emission intensity ranging between 1.5 and 1.9 kg CO_2-eq/kg FPCM.

In Latin America and the Caribbean, milk production in Mexico in both grassland and mixed arid and temperate areas represents 30 percent of the production within these regional climatic zones and emission intensity ranges between 1.4 and 1.9 kg CO_2-eq/kg FPCM.

High milk productivity systems in countries such as Israel and Saudi Arabia within the arid zones result in low emission intensity (range between 1.2-1.5 kg CO_2-eq/kg FPCM for Israel and 1.1-2.0 kg CO_2-eq/kg FPCM for Saudi Arabia). About 23 percent of production within the mixed temperate dairy system in East and Southeast Asia occurs in Japan with a range of emission intensity 1.2 to 1.4 kg CO_2-eq/kg FPCM.

This variation highlights the heterogeneity within each production system and emphasizes the opportunities for reducing emission intensity particularly in low productive regions by bridging the gap in emission intensities between efficient producers and producers with a potential for improvement. This mitigation potential doesn't require changes in farming systems and can be based on already existing technologies and practices. It is estimated to 30% of the sector's total emissions and further explored in the overview report published in parallel to the current one (FAO, 2013a). This situation is completed by case study analysis to explore regional dimensions of mitigation in the sector.

Table 9. Variation of small ruminants emissions intensities within regions, system and agro-ecological zone[1]

	Arid			Temperate			Humid		
	10% lowest	Average	10% highest	10% lowest	Average	10% highest	10% lowest	Average	10% highest
Grassland dairy									
W. Europe	2.8	4.9	6.4	2.5	5.1	6.5	1.6	2.9	4.4
E. Europe	4.2	4.7	5.1	2.6	3.6	5.0	NA	NA	NA
NENA	5.7	11.2	14.2	4.1	5.4	6.6	8.0	9.5	10.7
E & SE Asia	6.3	6.9	7.9	9.0	11.3	13.5	3.4	5.7	11.8
South Asia	3.3	6.0	8.1	3.8	6.5	8.8	2.5	2.6	2.7
LAC	3.0	8.0	11.7	3.2	8.1	11.6	3.2	9.6	11.4
SSA	5.1	6.6	9.4	6.1	7.0	8.3	7.2	8.7	10.6
Mixed dairy									
W. Europe	3.1	4.7	6.4	2.3	4.7	7.6	3.5	5.3	8.4
E. Europe	4.5	4.8	5.2	2.9	4.4	5.2	4.3	4.9	5.2
NENA	4.6	9.3	13.1	3.6	5.9	7.9	3.7	7.8	9.8
E & SE Asia	3.0	5.6	7.5	5.4	9.3	11.4	6.0	7.5	9.8
South Asia	2.9	4.2	6.3	3.0	5.1	7.7	3.0	5.9	7.9
LAC	2.7	5.9	10.2	2.9	4.8	10.4	1.9	5.5	11.1
SSA	5.3	7.4	10.2	6.5	7.5	8.6	5.7	7.3	8.9
Grassland meat									
W. Europe	7.8	12.7	20.2	9.6	20.4	23.8	19.2	19.9	21.5
NENA	11.4	24.7	42.2	18.2	42.9	57.5	15.3	16.1	16.8
E & SE Asia	19.1	24.6	32.0	18.3	25.8	32.4	9.4	13.2	19.0
Oceania	13.4	14.9	16.7	13.2	14.1	14.5	14.0	14.7	15.3
South Asia	9.3	26.7	35.4	8.5	16.6	24.5	20.8	22.1	23.7
LAC	18.6	24.6	29.9	17.4	29.0	38.5	18.3	24.9	33.8
SSA	16.8	26.2	37.4	20.3	22.4	30.0	21.7	33.8	46.3
Mixed meat									
W. Europe	7.4	15.2	21.6	9.7	18.8	22.6	18.0	25.4	26.7
NENA	12.9	23.4	41.1	14.8	32.6	51.7	14.3	16.1	17.9
E & SE Asia	13.9	20.4	29.9	18.0	22.2	26.5	9.3	15.5	23.7
Oceania	13.4	14.3	15.6	13.6	13.9	15.0	13.9	14.6	15.2
South Asia	17.2	32.8	44.5	9.9	29.5	45.8	14.7	20.0	35.5
LAC	17.2	22.7	27.5	22.1	30.4	38.5	16.4	23.5	30.4
SSA	18.0	34.0	49.7	19.3	28.2	34.7	25.4	35.6	43.3

[1] Regions representing less than 2% of global production within systems are not included.
Note: The 'average' is calculated at regional-climatic zone level. "10% lowest" is the upper bound of lowest emission intensities up to 10% of production. "10% highest" is the lower bound of highest emission intensities down to 90% of production.
NA: Not Applicable. Some regions may not have data for a combination of system and AEZ or production is insignificant within the system and AEZ.
Source: GLEAM.

5. Discussion

This section discusses the key drivers of variation in emissions from major processes in the ruminant supply chain that contribute significantly to the carbon footprint of ruminant species, highlighting differences among species and world regions. The section also discusses some of the parameters and assumptions that could strongly influence the results.

5.1 METHANE EMISSIONS FROM ENTERIC FERMENTATION

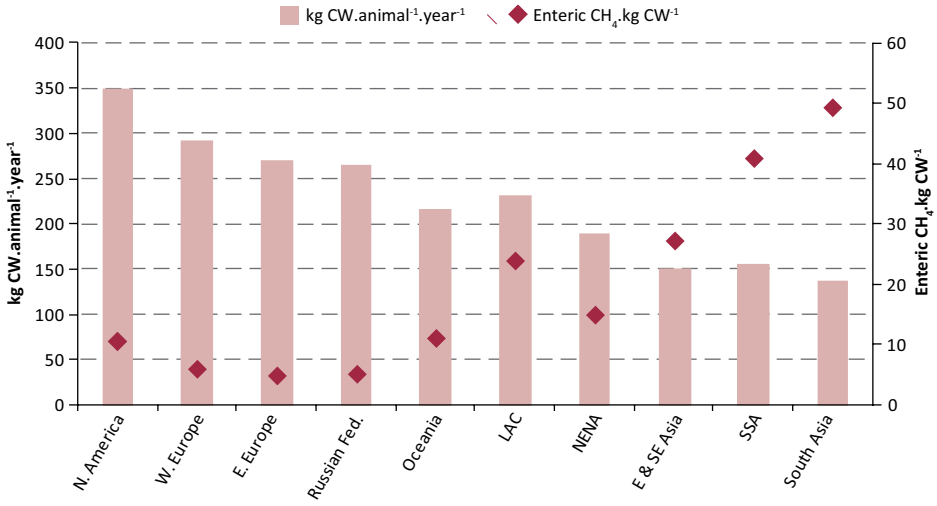
Regardless of the species, the largest source of GHG emissions in ruminant production is CH_4, with more than 90 percent originating from enteric fermentation and the rest from manure. Globally, enteric fermentation from cattle, buffalo, and small ruminants contributes 2 448 million tonnes CO_2-eq, of which 76 percent is emitted by cattle and 14 percent and 10 percent by buffalo and small ruminants, respectively. The production of enteric CH_4 from ruminants is mainly affected by feed intake and feed quality which, in turn, defines the total energy and nutrient intake and consequently animal performance.

Many of these factors are interrelated, some of which affect net emissions and others emission intensity. At animal level, net emissions are influenced by feed intake and digestibility, while emission intensity is a function of net emissions, yield per animal, health and genetics. At herd level, factors affecting net emissions are similar to those cited above, while emission intensity is determined by issues such as reproductive and mortality rates, herd structure, management, etc. The following sections discuss some of the important factors that drive the variation in enteric CH_4.

Productivity. Productivity is an important factor in explaining the variation of emissions among different production typologies. Studies show a close correlation between carbon footprint and yield per animal (Capper *et al.*, 2008; Gerber *et al.*, 2011; Cederberg and Flysjo, 2004), highlighting the trend of decreasing emission intensity with increasing productivity. Regions and production systems with greater productivity have lower emission intensity partly because high yields shift the distribution of feed towards less feed for maintenance functions and more for production. As productivity per animal increases, CH_4 emissions per animal are typically higher because of higher feed intake. However, as the productivity of each animal increases, the farmer can reduce the herd size to produce the same amount of output.

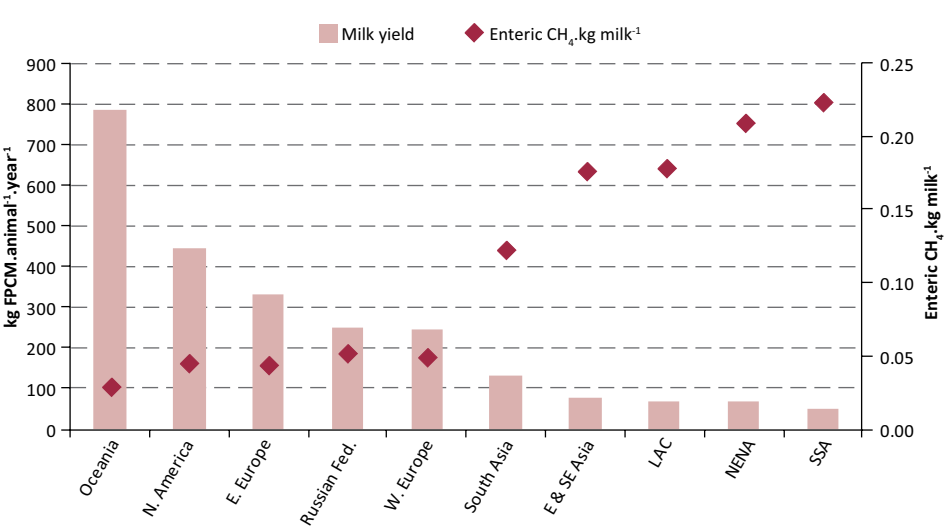
Figure 25a illustrates the differences in emission efficiency among the regions; the main reason for the differences is to be found in low productivity of the herd, which is in turn caused by low fertility, high mortality rates, low growth rates and low feed digestibility (see Appendix B). Gerber *et al.* (2011) have demonstrated the relationship between the carbon footprint of dairy cattle milk and productivity, and a similar trend has been established for small ruminants (Figure 25b). Lower-producing dairy animals tend to lose more feed energy as CH_4 per unit of milk produced. The benefits of improving animal productivity on CH_4 emissions results from the *dilution effect* of fixed maintenance where increasing productivity

Figure 25a.
Regional variation in productivity and CH_4 emissions from enteric fermentation for beef herds



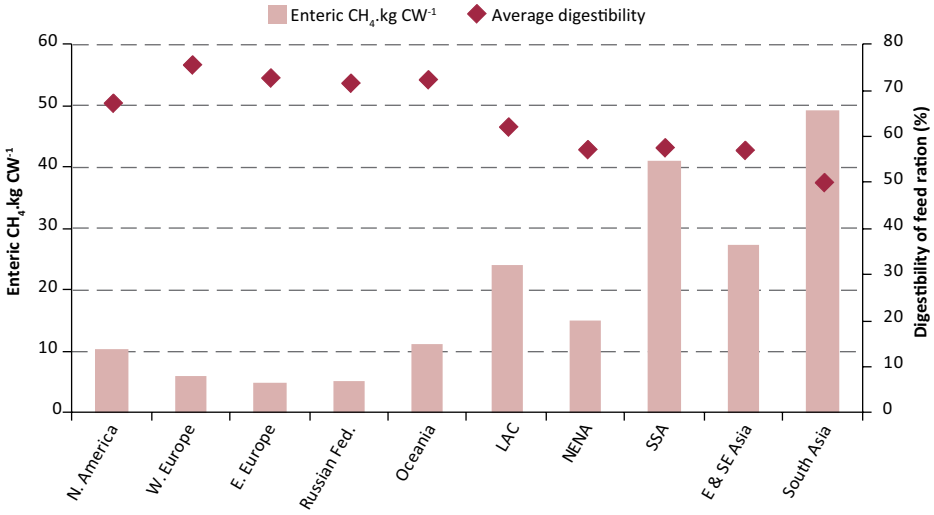
Source: GLEAM.

Figure 25b.
Regional variation in productivity and CH_4 emissions from enteric fermentation for dairy goats



Source: GLEAM.

Figure 26.
Regional variation in digestibility of the feed ration and CH_4 emissions from enteric fermentation for beef cattle



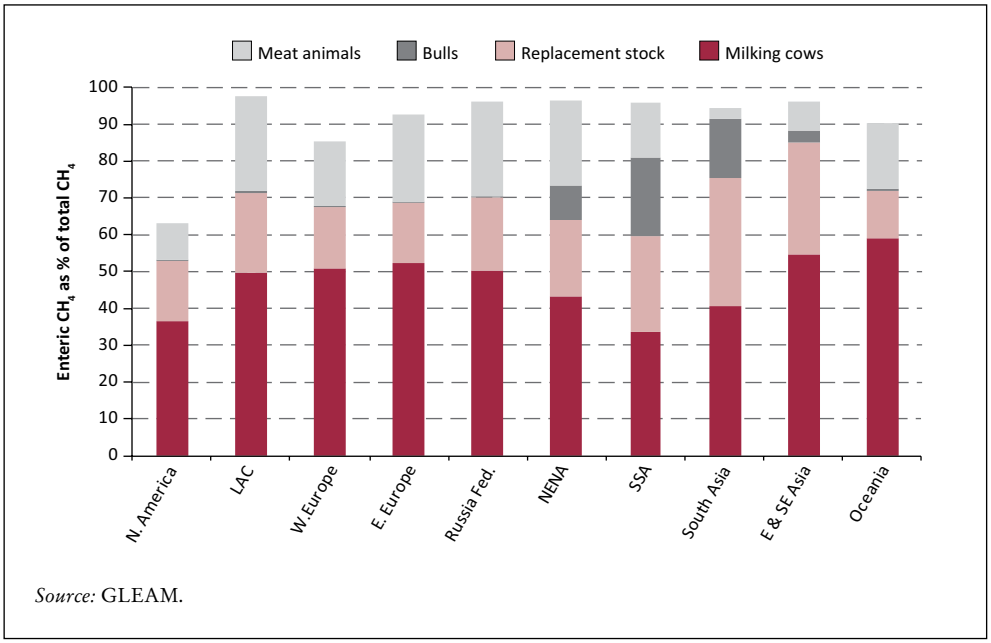
Source: GLEAM.

decreases the amount of CH_4 emitted per unit of product because emissions that arise from energy requirements for maintenance are spread over a larger output.

Feed digestibility. Enteric CH_4 emissions are also determined by feed properties, particularly the digestibility of the feed ration. The energy content of feed also affects the amount of CH_4 produced in enteric fermentation, with lower quality of feed causing greater CH_4 emissions (Figure 26). Regions with higher feed digestibility also often have higher proportion of high quality roughages, feed crops and concentrates in their diets, often an indication of higher quality ration (see Tables B7-B12 in Appendix B). As the digestibility of the feed ration increases, the amount of energy available to the animal also increases per kg of feed intake. With an increase in per kg of feed intake, more production can be realized and therefore CH_4 produced per kg of production decreases.

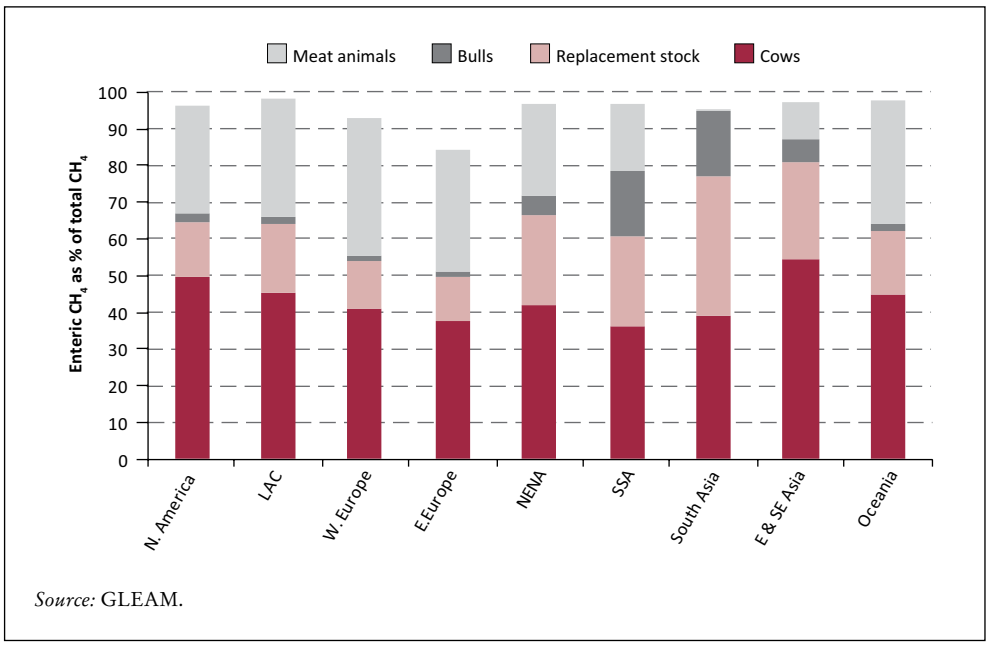
Herd structure. A key factor that explains the variations in emissions across regions is the structure of the herd. Breeding populations are required to maintain the herd and thus reproductive performance is important because the cost of maintaining and replacing breeding stock also affects feed efficiency. In regions where the composition of the herd is skewed towards higher number of animals in the breeding herd, overall CH_4 emissions and emission intensities are most likely high because demand is placed on feed (with a large share of feed energy used for maintenance requirements rather than production). Figures 27a and 27b present the percentage contribution of enteric fermentation to total CH_4 from beef and dairy cattle by cohort groups. A breakdown of enteric CH_4 emissions by source not only illus-

Figure 27a.
Regional variation in the relative contribution of animal cohorts to enteric CH_4 – dairy herds



Source: GLEAM.

Figure 27b.
Regional variation in the relative contribution of animal cohorts to enteric CH_4 – beef herds



Source: GLEAM.

trates the key hotspots of CH_4 emissions but also explains the variation in emission intensity among regions.

Figure 27a illustrates regional differences in dairy herd structure. Non-milk producing animals in dairy herds typically include replacement animals and adult bulls; these categories of animals are significant contributors to the CH_4 costs of producing milk at the herd level. While CH_4 from enteric fermentation is the main contributor to GHG emissions in all regions, there are major differences in the sources of emissions. Generally, in regions such as sub-Saharan Africa and South Asia, a large proportion of enteric CH_4 (approximately 50 percent) originates from the breeding herd and replacement stock, in combination with a low milk production per cow; hence a large proportion of the resources are used for other purposes such as maintenance and draught power. In these regions, non-milk productive functions contribute substantially to the maintenance energy requirement of the herd because they represent a significant use of energy and resources with no production of usable edible product produced.

In contrast, in Western and Eastern Europe, Oceania, Russian Federation, and East & Southeast Asia, more than 50 percent of the enteric CH_4 is from milking cows, pointing to increased use of feed for productivity purposes and thus explaining the lower emission intensity in these regions.

In typical beef systems, mature cows are kept for only calf production and have to be maintained along with bulls and replacement stock, which increases emissions per unit of carcass produced. The breeding stock in beef production systems (cows, replacement stock and bulls) accounts for 55-99 percent of the total feed requirements of the beef herd, and 52-97 percent of total CH_4 emissions. A higher slaughter generation (meat animals for fattening) is an indication of higher reproductive performance of the breeding herd and specialization of production such as in Oceania, Europe, North America and Latin America.

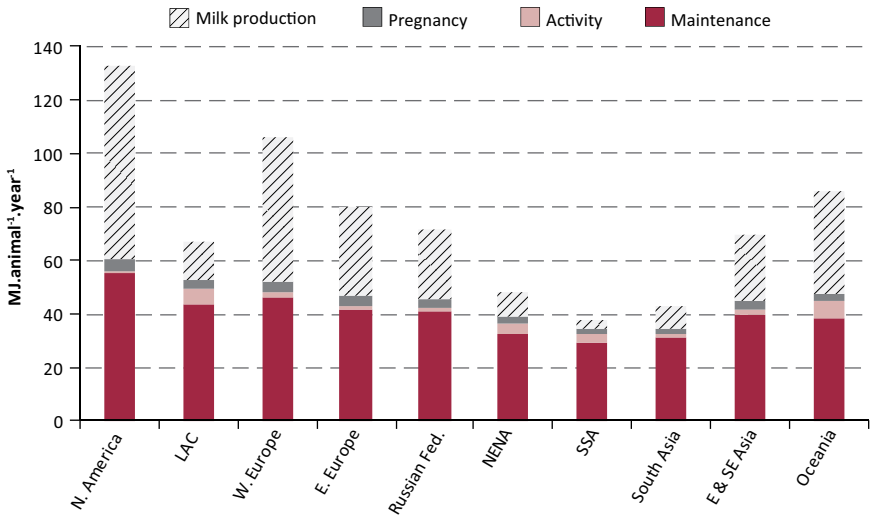
For small ruminants, there is no systematic difference in herd structure among regions, largely attributable to the greater fecundity in small ruminants and faster growth rates compared with cattle. The absence of draught power also reduces the gap among regions.

Energy partitioning and utilization. Methane is produced in the process of feed energy utilization within the animal. Changes in the efficiency of feed energy utilization therefore influence CH_4 emissions of animals. The efficiency of feed energy utilization depends on the type of animal, the type or quality and quantity of feed, environmental conditions, etc.

The way energy is partitioned between the different body functions (maintenance and production) also helps explain the variation in emission intensity. All animals have a necessary maintenance requirement that must be met and results in no production, yet are still associated with CH_4 losses. Ruminants partition feed energy over the following functions: maintenance, growth, lactation and reproduction; and in all cases, maintenance has priority. In situations where feed quality is low, relatively less energy is left for (re)productive functions.

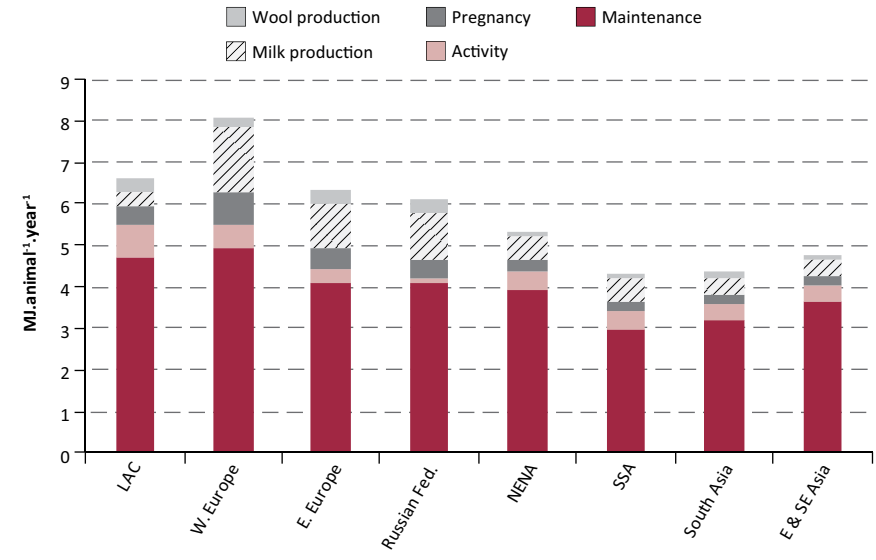
The proportion of feed energy expended on animal maintenance as opposed to productive purposes is higher in those regions with low production rates at both animal (Figures 28a, 28b and 28c) and herd (Figures 29a and 29b) level. Figures 28a, 28b and 28c present the partitioning of energy requirements across the world regions for

Figure 28a.
Regional comparison of energy partitioning across the different functions in milking cows



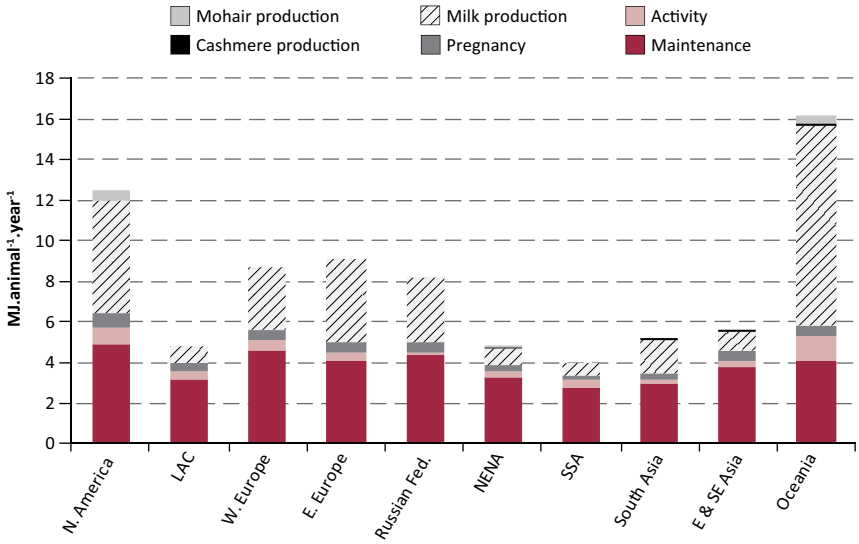
Source: GLEAM.

Figure 28b.
Regional comparison of energy partitioning across the different functions in milking ewes



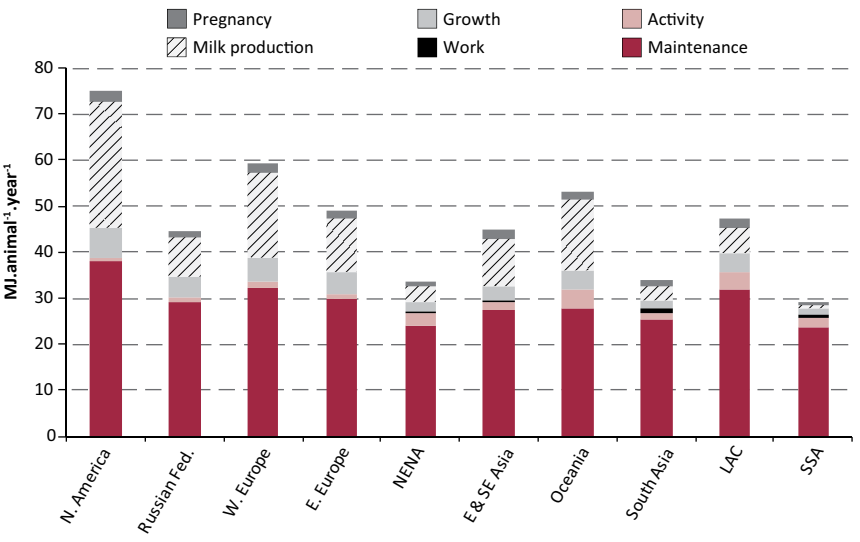
Source: GLEAM.

Figure 28c.
Regional comparison of energy partitioning across the different functions in adult female goats



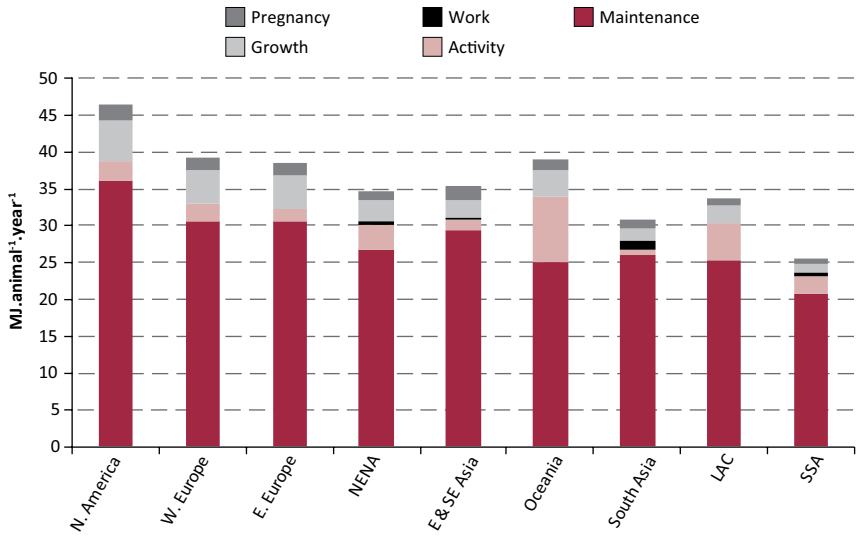
Source: GLEAM.

Figure 29a.
Regional comparison of energy partitioning across the different functions in dairy cattle herds



Source: GLEAM.

Figure 29b.
Regional comparison of energy partitioning across the different functions in beef cattle herds



Source: GLEAM.

milk production from cattle and small ruminants. For example, in dairy cattle in sub-Saharan Africa, NENA, South Asia and Latin America & Caribbean, energy intake is low and, as a consequence, a large proportion of energy is used for maintenance (78 percent, 67 percent, 72 percent and 67 percent, respectively) while in industrialized regions a greater share is used for lactation as illustrated in Figure 28a.

Key assumptions and uncertainties. Given that enteric CH_4 is the single largest contributor to GHG emissions in ruminant production, the method and EFs used for calculating CH_4 from enteric fermentation are fundamental for assessing the carbon footprint of ruminant species. Enteric CH_4 emissions were calculated on the basis of the IPCC Tier 2 approach (IPCC, 2006 Volume 4, Chapter 10), where CH_4 emissions are estimated for different animal categories in the herd as a direct function of gross energy requirements and the CH_4 conversion rate (see Appendix A).

Uncertainties in Tier 2 estimates may be associated with population data, production practices and performance data, including feeding strategy. The use of Tier 2 methodology requires a detailed characterization of the livestock population. Uncertainty in livestock population depends on the extent and reliability of livestock population data. In addition, different accounting conventions for animals, particularly for those that do not live for a whole year such as small ruminants, also add to the uncertainty. Furthermore, total animal numbers are often reported as single values and composition of the different cohorts in herds is not reported separately, making it difficult to characterize these populations.

To overcome this problem in this study, the population was modelled on the basis of a number of herd parameters (see Tables B2-B6 in Appendix B) obtained through

data collection and literature reviews. In addition, there is a scarcity of published data on production practices, dietary information, dry matter intake (DMI) and animal performance, which may contribute to the uncertainty of model prediction. While the feed rations used in this assessment represent the general diet characteristics within each region/country, there may be some uncertainty associated with local variation in feed as well as management practices which may also affect the ultimate energy requirements of the animal and consequently CH_4 emissions.

5.2 EMISSIONS FROM FEED PRODUCTION

Feed production constitutes 36 percent, 36 percent and 28 percent of the total emissions for cattle, small ruminants and buffalo, respectively. Emissions related to feed are a function of several factors:

- *Feed ration* (i.e. specific feed materials in the ration). Feed materials have different emission intensities because they are produced in different modes. Generally, rations with higher proportions of by-products and concentrates tend to have higher emission intensities. The regional average feed composition for ruminant species is presented in Appendix B.
- *Mode of feed production:* whether feed production utilizes additional production inputs such as fertilizers, pesticides, etc.
- *Source of feed materials:* reliance on off-farm produced feed or imported feed also has an impact on the emission intensity of the feed-crop.
- *Feed associated with LUC adds additional emissions* (see Appendix C on land use and LUC).

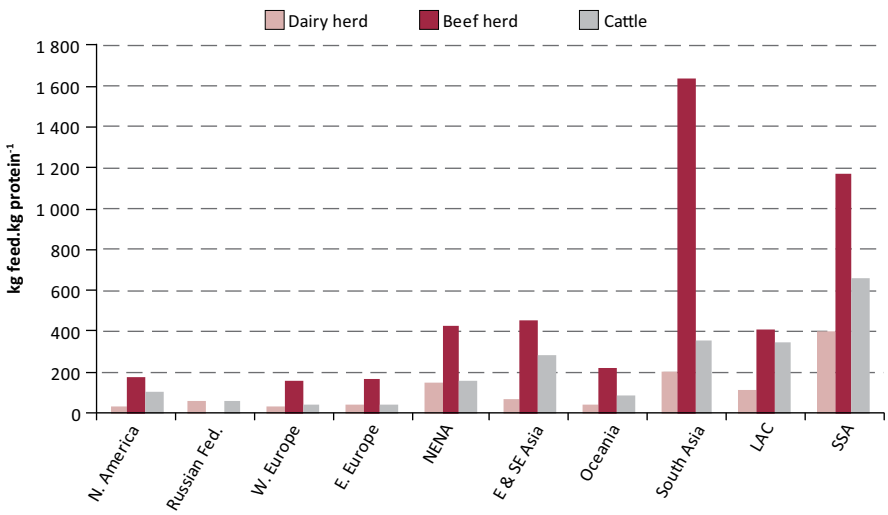
Feed conversion is a measure of the efficiency with which animals convert feed into a gain in body weight or usable product. There are large differences in feed conversions among the various species. The feed conversion of ruminants is usually much lower than that of non-ruminants. High feed consumption per kilogram of protein is partly due to the biological time-lag that it takes for an animal to reach slaughter weight or to calve, and partly due to the amount of feed required by the breeding stock. For example, a suckler cow gives birth to one calf per year. This calf needs between one to four years to reach slaughter weight, depending on production conditions.

Feed conversion also varies among regions for the following reasons:

- animals need a certain amount of feed as their maintenance energy requirement;
- the proportion of breeding stock in the herd – these animals also need to be fed even though they are unproductive;
- regions that rely on dairy herds for their meat supply have a higher feed conversion ratio (FCR) because they produce two products; and
- the characteristics of the production system are also important; aspects such as mortality rates (when animals die or are culled before they reach slaughter weight or first lactation represents significant loss of feed resources), growth rates, age at first calving (lower age at first calving reduces feed requirements during the growth period), etc. influence feed requirements.

Figure 30 compares feed utilization efficiency for dairy and beef herds by region expressed as DMI per unit of protein produced. Increased animal performance due to improved genetics, nutrition and management results in improved feed use efficiency. This improvement is largely a function of dilution of the growing animal's

Figure 30.
Regional variation in feed conversion ratio for the cattle sector



Source: GLEAM.

maintenance requirements in respect to their total feed requirements. A higher proportion of feed is used for growth and production while a lower proportion for maintenance.

In cattle production, emissions of N_2O are the predominant emissions in feed production in all regions (Figure 31a). This trend is similar for small ruminants, with the exception of North America and Western Europe where both N_2O and CO_2 emissions contribute equal shares of emissions, while in Eastern Europe CO_2 emissions per kg of feed intake are higher (Figure 31b). In cattle production, South Asia has the lowest emission intensity per kg of DMI, a consequence of the large proportion of crop residues used as feed material which make up more than 60 percent of the feed ration (see Tables B7 and B8, Appendix B).

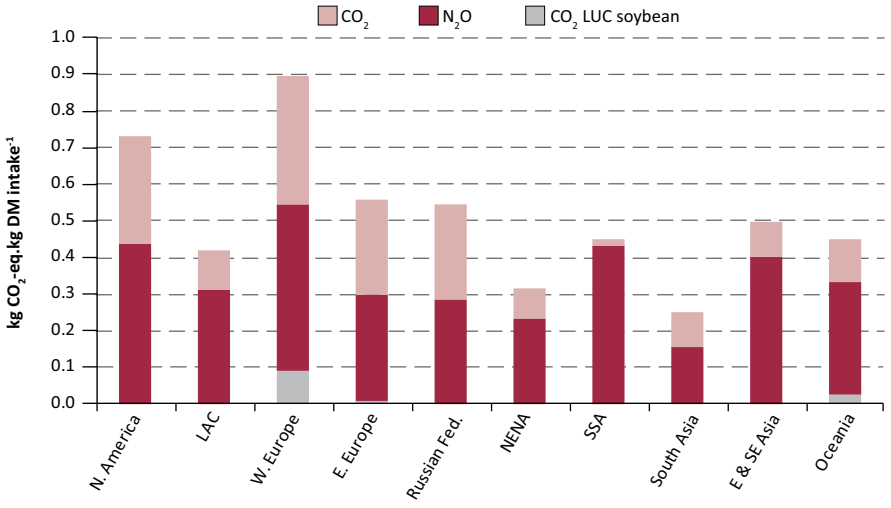
5.2.1 Nitrous oxide from feed production

Nitrous oxide emissions associated with feed production are related to the use of N fertilizer in feed production, N_2O arising from the deposition of manure on grazing land, N from crop residues returned to soils, and N_2O emissions from the application of manure to land.

Manure is an important source of N_2O emissions, and in ruminant production systems manure N_2O emissions from feed production result from manure deposited directly by animals on pasture as well as the manure applied to crops. In the latter case, manure applied to land comprises of all manure that is handled in MMS and includes manure from other species.

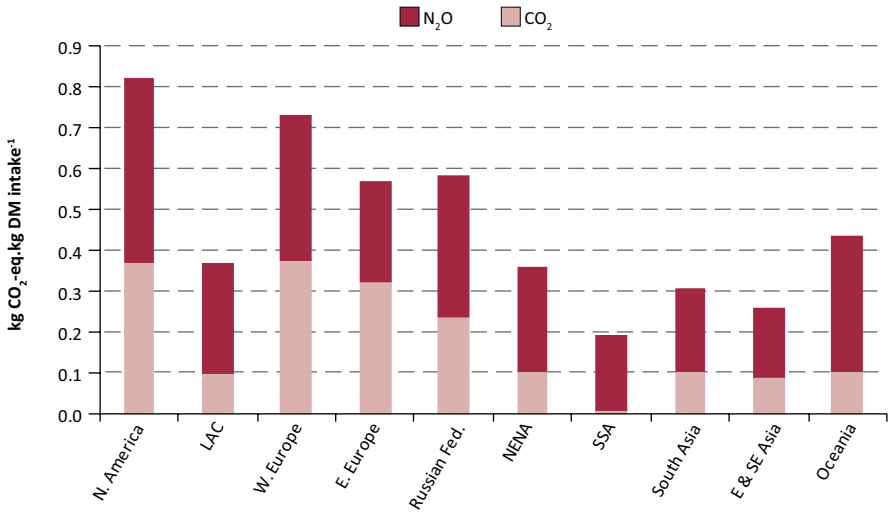
N_2O emissions may arise directly as a result of application of the N sources mentioned above. In addition to the direct emissions, N inputs may also lead to indirect formation of N_2O after leaching or following gaseous losses and deposition of ammonia and nitric oxides. In ruminant production, the main source of N_2O

Figure 31a.
Regional difference in N_2O and CO_2 emission intensity of feed – cattle



Source: GLEAM.

Figure 31b.
Regional difference in N_2O and CO_2 emission intensity of feed – small ruminants



Source: GLEAM.

emissions is manure, with most of the N_2O losses originating from manure that has been deposited or applied.

Figures 32a and 32b present emission intensities for feed for cattle and small ruminants illustrated by region and source of N. In all developing regions, as well as in Oceania and Western Europe, the predominant source of N_2O emissions associated with both cattle and small ruminant species is manure deposited during grazing and applied manure. On the contrary, N_2O emissions from fertilizer application (N fertilizer) are important in North America and to a lesser extent in Europe.

The composition of the feed ration is a key factor in explaining the variation in N_2O emissions because of the vast differences in feed production (see Tables B7-B12, Appendix B, for detailed feed basket composition). For example, in regions where fresh grass is the dominant source of feed, N inputs within the system are more likely to come from manure. However, in intensive grazing systems, N_2O emissions are also likely to be important due to the use of N chemical fertilizer to maintain the productivity of pastures. High N_2O emissions from grazing in regions such as Latin America and the Caribbean and sub-Saharan Africa are mainly a consequence of the importance of pasture as a source of feed. For small ruminants, N_2O emissions from grazing are concentrated in Oceania, sub-Saharan Africa and Latin America.

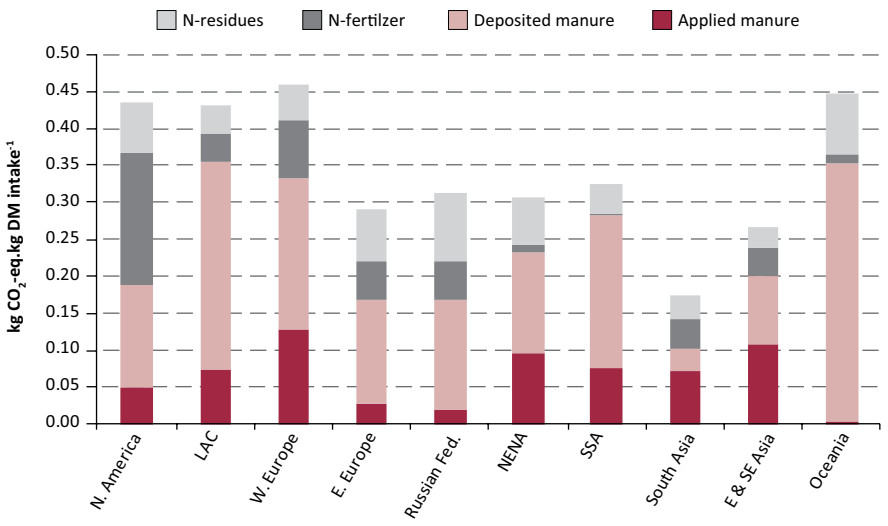
Regions with a high proportion of concentrates in the feed basket (and to a certain extent hay produced off-farm and silage), are likely to have a larger proportion of N_2O emissions from nitrogen fertilizer. N_2O emissions from fertilizer use in feed production for cattle are significant in North America, and Europe due to the high N application rates on feed in these regions. In the rest of the world's regions, use of fertilizer is negligible; in these regions, N nutrients for feed crop production are largely met from manure. It is also important to note that fertilizer input for other crops can be high in these regions as a consequence of large differences in crop yield and N fertilizer use. N_2O emissions from feed production can be very different for the same feed crop in grown in different locations.

Assumptions and uncertainties. Determining N_2O emissions is often difficult due to the high spatial and temporal variability of N_2O fluxes. N_2O emissions related to feed are based on the IPCC guidelines (2006) following the Tier 1 protocol, and in the modelling of N_2O emissions we adopted a simplified approach that took into account only N additions from fertilizer, manure and biomass on pasture and feed crops. However, other factors also drive N_2O emissions, such as local climatic conditions and soil properties (including water and N dynamics, soil type and structure), and management practices (tillage, irrigation, N application techniques, etc.), thus rendering the quantification of N_2O emissions challenging, which also implies that the results may contain substantial uncertainty.

There are additional uncertainties related to N_2O emissions, such as those related to N application rates coupled with limited information on manure application techniques and timing; the fate of manure and the lack of detailed estimates of the proportion of manure excreted at pasture; and how residues are managed (whether burned or incorporated). In addition, the N content in pasture and manure can vary during the year due to climatic conditions and stages of grass growth. All these aspects are difficult to capture given the scale of the analysis.

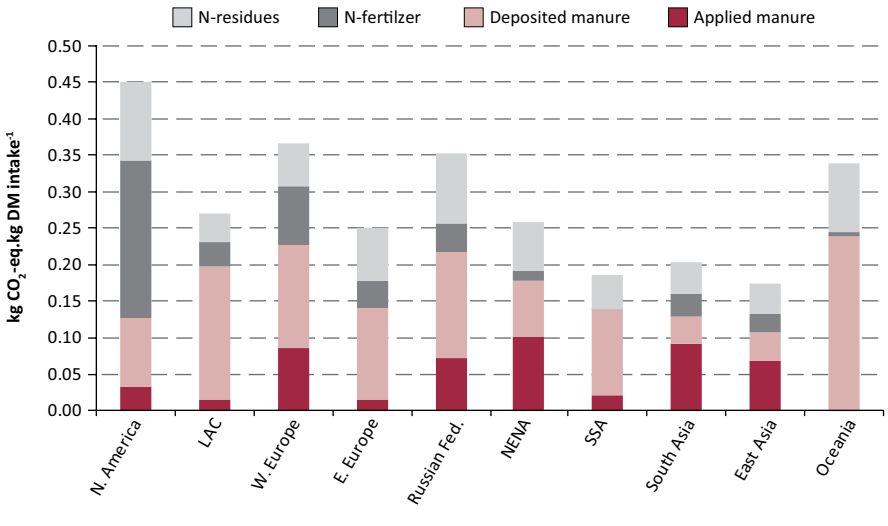
In this study, it is also assumed that all managed manure is applied to crops pro-

Figure 32a.
Regional difference in N_2O emission intensity of feed – cattle



Source: GLEAM.

Figure 32b.
Regional difference in N_2O emission intensity of feed – small ruminants



Source: GLEAM.

duced in the same location that production takes place. This may result in high N_2O emissions from applied manure particularly in areas where crop yields are low.

Another important aspect that influences the emissions from feed production is the choice of feed material; for example, in regions where the use of crop residues and by-products is important, there will be a tendency towards lower emission intensities per kg of DM because part of those emissions have been allocated to the main crop while regions that rely on concentrate feed, cultivated pasture, grains as a source of feed are likely have to have higher emissions intensities.

5.2.2 Carbon dioxide emissions from fossil fuel use in feed production

Carbon dioxide emissions from feed production are related to the use of fossil fuels, particularly diesel in tractors and harvesting machinery, oil in dryers, and natural gas in the manufacture and application of synthetic fertilizer and LUC. In the post-farm stages of feed production, CO_2 is emitted in conjunction with various feed processes (with drying being important) and transport.

In general, CO_2 emissions from energy use in feed production, processing and transport are strongly correlated to the feed ration. Other factors that also explain the variation in emission intensity among world regions include: the level of mechanization, the rate of fertilizer application, dependence on imported feed and source of feed (a key determinant of emissions related to transport of feed) and the extent to which the feed in question is associated with LUC.

Figures illustrate the emission intensity of feed by different processes in feed production and by region for both cattle (Figure 33a) and small ruminants (Figure 33b). In both cases, CO_2 emissions from fossil fuel use in feed production are important in industrialized regions. In these regions, two key factors explain the high emission intensities: (i) high fertilizer application rates; and (ii) transport of feed due to the higher proportion of by-products, feed crops or imported hay in the feed ration.

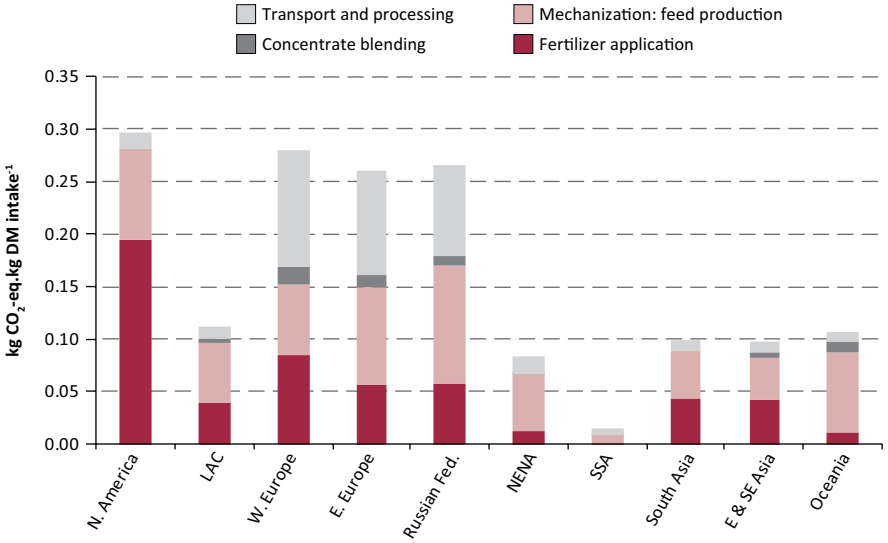
In other world regions, emission intensity is low and dominated by CO_2 emissions from energy use in field work. In both cattle and small ruminant production, sub-Saharan Africa has the lowest CO_2 feed emissions and there are several reasons for this: (i) reliance on natural pasture as a source of feed and low concentrate feed use; (ii) low use/negligible use of inputs such as fertilizer in the production of feed; and (iii) the low level of mechanization in the region.

Assumptions and uncertainties. The estimation of CO_2 emissions in this study are influenced by a number of assumptions and factors such as energy source and related emission coefficients used (see Table B14, Appendix B); level of mechanization (Table A1, Appendix A); and where feed is sourced and composition of the feed ration – both of which are variable.

5.2.3 Carbon dioxide emissions from land-use change

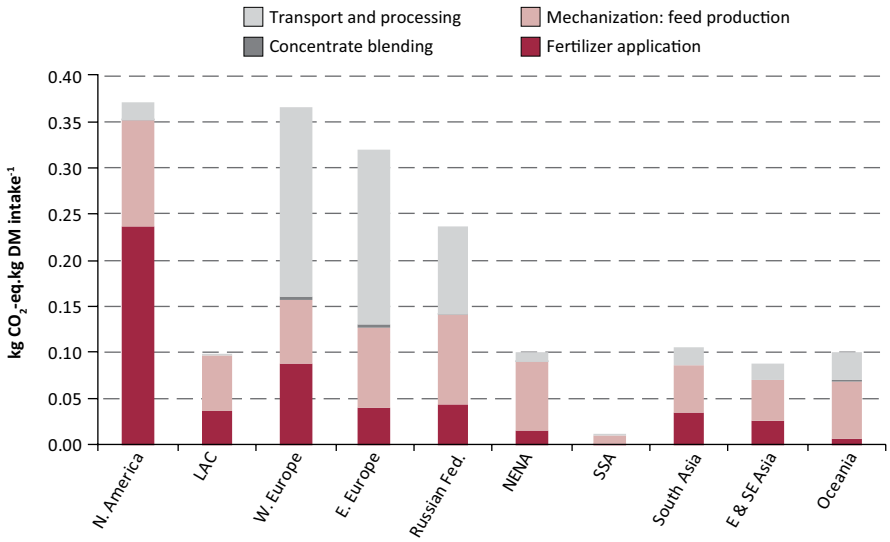
Emissions from LUC attributable to the ruminant sector amount to 450 million tonnes CO_2-eq, the bulk of these emissions (93 percent) are related to pasture expansion into forest areas for beef production in Latin America. The use of soybean produced on previously forested land as feed especially for dairy production contributes another 30 million tonnes CO_2-eq. The approach used in this assessment for estimating emissions from C stock changes associated with livestock induced LUC is further elaborated in Appendix C.

Figure 33a. Regional variation in CO_2 (fossil fuel-related) emission intensity of feed – cattle



Source: GLEAM.

Figure 33b.
Regional variation in CO_2 (fossil fuel-related) emission intensity of feed – small ruminants



Source: GLEAM.

Table 10. Regional sources of soybean and soybean cakes in 2005

	Brazil		Argentina		Other	
	Soybean	Soybean Cake	Soybean	Soybean Cake	Soybean	Soybean Cake
	percentage					
LAC	42	49	41	15	17	36
E & SE Asia	17	7	14	10	68	83
E. Europe	0	9	0	27	100	63
N. America	0	0	0	0	100	100
Oceania	0	60	0	0	100	40
Russian Fed.	5	5	0	37	95	57
South Asia	6	2	1	0	93	98
SSA	0	0	1	60	99	39
NENA	12	7	19	23	69	69
W. Europe	61	34	0	38	38	28

Source: FAOSTAT (2013).

Table 11. Main exporters of soybean and soybean cakes in 2005

	Soybean		Soybean cake	
	Exports *(million tonnes)*	Share of global exports	Exports *(million tonnes)*	Share of global exports
Argentina	20.8	37%	10.0	15%
Brazil	14.4	26%	22.4	34%
United States of America	5.1	9%	25.7	39%
India	4.8	8%	0.0	0%
Paraguay	0.8	1%	3.0	5%

Source: FAOSTAT (2013).

Soybean expansion. In quantifying total emissions associated with the transformation of forest for soybean cultivation, LUC emissions are attributed to only those countries supplied by Brazil and Argentina with soybean and soybean cake. Tables 10 and 11 present the regional share of soybean and soybean cake sourced from Brazil and Argentina and main exporting countries, respectively.

This analysis shows that about 224 million tonnes CO_2-eq are emitted *per annum* from the expansion of soybean production in Brazil and Argentina to meet global demand for pigs, chickens and cattle feed. The bulk of these emissions arise in response to soybean demand in Europe, East Asia and LAC (Table 12) which source large quantities of their soybean feed from Argentina and Brazil. The emissions estimated for the livestock sector in Western Europe are particularly high, which not only indicates a high reliance on imported soybean and soybean cake for feed, but also use of soybean with a high emission intensity, particularly because a large share is sourced from Brazil (see Table 10).

On a species level, the largest share of these emissions is attributed to the non-ruminant sector, equivalent to 195 million tonnes CO_2-eq (87 percent). This is not

Table 12. Regional comparison of land-use change emissions associated with soybean production

Region	Cattle	Pigs	Chicken
	(million tonnes CO_2-eq)		
Latin America	5.2	19.3	47.9
East and Southeast Asia	0.9	25.3	25.1
East Europe	0.6	2.1	0.4
North America	0.5	0.0	0.1
Oceania	2.4	1.5	1.6
Russian Federation	0.1	0.1	0.1
South Asia	0.0	0.0	4.5
Sub-Saharan Africa	0.0	0.0	0.5
Near East and North Africa	0.2	0.0	5.6
Western Europe	19.6	36.7	23.9
World	**29.6**	**85.0**	**109.6**

Source: GLEAM.

surprising because of the high share of soybean in diets of non-ruminants. Regarding the cattle sector, LUC emissions from soybean are important in Europe where it is utilized in dairy production. The results suggest that emissions are largely influenced by: (i) the quantity of soybeans and soybean cake imported from the two countries; and (ii) the share of soybean in the ration of the diet.

Pasture expansion. According to our estimations, about 13 million hectares of forest land in Latin America were converted to pasture land between 1990 and 2006. Deforestation for pasture establishment in the region emitted about 420 million tonnes CO_2-eq per year, releasing on average 32 tonnes CO_2-eq ha^{-1} yr^{-1}. At country level, changes in C stocks range between 30 and 35 tonnes CO_2-eq ha^{-1} yr^{-1} (Table 13). The estimates of GHG emissions due to pasture-driven LUC presented here represent a first step towards an estimation of LUC emissions. The analysis is consistent with the Tier 1 methodology outlined in the IPCC guidelines (IPCC, 2006). In order to progress towards better methodologies, certain gaps in data, methods, and in scientific understanding need to be addressed.

These preliminary estimates indicate that the inclusion of CO_2 emissions from land-use change have a significant influence on the carbon footprint of livestock products. However, changes in soil carbon sequestration due to land use are important are important and need to be considered.

Assumptions and uncertainties. Due to the uncertainty in the methods and data for calculating the impacts of LUC, we recognize the high level of uncertainty associated with this estimation. There is much uncertainty regarding the magnitude of LUC emissions due to (a) uncertainty in the estimates of deforestation rates; (b) uncertainty in the carbon storage capacity of different forests, (c) the modes of C release, and (d) uncertainties in the dynamics of land use, thus limiting the accuracy of the estimated carbon loss (Houghton and Goodale, 2004; Ramankutty *et al.*, 2006).

Table 13. Annual carbon stock changes and emissions from pasture expansion in Latin America

Countries	Average emissions		Total carbon losses
	tonnes CO_2/ha	*tonnes CO_2/ha/yr*	*million tonnes CO_2-eq*
Brazil	- 509.7	- 31.9	-325.3
Chile	- 510.7	- 31.9	-36.7
Paraguay	- 488.1	- 30.5	-31.7
Nicaragua	- 485.3	- 30.3	-13.8

Source: Authors' calculations.

This analysis also relies on a Tier 1 approach and use of IPCC default values and is therefore subject to high levels of uncertainty. We test other existing methods and assumptions in Appendix C to illustrate the range of uncertainty that exists.

The way in which the LUC emissions should be allocated over beef production is a question for further research. Within this analysis, we allocate emissions to total beef produced within the country; however, not all beef production is carried out on deforested land. A related methodological issue is the debate on the allocation of emission related to LUC because of the complexity in ascertaining the key driver of land-use change. In addition, the calculated emission intensity is highly sensitive to the time period selected over which emissions from the initial deforestation are annualized. Appendix C explores alternative approaches to estimating emissions related to LUC, incorporating some of the issues discussed here.

5.3 EMISSIONS FROM MANURE MANAGEMENT

5.3.1 Methane from manure management

Animal manure emits CH_4 depending on the way it is produced and managed. Ruminants (cattle, buffalo and small ruminants) contribute 109 million tonnes of CH_4 from manure (2 percent of total emissions from ruminants), of which 86 percent is from cattle. Three primary factors affect the quantity of CH_4 emitted from manure management operations: type of treatment or storage facility, climate and composition of the manure.

Storage and treatment of manure in liquid systems such as lagoons or ponds leads to the development of anaerobic conditions which result in high CH_4 emissions. In addition, higher ambient temperature and moisture content also favour CH_4 production. The composition of manure is directly related to animal types and diets.

Manure CH_4 emissions are lower in regions where manure is handled in dry systems. In dairy and beef cattle production, where liquid MMS (lagoons, liquid/slurry systems) are common, the proportion of manure CH_4 emissions in total CH_4 emissions is considerable, and particularly in regions where animals are confined for a part of the year, such as Europe and North America. For dairy, this ranges from 5 percent in Eastern Europe to 35 percent in North America; on the other hand, in beef production the use of liquid systems is confined to Western Europe and Eastern Europe where 6 percent and 14 percent of CH_4 emissions originate from manure, respectively. The anaerobic nature of liquid manure systems increases the potential for CH_4 production and reduces N_2O production.

In the other world regions, a large fraction of the manure from cattle is handled in dry systems, while in small ruminant production manure is managed in dry systems, including drylots and solid systems, or deposited on pastures and ranges.

Maps 9 and 10 in Appendix G present the CH_4 conversion factor that defines the portion of CH_4 producing potential achieved by each manure management system. Methane conversion factor is higher in North America and Europe, which explains the higher CH_4 emissions. The high CH_4 conversion factor in North America and Europe is due to the use of liquid MMS.

Assumptions and uncertainties. In this study, CH_4 emissions from manure management are calculated using the IPCC Tier 2 approach. This approach uses country-specific inputs of volatile solids estimated from DMI, feed digestibility and ash content of manure, a CH_4 conversion factor based on climate and type of manure management and storage system, and the maximum CH_4 potential (Bo) of manure based on species and diet.

Uncertainties related to estimation of CH_4 from manure management derive from: limited activity data on manure management; differences in manure management practices; and the effect of time-related aspects such as storage periods, as well as seasonal temperature variations in emission rates which are not explicitly accounted for in the calculations.

5.3.2 Nitrous oxide from manure management

Nitrous oxide is produced directly and indirectly during storage and treatment of manure before it is applied to land. Indirect N_2O emissions result from volatile N losses that occur mainly from ammonia (NH_3) and NO_X and leaching of nitrate. Key important variables that influence N_2O emissions from manure management include the amount of N excreted and the way in which manure is managed. A considerable amount of N entering the livestock food chain through feed is wasted; ruminants excrete between 75 percent and 95 percent of the N they ingest (Castillo *et al*., 2000; Eckard *et al*., 2007). Maps 11 and 12 in Appendix G compare the proportion of feed nitrogen retained by dairy and beef herds.

Animal productivity is important for N excretion; as more milk or meat is produced per animal, the maintenance requirement of protein per unit of production is reduced. Thus, the animal product can be produced with less N consumed and excreted. Figure 34 illustrates the relationship between animal performance and N excretion per kg of milk protein; a comparison among regions reveals that, on average, high-producing animals excrete less N per unit of protein produced because more nutrients are directed towards production.

Manure handling and storage also influence N_2O emissions from manure. A large proportion of N_2O from manure management is released as direct N_2O, the bulk of which originates from dry systems (with approximately 60 percent and 65 percent from drylot systems in beef and dairy cattle production). All manure from small ruminants and buffalo is managed in dry systems (drylot and solid systems). Nitrous oxide emissions are most likely to occur in dry manure handling systems that have aerobic conditions (in the presence of oxygen), but that also contain pockets of anaerobic (in the absence of oxygen) conditions.

For dairy and beef cattle, most N_2O emissions from manure management are found in developing regions. Oceania is the only region without N_2O emissions

Figure 34.
Nitrogen excretion per kg milk protein versus average regional milk yield – dairy cattle



Source: GLEAM.

associated with manure management because all manure from beef and small ruminants in Oceania is assumed to be deposited on pasture. The proportion of N_2O from leaching is insignificant and has a limited impact on total N_2O from manure management because only a small proportion of leached N is converted to N_2O.

Assumptions and uncertainties. The basis for the estimation of N emissions is the total mass of N excreted. Excretion is determined as the difference between crude protein intake and retention within the animal. N_2O emissions associated with manure deposited on pasture, ranges and paddocks are not included in these estimates but considered as part of the feed production component (cf. Appendix A), because they are considered as a source of N fertilizer in feed production.

5.4 COMPARISON WITH OTHER STUDIES

A direct comparison with literature values from other LCAs is often complicated by the use of differing boundaries, functional units, disparate assumptions and algorithms in calculating emissions. Nevertheless, comparisons can be useful to provide an indication of the validity of results and contribute to drawing conclusions. Tables 14 and 15 compare existing studies for beef cattle and small ruminants with the current study. While several studies have focused on the cattle sector and to a limited extent small ruminants, many of these estimates are at a much smaller scale and are often specific to regions or production systems within countries (e.g. Verge *et al.*, 2008; Peters *et al.*, 2009; Biswas *et al.*, 2010; Beauchemin *et al.*, 2010; Pelletier *et al.*, 2010; Nguyen *et al.*, 2010; Kanyarushoki *et al.*, 2010; Zhou *et al.*, 2007, Zervas and Tsiplakou, 2012; Edwards-Jones *et al.*, 2009). For purposes of this comparison, only those studies with a national or regional scope were selected.

Table 14. Comparison of emission intensities for beef cattle

Study	Country	System	Scope							Emission Intensities/Emissions	
			Enteric CH_4	Manure CH_4	Manure N_2O	Feed N_2O	Feed CO_2	Energy	Post farmgate	Study	GLEAM
Foley *et al.* (2011)	Ireland	Pastoral suckler (National average farm scenario)	Y	Y	Y	Y	Y	N	N	23.1 kg CO_2-eq/kg CW	27.7 kg CO_2-eq/kg CW
Leip *et al.* (2010)	EU27	Beef	Y	Y	Y	Y	Y	Y	N	22.2 kg CO_2-eq/kg CW	24.1 kg CO_2-eq/kg CW
Cederberg *et al.* (2009)	Brazil		Y	Y	Y	Y	Y	Y	N	28 kg CO_2-eq/kg CW (without LUC)	32.4 kg CO_2-eq/kg CW (without LUC)
Williams *et al.* (2006)	Brazil		Y	Y	Y	Y	Y	Y	Y	32.2 kg CO_2-eq/kg CW (without LUC)	32.4 kg CO_2-eq/kg CW (without LUC)
Casey and Holden (2006)	Ireland	Typical Irish beef	Y	Y	Y	Y	Y	Y	N	11.26 kg CO_2-eq/kg LW	19.1 kg CO_2-eq/kg LW
Ogino *et al.* (2007)	Japan		Y	Y	Y	Y	Y	N	N	32.1 kg CO_2-eq/kg CW	39.0 kg CO_2-eq/kg CW
Ominski *et al.* (2003)	Canada		Y	N	N	N	N	N	N	16.1 million tonnes CO_2	17.5 million tonnes CO_2

Y: emission category included; N: emission category excluded.

Table 15. Comparison of emission intensities for small ruminants

Study	Country	Species	System	Scope							Emission Intensity	
				Enteric CH_4	Manure CH_4	Manure N_2O	Feed N_2O	Feed CO_2	Energy	Post farmgate	Study	GLEAM
Leip *et al.* (2010)	EU27	Small ruminant meat		Y	Y	Y	Y	Y	Y	N	20.3 kg CO_2-eq/kg CW	18.1 kg CO_2-eq/kg CW
Leip *et al.* (2010)	EU27	Small ruminant milk		Y	Y	Y	Y	Y	Y	N	2.9 kg CO_2-eq/kg milk	4.7 kg CO_2-eq/kg milk
Ledgard *et al.* (2011)	New Zealand	Lamb		Y	Y	Y	Y	Y	Y	Y	19 kg CO_2-eq/kg CW	14.8 kg CO_2-eq/kg CW (with allocation to wool) 19.0 kg CO_2-eq/kg CW (without allocation to wool)
Ripoli-Bosch *et al.* (2010)	Spain	Lamb	Grazing Mixed Zero-grazing	Y	Y	Y	Y	Y	Y	N	Grazing: 56.7 Mixed: 48.5 kg CO_2-eq/kg CW	25.9 kg CO_2-eq/kg CW
Yamaji *et al.* (2003)	China	Goats		Y	Y	N	N	N	N	N	869 gigagrams CH_4	641 gigagrams CH_4
Yamaji *et al.* (2003)	China	Sheep		Y	Y	N	N	N	N	N	760 gigagrams CH_4	925 gigagrams CH_4

Y: emission category included; N: emission category excluded.

The following factors have been identified as potential reasons for the deviation in results.

Scope. Studies can: (a) have different system boundaries; (b) include different emissions categories within the same system boundaries; (c) have different functional units; or (d) include different emission sources within an emission category.

Input data/assumptions. Quantifying emissions requires input data on key parameters such as livestock population numbers and distributions, herd structures and crop yields. Ideally, validated empirical data sets should be used, but there are often gaps in the data on key parameters, which necessitate assumptions. In many cases, key input data have been found to vary; for example a comparison of small ruminant population numbers in the 27 Member States of the European Union (EU27) revealed that the small ruminant population for these countries used in this current study are 30 percent higher than those used by Leip *et al*. (2010). The authors also noted that there was an observed difference between the small ruminant inventory that they utilized and national inventory reports. The animal inventory utilized in this study was, however, found to be consistent with those reported by the countries.

Calculation methods. A review of the studies revealed the major differences in methodology across all studies particularly in the use of different approaches such as use of Tier 1 vs. Tier 2 approaches, and differences in allocation technique applied. Generally, due to the importance of enteric fermentation, most recent studies apply a Tier 2 approach, particularly for cattle. While the approach may be similar, studies may obtain different results which may largely depend on data inputs such as animal weights, feed digestibility and feed composition, all of which are important in assessing emissions from enteric fermentation. On the other hand, the assessment of enteric fermentation in small ruminants in the few studies conducted (Leip *et al.,* 2010; Yamaiji *et al.*, 2003; Edward-Jones *et al.*, 2009) has largely been based on the Tier 1 approach using the IPCC default value of 8 kg CH_4 per head.

The allocation technique applied may also explain variations in emission intensity. Significant differences were found between this study and the EU27 study (Leip *et al*., 2010) for small ruminant milk production (cf. Table 14), which is also explained by the differences in allocation techniques. The authors allocate emissions between three outputs: milk, meat and lamb/kids based on the nitrogen content of the products, and emissions related to the raising of young animals during pregnancy are allocated to meat. In contrast, this study allocates emissions between milk, meat and wool based on economic value of the products and subsequently utilizes protein content of products to allocate emissions among the edible products (see allocation technique in Appendix A). A key explanation of the deviation between the current study and EU27 study is related to the fact that a large part of the total dairy herd emissions (i.e. emissions associated with the adult females and male animals and replacement animals) in our study are allocated to milk, while only emissions of the dairy activity (time from the first lactation to the slaughtering of the animal) are allocated to milk in the EU27 study (Weiss and Leip, 2012).

The overlying issues with comparison lie in the lack transparency of information and a standardized methodology or protocol for conducting LCAs and reporting results. The variability among studies in methods used places emphasis on the need to clearly define and agree on methodologies for estimating GHG emissions from the ruminant sector.

5.5 ANALYSIS OF UNCERTAINTY

Estimates of GHG emissions are subject to large uncertainties. Fundamentally, uncertainties are associated with the variables used in the calculation of EFs, in estimates of activity data (e.g. animal populations and herd parameters) and assumptions made. This section presents a partial analysis of uncertainty, based on the Monte Carlo (MC) Simulation approach.

In order to focus the analysis of uncertainty, parameters that had the greatest influence on emission intensity were identified. Key contributors to emissions were defined as those emissions categories contributing more than 10 percent of the emissions and with a high degree of uncertainty arising from either the lack of data or inherent

Table 16. Summary of parameters and uncertainty distributions used in the Monte Carlo simulation runs for dairy and beef in France

Parameters and emission factors	Distribution	CV[1]	Min	Max	Reference and basis for uncertainty estimates
Parameters					
Feed digestibility	Normal	0.10			Assuming IPCC uncertainty range of ±20% (IPCC, 2006 – Volume 4, Chapter 10, Section 10.2.3)
Dairy: Milk yield	Normal	0.2			Institut de l'Élevage, 2011
Dairy: Age at first calving	Normal	0.19			Institut de l'Élevage, 2011
Beef: Age at slaughter	Normal	0.23			Institut de l'Élevage, 2011
Beef: Age at first calving	Normal	0.17			Institut de l'Élevage, 2011
Emission factors					
Enteric CH_4 emission factor	Normal	0.10			Assuming IPCC (2006, Volume 4, Chapter 10, Section 10.3.4) uncertainty range of ±20%
EF1: N_2O emission factor, synthetic and organic N	Beta Pert		0.003	0.03	IPCC (2006, Table 11.1)
EF3: N_2O emission factor, pasture, rangeland and paddock	Beta Pert		0.007	0.06	IPCC (2006, Table 11.1)
EF4: Emission factor, N volatilization	Beta Pert		0.002	0.05	IPCC (2006, Table 11.3)
EF5: Emission factor, leaching	Beta Pert		0.0005	0.025	IPCC (2006, Table 11.3)
Fraction of applied synthetic N to volatilization NH_3, No_x	Beta Pert		0.03	0.3	IPCC (2006, Table 11.3)
Fraction of applied organic N to volatilization NH_3, No_x	Beta Pert		0.05	0.5	IPCC (2006, Table 11.3)
Ammonium Nitrate manufacture EF	Normal	0.27			Based on values for fertilizer CO_2 EFs in Wood and Cowie (2004)
Soybean scenario 1: GLEAM	Normal	0.08			See Appendix C on LULUC
Soybean scenario 2: PAS 2050-1:2012	Normal	0.15			See Appendix C on LULUC
Soybean scenario 3: One-Soy	Normal	-			See Appendix C on LULUC
Soybean scenario 4: Reduced time-frame	Normal	0.08			See Appendix C on LULUC

[1] CV – Coefficient of Variation is the ratio of the standard deviation to the mean. The 95 percent confidence interval is approximately equal to the standard deviation or coefficient multiplied by two.

variability or assumptions made. For the ruminant sector, emission categories that contribute more than 10 percent include CH_4 from enteric fermentation, CO_2 from land-use change, and N_2O from feed production (see Section 4). Section 5.4 highlighted some of the important factors that are likely to influence emissions. The MC simulation was applied to two countries, France and Paraguay. In France, uncertainties in both mixed dairy and beef production systems were assessed, while in Paraguay the focus was on grazing systems. The choice of countries was based on criteria such as the availability of statistics for inventory data [standard deviation (SD), confidence interval or ranges], and relative importance of production in these countries.

5.5.1 The approach

Choice of probabilistic distributions of input variables. Monte Carlo simulations enable an investigation into how input uncertainty propagates through the life-cycle emissions model. However, there is little data on probability distributions of the input data required to perform a MC simulation.

In this assessment, the probability distributions were defined using the SD from a number of sources and applying the coefficient of variation indicated in Tables 16 and 17, and normal distributions were assigned to technical parameters for which no choice of mode could be justified given available information.

Table 17. Summary of parameters and uncertainty distributions used in the Monte Carlo simulation runs for beef in Paraguay

Parameters and emission factors	Distribution	CV[1]	Min	Max	Reference and basis for uncertainty estimates
Parameters					
Feed digestibility	Normal	0.10			Assuming IPCC uncertainty range of ±20% (IPCC, 2006 – Volume 4, Chapter 10, Section 10.2.3)
Beef: Age at slaughter	Normal	0.24			Ferreira *et al.* (2007); Fréchou (2002)
Beef: Age at first calving	Normal	0.02			Ferreira *et al.* (2007); Fréchou (2002)
Emission factors					
Enteric CH_4 Emission factor	Normal	0.10			Assuming IPCC (2006, Volume 4, Chapter 10, Section 10.3.4) uncertainty range of ±20%
EF1: N_2O emission factor, synthetic and organic N	Beta Pert		0.003	0.03	IPCC (2006, Table 11.1)
EF3: N_2O emission factor, pasture, rangeland and paddock	Beta Pert		0.007	0.06	IPCC (2006, Table 11.1)
EF4: Emission factor, N volatilization	Beta Pert		0.002	0.05	IPCC (2006, Table 11.3)
EF5: Emission factor, leaching	Beta Pert		0.0005	0.025	IPCC (2006, Table 11.3)
Fraction of applied synthetic N to volatilization NH_3, No_x	Beta Pert		0.03	0.3	IPCC (2006, Table 11.3)
Fraction of applied organic N to volatilization NH_3, No_x	Beta Pert		0.05	0.5	IPCC (2006, Table 11.3)
Ammonium Nitrate manufacture EF	Normal	0.27			Based on values for fertilizer CO_2 EFs in Wood and Cowie (2004)
Land-use change: Pasture expansion (combined scenario)	Normal	0.28			Combined uncertainty range calculated based on IPCC default uncertainty values for carbon pools and uncertainty in land area estimates

[1] CV – Coefficient of Variation is the ratio of the standard deviation to the mean. The 95 percent confidence interval is approximately equal to the standard deviation or coefficient multiplied by two.

Table 18. Emission intensity for imported soybean and soybean cake used in France

Approach	Soybean Cake	Soybean
	kg CO_2-eq/kg product	
GLEAM	4.81	5.35
PAS 2050-1:2012	1.42	1.58
One-Soy	2.98	3.31
Reduced time-frame	2.31	2.56

Source: Authors' calculations.

Table 19. Default carbon stock values for Paraguay and uncertainty values of carbon pools

	Carbon stocks	Uncertainty of the carbon pool[1]
	tonnes C/ha	*percentage*
Previous land: Forest		
Biomass	260.4	±24%
Soil carbon	65	±95%
Dead organic matter (DOM)	2.8	±30%
Total carbon stocks	**328.2**	
Land-use after conversion: Grassland		
Biomass	0	0[2]
Soil carbon	63	±95%
Dead organic matter	0	0[3]
Total Carbon stocks	**63**	
Carbon stock change	**265.2**	

[1] Two standard deviation CI 95%.
[2] No uncertainty analysis is needed for Tier 1 since the default assumption is that all biomass is cleared and therefore the default biomass after conversion is zero.
[3] No uncertainty analysis is needed for Tier 1 since the default assumption is unchanging carbon stocks in DOM.
Source: Authors' calculations.

For the IPCC parameters, these are mainly provided with a potential range, often estimated by expert opinion or drawn from studies. The ranges for EF1, EF3, EF4, EF5 were taken from IPCC (2006) and beta-pert distributions were used to model parameters from IPCC based on the maximum and minimum value. These distributions and underlying data sources are also summarized in Tables 16 and 17.

We also employed MC simulation analysis to understand the uncertainty associated with LUC. The approaches described in Appendix C were used to generate parameter ranges used in the MC simulation. The three alternative soybean approaches were only applied to the French case study where imported soybean cake is used as feed. The soybean emission intensity calculated for the GLEAM and the three additional scenarios for soybean imported by France from Brazil and Argentina are presented in Table 18.

The approach for assessing the uncertainty related to changes in C stocks resulting from pasture expansion into forest areas takes into account the *uncertainty associated with carbon fluxes from carbon pools considered* and the *uncertainty as-*

sociated with the land area estimates. The two uncertainties were run separately and then combined. The IPCC guidelines (2006) indicate that, if using aggregate land use area statistics for activity data (e.g. FAO data on land area), as is the case in this study, a default level of uncertainty for the land area estimates of ±50 percent may be applied.

Estimates of the carbon loss on land conversion include uncertainties in several underlying quantities: the carbon in the above-ground biomass, the carbon in the below-ground biomass (generally estimated as a percentage of the above-ground biomass), the carbon in the soil, and the fraction of all carbon lost upon conversion. The uncertainty associated with carbon fluxes from three carbon pools considered in this study are taken from IPCC guidelines (2006, Volume 4) and the "Good Practices Guidelines" for national GHG inventories (IPCC, 2003) and are presented in Table 19.

Total uncertainty combining uncertainty in carbon stock changes per hectare with the uncertainty in land area converted was calculated using the *error propagation approach* outlined in Chapter 6, IPCC Good Practice Guidance (2000, Chapter 6 equations 6.3 and 6.4) that combines different uncertainties to provide an uncertainty estimate for an inventory. The result of the combined uncertainty used as input in the Monte Carlo simulation is presented in Table 17.

Uncertainty estimates and sensitivity analysis. In this assessment, the number of simulations run was 10 000. For any analysis of this type, it is important to determine the sources of uncertainty and the impact that parameters and their embedded assumptions have on the results. A sensitivity analysis was therefore used to identify parameters that have a significant effect on the uncertainty estimates. Sensitivity analysis also identifies the most influential parameters indicating emissions sources that offer the opportunity to decrease the overall uncertainty associated with life-cycle of milk and beef production emissions. The relative sensitivity of input variables was assessed by Monte Carlo using the *Rank Correlation Coefficient (RCC)*[8] calculated between all inputs variables and the emission intensity as their contribution to the overall uncertainty.[9]

5.5.2 Results from the uncertainty analysis

France

The mean emission intensity for milk production in mixed farming system in kg CO_2-eq calculated on the basis of kg milk was estimated to be 1.9 kg CO_2-eq/kg milk (±0.95 kg CO_2-eq/kg milk at the $CI_{95\%}$). The range of values around the mean obtained with the uncertainty analysis was 0.9-2.8 kg CO_2-eq/kg milk (Figure 35 and Table 20). The average emission intensity for beef is 15.6 kg CO_2-eq/kg CW (±8.0 kg CO_2-eq/kg CW) (Figure 36 and Table 20) The range of values was 7.5-23.6

[8] RCC is a measure of the strength and direction of association between input variables and output estimates. If an input parameter and an output estimate have a high correlation coefficient, it means that the input has a significant impact on the output; positive correlation coefficients indicate that an increase in the input is associated with an increase in the output estimate while negative coefficients indicate an inverse relationship. The larger the absolute value of the correlation coefficient, the stronger the relationship.

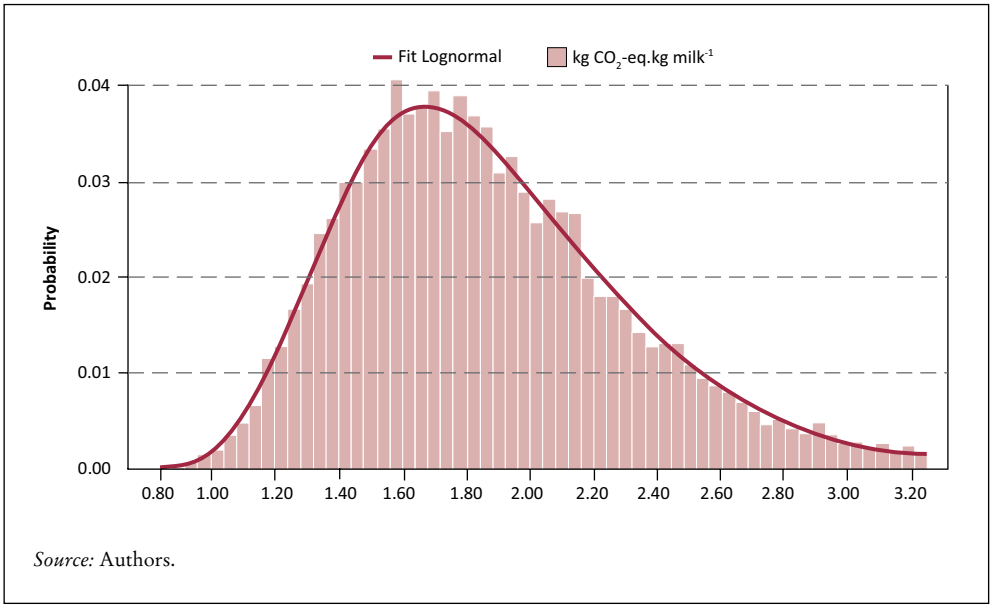
[9] Crystal ball computes the rank correlation between inputs and each output parameter then normalizes these to sum to 100 percent. This provides a measure of sensitivity, i.e. the contribution of each parameter to the overall uncertainty of emission intensity.

Table 20. Summary of results from Monte Carlo analysis for mixed dairy and beef production in France

	Mixed dairy production	Mixed beef production
Mean emission intensity	1.89 kg CO_2-eq/kg milk	15.6 kg CO_2-eq/kg CW
EI standard deviation	0.49	4.10
Coefficient of Variation	26%	26%

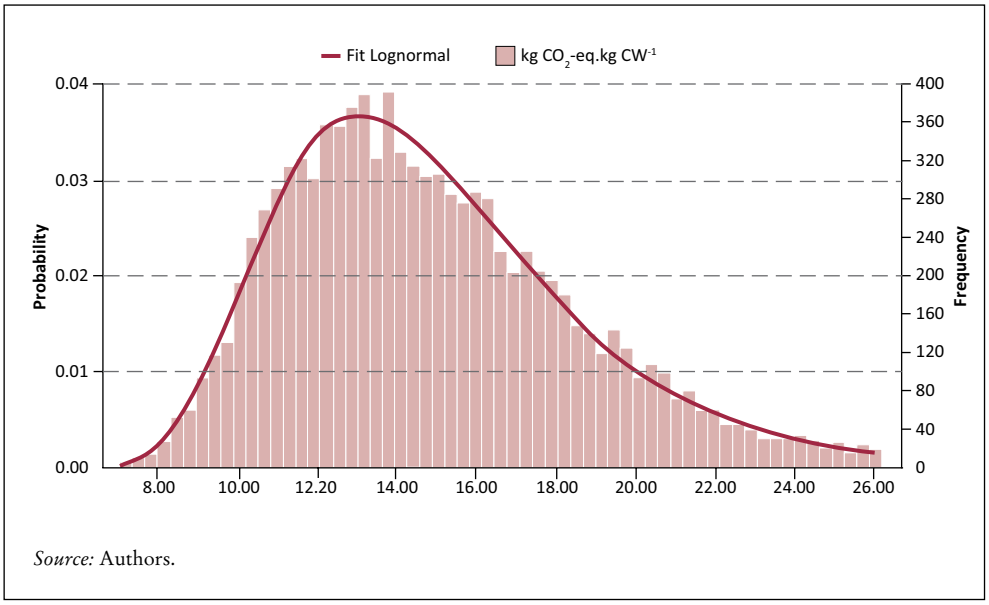
Source: Authors' calculations.

Figure 35.
Probability distribution for milk emission intensity in France



Source: Authors.

Figure 36.
Probability distribution for beef emission intensity in France



Source: Authors.

Table 21. Impact of alternative soybean scenarios on emission intensity for dairy and beef in France

	GLEAM	PAS 2050-1:2012	One-Soy	Reduced time-frame
Beef				
Mean Emission intensity *(kg CO_2-eq/kg CW)*	15.6	14.9	15.2	15.0
Contribution to variance	0%	0.1%	0%	0%
Dairy				
Mean Emission intensity *(kg CO_2-eq/kg milk)*	1.89	1.78	1.82	1.81
Contribution to variance	0%	0%	0%	0%

Source: Authors' calculations.

kg CO_2-eq/kg CW. Both probability distribution frequencies (PDFs) for France are positively skewed indicating that the distribution has a longer right tail (Figures 35 and 36).

The coefficient of variation defines the standard deviation as a percentage of the mean and can be used to compare SDs with different means. Despite the markedly different means and SD for milk and beef, the coefficient of variation for both milk and beef in France is 26 percent of the mean.

Impact of alternative soybean approaches on emission intensity. Different scenarios to assess the impact of soybean-related LUC were tested for both dairy and beef production systems in France and the results are presented in Table 21. Soybean cake accounts for a small proportion of the feed ration (between 2-6 percent of the feed ration for both dairy and beef) and hence has a negligible impact on emission intensity.

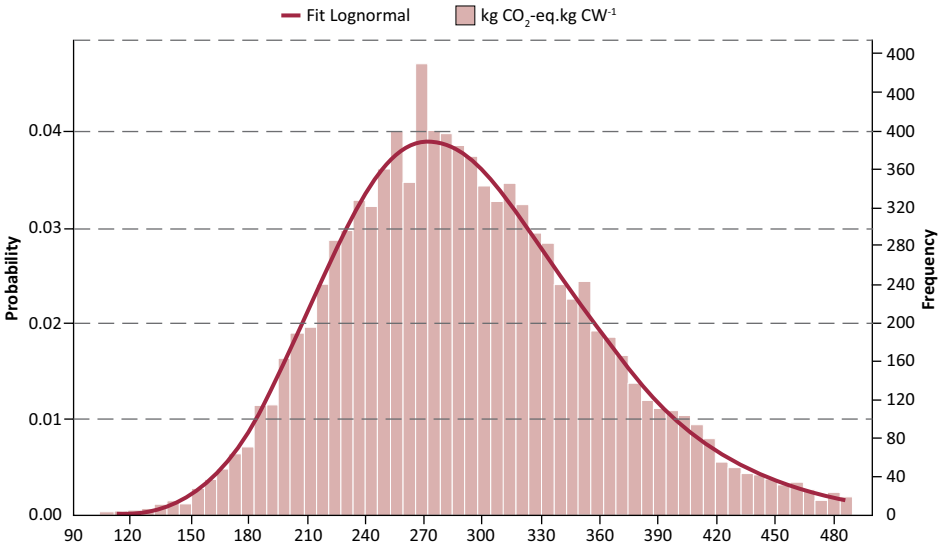
Paraguay

Figure 37 presents the results from the Monte Carlo simulation for Paraguay. The mean value for the emission intensity of beef produced in grazing systems in Paraguay (including carbon losses from deforestation for pasture) is 294.2 kg CO_2-eq/kg CW (±136.3 kg CO_2-eq/kg CW), with the 95 percent certainty interval around the mean ranging from 157.8-430.6 kg CO_2-eq/kg CW. The coefficient of variation (CV) is estimated at 24 percent of the mean.

Impact of LUC uncertainty on emission intensity of beef in Paraguay. Table 22 presents the results from the propagation of uncertainty associated with land area estimates, carbon stock losses per hectare as well as the combined scenario of the two uncertainties.

The assumptions and uncertainties in total land area converted and carbon stocks and their impact on the mean were about the same magnitude. The sensitivity analysis showed that uncertainty in the total land area converted is the single largest contributor to variance, accounting for 27 percent of the variance, while uncertainty in estimates of the carbon in soil and biomass accounts for nearly 9 percent of the variance.

Figure 37.
Probability distribution for beef emission intensity in Paraguay



Source: Authors.

Table 22. Effects of alternative LUC uncertainty estimates on average emission intensity for beef production in Paraguay

	Emission intensity *(kg CO_2-eq/kg CW)*		
		95% probability range	
	Mean	**Low**	**High**
Land area	292.1 (22%)*	163.7	420.6
Carbon stocks	293.4 (21%)*	173.0	413.7
Baseline (combined scenario)	294.2 (24%)*	157.9	430.6

* Percentages in brackets relate to Coefficient of Variation (CV)
Source: Authors' calculations.

Analysis of sensitivity. Tables 23 and 24 illustrate the *contribution to variance* (CoV)[10] and the *RCC* for the uncertain input parameters (above a 1 percent threshold) and presents the most important factors affecting the total uncertainty measured by the absolute value of *RCC* between the parameters and the emission intensity. For milk production in mixed systems in France, three parameters contribute about 90 percent of the total variance in the emission intensity; feed digestibility is the largest contributor to variance, accounting for almost half of the total, and the uncertainty in N_2O EF3 and milk yield contributing another 22 and 20 percent of the variance, respectively. In beef production, the N_2O EF3 and feed digestibility parameters contribute 93 percent of the variance (Table 23).

[10] The contribution to variance (CoV) provides information on how much each variable contributed to the uncertainty of emission intensity relative to the contribution of other variables.

Table 23. Percent Contribution to Variance (CoV) and Rank Correlation Coefficient (RCC) in mixed dairy and beef systems in France

Parameter	Dairy		Beef	
	CoV	**RCC**	**CoV**	**RCC**
Feed digestibility	47%	-0.66	42.2%	-0.63
N_2O EF3 Pasture, ranging and paddock	22.2%	0.45	51.5%	0.69
Milk yield	20.4%	-0.43	NA	NA
Age at first calving	5.4%	0.22	NS	NS
EF for enteric fermentation	1.7%	0.12	NS	NS
EF 1 for synthetic and organic N	1.0%	0.09	2.5%	0.15
EF 4 for N volatilization	NS	NS	1.5%	0.12
EF 5 for N leaching	NS	NS	1.2%	0.1

NA: Not Applicable; NS: Not Significant.
Source: Authors' calculations.

Table 24. Percent Contribution to Variance (CoV) and Rank Correlation Coefficient (RCC) for grazing beef systems in Paraguay

Parameter	Beef	
	CoV	**RCC**
N_2O EF3 Pasture, ranging and paddock	44%	0.64
Land-use change pasture: combined scenario	34%	0.52
Feed digestibility	17%	-0.40
Age at slaughter	5%	0.21

Source: Authors' calculations.

The sensitivity analysis shows that the key parameters contributing to uncertainty for both the dairy and beef scenarios are:

- the feed digestibility variable plays a significant role in total emissions; 47 percent and 42 percent of the uncertainty in emission intensity of milk and beef is caused by the uncertainty in feed digestibility variable, respectively. Digestibility is a dominant factor in the calculations of a number of emission sources and hence its role in influencing the uncertainty in emission intensity.
- N_2O EF3 for manure deposited on pasture due to the high degree of uncertainty i.e., wide distribution (large natural variability) of possible values.
- In dairy production, milk yield has an impact on the uncertainty of milk emission intensity due to the high variability in milk production.

For Paraguay, the sensitivity analysis shows that 4 parameters: N_2O EF3 Pasture, ranging and paddock, feed digestibility and land-use change, and age at slaughter contribute 99 percent of the variance to the emission intesity of beef in Paraguay (Table 24).

The uncertainty in N_2O EF3 is the largest contributor to variance (44 percent); the rate of emissions of N_2O (per unit N applied/deposited) is perhaps the most uncertain effect in GHG emission profile. In addition to the wide distribution N_2O EF3 (the N_2O emissions factor for N deposited on pasture, range or paddock), it is assumed that 95 percent of the manure in this case is deposited directly on pasture

hence the high N_2O emissions. The uncertainty in the estimates of LUC combined scenario (carbon stock losses per hectare and in the land area estimates) account for 34 percent of the variance.

In conclusion, the uncertainty performed for the two case studies show that relatively few parameters (N_2O EF3 Pasture, ranging and paddock, feed digestibility and LUC) are responsible for most of the variance. Although the present analysis captures several important parameter uncertainties, significant model uncertainties still remain.

Point estimates from LCAs describe only an average situation and many scenarios may be equally plausible. Uncertainty analysis such as these offer the opportunity to understand and estimate the imprecision of the average result resulting from uncertainties in input data as well as deliver more meaningful results.

6. Conclusion

Globally, ruminant supply chains are estimated to produce 5.7 gigatonnes CO_2-eq *per annum* of which 81 percent, 11 percent and 8 percent is associated with cattle, buffalo and small ruminant production.

This report provides the first comprehensive and disaggregated global assessment of emissions from the ruminant sector, which enables the understanding of emission pathways and hotspots. This is a fundamental, initial step towards identification of mitigation strategies.

Average emission intensity for products from ruminants were estimated at 2.8, 3.4 and 6.5 kg CO_2-eq/kg FPCM for cow milk, buffalo and small ruminant milk, respectively, and 46.2, 53.4, and 23.8 kg CO_2-eq/kg CW for beef, buffalo and small ruminant meat, respectively. Although there is great heterogeneity among production systems, some commodities are associated with particularly high emission intensities. These emission profiles and the on-going growth in output call for the adoption of mitigation practices.

The ranges of emission intensity within supply chains suggest that there is room for improvement (Tables 7 to 9). This mitigation potential is further explored in an overview report published in parallel to this one (FAO, 2013a). It is estimated to reach 30% of the sector's global emissions. The overview report also explores regional mitigation potentials through case study analysis. When drawing any conclusions about scope for improvement, one must distinguish those production parameters that can be managed from those that are related to agro-ecological conditions and cannot be managed. This is particularly true for extensive production systems, where the environment cannot be controlled, or at prohibitive costs.

Regarding these systems, and those facing particularly harsh environments, mitigation practices should not be proposed at the cost of diminished resilience and food security. Bearing these caveats in mind, the results of this study indicate six areas of possible interventions to reduce the emission intensity from ruminant supply chains:

- Reducing LUCs arising from pasture expansion and feed crop cultivation;
- Improving feeding practices and digestibility of diets;
- Improving grazing and pasture management to increase soil organic carbon (SOC) stocks;
- Increasing yields, e.g. through genetics, feeding and animal health;
- Improving manure management – reducing the use of uncovered liquid MMS, particularly in dairy systems; and
- Increasing energy use efficiency, especially in postfarm part of the supply chain.

Comparison of this study with others shows that methods matter. Discrepancies in results are well explained by different system boundaries, allocation methods and computation of emissions, especially with regard to LUC, enteric CH_4 and feed N_2O. The many different methods that are being used to measure and assess the emissions of animal rearing make it difficult to compare results and set priori-

ties for the continuous improvement of environmental performance along supply chains. This calls for an effort to harmonize approaches and data used in this kind of analysis.

This report presents an update and refinement of the previous assessment in *Livestock's long shadow* (FAO, 2006). It should be understood as one step in a series of assessments, to measure and guide progress in the sector's environmental performance.

Numerous hypothesis and methodological choices were made, introducing a degree of uncertainty in the results. Furthermore, data gaps forced the research team to rely on generalizations and projections. A partial sensitivity analysis was conducted in order to illustrate the effect of these approximations. Results were tested for methodological choices regarding land-use change emissions and input data uncertainty. This partial analysis showed that the emission intensity at 95% confidence interval is ±50%

Priorities for refinement of GLEAM include:

- Information about the feed rations, particularly the amount of roughage, by-products and concentrates in the ration;
- Information on manure management;
- Methods for allocation of emissions, especially for slaughter by-products;
- Quantification of the emissions associated with land use and LUC;
- Quantification of feed N_2O that better reflect where and how manure N is applied to crops.

Methodological developments are been carried out by private and public sector organizations to improve the accuracy and comparability of results over time. LEAP – the Partnership on Livestock Environmental Assessment and Performance[11] will be instrumental to these developments; this multi-stakeholder initiative is facilitated by FAO and involves government representatives, private sector organizations and civil society in an effort to harmonize indicators and methods for the assessment of environmental performance in the livestock sector.

Although estimating GHG emissions from the sector provides an important starting point for understanding the sector's potential for mitigating emissions, identifying approaches to reduce emissions requires complementary analysis.

First, the private and public costs of mitigation, as well as the social dimensions associated with technology changes and the impact of mitigation efforts on food consumption trends, should be understood in order to identify viable and acceptable options. Several groups are addressing these questions, including FAO. There is also a need to broaden the scope of environmental performance assessment beyond GHG emissions, in order to avoid undesired policy outcomes. GLEAM will progressively be adapted to compute a wider set of metrics that enable several environmental parameters to be quantified. The model provides a consistent and transparent analytical framework within which to explore proposed mitigation methods, thereby providing an empirical basis for policy-making.

[11] http://www.fao.org/ag/againfo/livestock-benchmarking/en/

References

Beauchemin, K.A., Janzen, H.H., Little, S.M., McAllister, T.A. & McGinn, S.M. 2010. Life cycle assessment of greenhouse gas emissions from beef production in western Canada: A case study. *Agricultural Systems*, 103: 41–50.

Biswas, W.K., Graham, J., Kelly, K. & John, M.B. 2010. Global warming contributions from wheat, sheep meat and wool production in Victoria, Australia – A life cycle assessment. *Journal of Cleaner Production*, 18(14): 1386–1392.

BSI. 2008. PAS 2050:2008. Specification for the assessment of the life cycle greenhouse gas emissions of goods and services. British Standards Institution. London.

BSI. 2012. PAS 2050-1:2012. Assessment of life cycle greenhouse gas emissions from horticultural products Supplementary requirements for the cradle to gate stages of GHG assessments of horticultural products undertaken in accordance with PAS 2050. British Standards Institution. London.

Capper, J., Cady, R.A. & Bauman, E.D. 2008. The relationship between cow production and environmental impact.

Casey, J.W. & Holden, N.M. 2006. Quantification of GHG emissions from suckler-beef production in Ireland. *Agricultural Systems*, 90: 79-98.

Castillo, A.R., Kebreab, E., Beever, D.E. & France, J. 2000. A review of efficiency of nitrogen utilization in dairy cows and its relationship with environmental pollution. *J. Anim. Feed Sci.* 9: 32.

Cederberg, C. & Flysjö, A. 2004. Environmental assessment of future pig farming systems - quantifications of three scenarios from the FOOD 21 synthesis work. *The Swedish Institute for Food and Biotechnology,* SIK Report No. 723: 1–54.

Cederberg, C. & Stadig, M. 2003. System expansion and allocation in life cycle assessment of milk and beef production. *Int. J. Life. Cycle Assess.*, 8(6): 350–356.

Cederberg, C., Meyer, D. & Flysjö, A. 2009. *Life cycle inventory of greenhouse gas emissions and use of land and energy in Brazilian beef production*. SIK Report No. 792.

de Vries, M. & de Boer, I.J.M. 2010. Comparing environmental impacts for livestock products: A review of life cycle assessments. *Livestock Science,* 128: 1-11.

Del Prado, A. & Scholefield, D. 2008. Use of SIMSDAIRY modelling framework system to compare the scope on the sustainability of a dairy farm of animal and plant genetic-based improvements with management-based changes. *Journal of Agricultural Science*, 146: 195-211.

Eckard, R.J., Chapman, D.F. & White, R.E. 2007. Nitrogen balances in temperate perennial grass and clover dairy pastures in south-eastern Australia. *Aust. J. Agric. Res*., 58: 1167–1173.

Ecoinvent. 2009. Swiss Centre for Life Cycle Inventories database. Available at http://www.ecoinvent.ch/

Edward-Jones, G., Plassmann, K. & Harris, I.M. 2009. Carbon footprinting of lamb and beef production systems: insights from an empirical analysis of farms in Wales, UK. *Journal of Agricultural Science*, 147: 707-719.

FAO. 1996. *World livestock production systems: current status, issues and trends*, by Seré, C. & Steinfeld, H. FAO Animal Production and Health Paper 127. FAO. Rome.

FAO. 2006. *Livestock's long shadow – Environmental issues and options,* by Steinfeld, H., Gerber, P., Wassenaar, T., Castel, V., Rosales, M. & de Haan, C. FAO. Rome.

FAO. 2007. *Gridded livestock of the world 2007*, by Wint, W. & Robinson, T. FAO. Rome.

FAO. 2010. *Greenhouse gas emissions from the dairy sector – A life cycle assessment,* by Gerber, P., Opio, C., Vellinga, T., Herderson, B. & Steinfeld, H. FAO. Rome.

FAO. 2013a. *Tackling climate change through livestock*, by Gerber, P., Steinfeld, H., Henderson, B., Opio, C., Mottet, A., Dijkman, J., Falcucci, A. & Tempio, G. FAO. Rome.

FAO. 2013b. *Greenhouse gas emissions from pig and chicken supply chains – A life cycle assessment*, by MacLeod, M., Gerber, P., Mottet, A., Tempio, G., Falcucci, A., Opio, C., Henderson, B. & Steinfeld H. FAO. Rome.

FAOSTAT. 2009. FAO Statistical Database. Accessed 2009.

FAOSTAT. 2011. FAO Statistical Database. Accessed 2011.

FAOSTAT. 2012. FAO Statistical Database. Accessed 2012.

Ferreira, N., Cattoni, C.J., Caceres, S.C. & Frutos, J. 2007. An economic opportunity survey of small dairy farms in Paraguay. *Trop. Anim. Health Prod.*, 39: 603-610.

Flysjö, A., Cederberg, C. & Strid, I. 2008. LCA-databas för konventionella fodermedel - miljöpåverkan i samband med production. *SIK rapport No. 772*, Version 1.1.

Foley, P.A., Crosson, P., Lovett, D.K., Boland, T.M., O'Mara, F.P. & Kenny, D.A. 2011. Whole-farm systems modeling of greenhouse gas emissions from pastoral suckler beef cow production systems. *Agriculture, Ecosystems & Environment,* 142: 222-230.

Fréchou, R.V. 2002. Las actividades percuarias en el MERCOSUR.

Gerber, P., Vellinga, T., Opio, C. & Steinfeld, H. 2011. Productivity gains and greenhouse gas emissions intensity in dairy systems. *Livestock Science*, 139(1-2): 100–108.

Haberl, H., Erb, K.H., Krausmann, F., Gaube, V., Bondeau, A., Plutzar, C., Gingrich, S., Lucht W. & Fischer-Kowalski M. 2007. Quantifying and mapping the global human appropriation of net primary production in Earth's terrestrial ecosystem. *Proceedings of the National Academy of Sciences of the USA* 104: 12942-12947.

Houghton, R.A. & Goodale, C.L. 2004. Effects of LUC on the carbon balance of terrestrial ecosystems. *In* DeFries, R.S., Asner, G.P. & R.A. Houghton, eds. *Ecosystems and Land-use change*. Washington, D.C., American Geophysical Union.

IEA. 2009. International Energy Agency – Statistical database. http://www.iea.org.

Institut de l'Élevage. 2011. Institut de l'Élevage, France. http://www.inst-elevage.asso.fr/

IPCC. 2000. Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories. Penman, J., Kruger, D., Galbally, I., Hiraishi, T., Nyenzi, B., Enmanuel, S., Buendia, L., Hoppaus, R., Martinsen, T., Meijer, J., Miwa, K. and Tanabe, K. (Eds). Intergovernmental Panel on Climate Change (IPCC), IPCC/OECD/IEA/IGES, Hayama, Japan.

IPCC. 2003. Good Practice Guidance for Land Use, land-Use Change and Forestry. Penman, J., Gytarsky, M., Hiraishi, T., Kruger, D., Pipatti, R., Buendia, L., Miwa, K., Ngara, T., Tanabe, K. and Wagner, F. (eds). Intergovernmental Panel on Climate Change (IPCC), IPCC/IGES, Hayama, Japan.

IPCC. 2006. *2006 IPCC Guidelines for National Greenhouse Gas Inventories prepared by the National Greenhause Gas Inventories Programme,* Eggleston, H.S., Buenida, L., Miwa, K., Nagara, T. & Tanabe, K. (eds). Published: IGES, Japan.

IPCC. 2007. *Climate change 2007: IPCC Fourth Assessment Report*. Cambridge University Press, UK.

ISO. 2006. *Environmental management – Life Cycle Assessment – Requirements and guidelines*. ISO 14044. Geneva.

Kanyarushoki, C., van der Werf, M.G.H. & Fuchs, F. 2010. Life cycle assessment of cow and goat milk chains in France. *Proceedings of LCA Food 2010*. Bari, Italy.

Ledgard, S.F., Lieffering, M., Coup, D. & O'Briens, B. 2011. Carbon footprinting of New Zealand lamb from the perspective of an exporting nation. *Animal Frontiers*, 1(1): 40–45.

Leip, A., Weiss, F., Wassenaar, T., Perez, I., Fellmann, T., Loudjani, P., Tubiello, F., Grandgirard, D., Monni, S. & Biala, K. 2010. *Evaluation of the livestock sector's contribution to the EU greenhouse gas emissions (GGELS) - Final Report*, European Commission, Joint Research Centre.

Nguyen, T.L.T., Hermansen, J.E. & Mogensen, L. 2010. Environmental consequences of different beef production systems in the EU. *J. Clean. Prod*. 18: 756-766.

Oenema, O., Wrage, N., Velthof, G. L., van Groenigen, J. W., Dolfing, J. & Kuikman, P. J. 2005. Trends in global nitrous oxide emissions from animal production systems. *Nutrient Cycling in Agroecosystems,* 72(1): 51-65.

Ogino, A., Orito, H., Shimada, K. & Hirooka, H. 2007. Evaluating environmental impacts of the Japanese beef cow-calf system by the life cycle assessment method. *Animal Science Journal,* 78: 424–432.

Ominski, K.H., Boadi, D.A., Wittenberg, K.M., Fulawka, D.L. & Basarab, J.A. 2003. Estimates of enteric methane emissions from cattle in Canada using the IPCC Tier-2 methodology.

Pelletier, N., Pirog, R. & Rasmusssen, R. 2010. Comparative life cycle environmental impacts of three beef production strategies in the upper Midwestern United States. *Agricultural Systems*, 103: 41–50.

Perera, B.M.A.O. 2011. Reproductive cycles of buffalo. *Anim Reprod Sci*, 124(3-4): 194-99.

Peters, G.M., Rowley, H.V, Wiedemann, S., Tucker, R., Short, M.D. & Schulz, M. 2010. Red meat production in Australia: Life cycle assessment and comparison with overseas studies. *Environ. Sci. Technol.*, 44(4): 1327–1332.

Ramankutty, N., Gibbs, H.K., Achard, F., Defries, R., Foley, J.A. & Houghton, R. A. 2006. Challenges to estimating carbon emissions from tropical deforestation. *Global Change Biol*., 13: 51–66, 2007.

Ripoli-Bosch, R., de Boer, I.J.M., Bernues, A. & Vellinga, T. 2010. Greenhouse gas emissions throughout the life cycle of Spanish lamb-meat: a comparison of three production systems. In: *Economic, social and environmental sustainability in sheep and goat production systems*. 7th International Seminar of the FAO-CIHEAM Network on Sheep and Goats, Sub- Network on Production Systems, Zaragoza, Spain.

Schils, R.L.M., de Haan, M.H.A., Hemmer, J.G.A., van den Pol-van Dasselaar, A., de Boer, J.A., Evers, A.G., Holshof, G., van Middelkoop, J.C. & Zom, R.L.G. 2007. DairyWise, a whole-farm dairy model. *J. Dairy Sc.,* 90: 5334–5346.

Thomassen, M. A., Dalgaard, R., Heijungs, R. & de Boer, I. 2008. Attributional and consequential LCA of milk production. *International Journal of Life Cycle Assessment*, 13(4): 339–349.

UNFCCC. 2009a. 2009 Annex I Party GHG Inventory Submissions. from http://unfccc.int/national_reports/annex_i_ghg_inventories/national_inventories_submissions/items/4771.php.

UNFCCC. 2009b. Non-Annex I National Communications. from http://unfccc.int/national_reports/non-annex_i_natcom/items/2979.php.

Verge, X.P.C., Dyers, J.A., Desjardins, R.L. & Worth, D. 2008. Greenhouse gas emissions from the Canadian beef industry. *Agricultural Systems*, 98(2): 126–134.

Weiss, F. & Liep, A. 2012. Greenhouse gas emissions from the EU livestock sector: a life cycle assessment carried out with the CAPRI model. *Agriculture, Ecosystems & Environment*, 149: 124–134.

Williams, A., Audsley, E. & Sandars, D.L. 2006. *Determining the environmental burdens and resource use in the production of agricultural and horticultural commodities.* DEFRA project report IS0205. Department for Environment, Food and Rural Affairs. London.

Wood, S. & Cowie, A. 2004. *A review of greenhouse gas emission factors for fertiliser production.* Research and Development Division, State Forests of New South Wales. Cooperative Research Centre for Greenhouse Accounting for IEA Bioenergy Task 38.

Yamaji, K., Ohara, T. & Akimoto, H. 2003. A country-specific, high resolution emission inventory for methane from livestock in Asia in 2000. *Atmospheric Environment*, 37: 4393–4406.

You, L., Crespo, S., Guo, Z. Koo, J., Ojo, W., Sebastian, K., Tenorio, T.N., Wood, S. & Wood-Sichra, U. 2010. Spatial Production Allocation Model (SPAM) 2000, Version 3. Release 2. Available at http://MapSPAM.info

Zervas, G. & Tsiplakou, E. 2012. An assessment of GHG emissions from small ruminants in comparison with GHG emissions from large ruminants and monogastric livestock. *Atmospheric Environment*, 49: 13–23.

Zhou, J.B., Jiang, M.M., & Chen, G.Q. 2007. Estimation of methane and nitrous oxide emission from livestock and poultry in China during 1949–2003. *Energy Policy,* 35: 3759–3767

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APPENDIX A

The Global livestock environmental assessment model (GLEAM)

1. INTRODUCTION

The Global Livestock Environmental Assessment Model (GLEAM) is a process-based static model that simulates the functioning of livestock production systems. The current version of the model (V1.0) focuses primarily on the quantification of GHG emissions, but future versions will include other processes and flows for the assessment of other environmental impacts, such as those related to water, nutrient and land use.

The model differentiates the 11 main livestock commodities, which are: meat and milk from cattle, sheep, goats and buffalo; meat from pigs; and meat and eggs from chickens. It calculates the GHG emissions and production for a given production system within a defined spatial area, thereby enabling the calculation of the emission intensity for combinations of commodities, farming systems and locations.

The main purpose of this appendix is to explain the way in which GLEAM calculates the emission intensity of livestock products. The input data used in GLEAM (and associated issues of data quality and management) are addressed in Appendix B. The focus of this appendix is on:

- providing an overview of the main stages of the calculations;
- outlining the formulae used; and
- explaining some of the key assumptions and methodological choices made.

2. MODEL OVERVIEW

The model is GIS-based and consists of:

- input data layers;
- routines written in Python (http://www.python.org/) that calculate intermediate and output parameters; and
- procedures for running the model, checking calculations and extracting output.

The basic spatial unit used in the GIS is a cell of 3 arc minutes. The emissions and production are calculated for each cell using input data of varying levels of spatial resolution (see Appendix B). The overall structure of GLEAM is shown in Figure A1, and the purpose of each module summarized below.

- The **herd module** starts with the total number of animals of a given species and system within a cell (see Appendix B for a brief description of the way in which the total animal numbers are determined). The module also determines the herd structure (i.e. the number of animals in each cohort group, and the rate at which animals move between cohort groups) and the characteristics of the average animal in each cohort (e.g. weight and growth rate).
- The **manure module** calculates the rate at which excreted N is applied to pasture and crops.

- The **feed module** calculates key feed parameters, i.e. the nutritional content and emissions per kg of the feed ration.
- The **system module** calculates each animal's energy requirement, and the total amount of animal product (milk, meat and fibre) produced in the cell each year. It also calculates the total annual emissions arising from manure management, enteric fermentation and feed production.
- The **allocation** module combines the emissions from the system module with the emissions calculated outside GLEAM, i.e. emissions arising from (a) direct on-farm energy use; (b) the construction of farm buildings and manufacture of equipment; and (c) post-farm transport and processing. The total emissions are then allocated to output in the form of products and services (milk, meat and eggs, fibre and draught power) and the emission intensity per unit of commodity calculated. Each of the stages in the model is described in more detail below.

3 HERD MODULE

The functions of the herd module are to:

- Determinate the herd structure, i.e. the proportion of animals in each cohort, and the rate at which animals move between cohorts; and
- Calculate the characteristics of the animals in each cohort, i.e. the average weight and growth rate of adult females and adult males.

Emissions from livestock vary depending on animal type, weight, phase of production (e.g. whether lactating or pregnant) and feeding situation. Accounting for these variations in a population is important if emissions are to be accurately characterized. The use of the IPCC (2006) Tier 2 methodology requires the animal population to be categorized into distinct cohorts. Data on animal herd structure are generally not available at the national level. Consequently, a specific herd module was developed to decompose the herd into cohorts. The herd module characterizes the livestock population by cohort, defining the herd structure, dynamics and production.

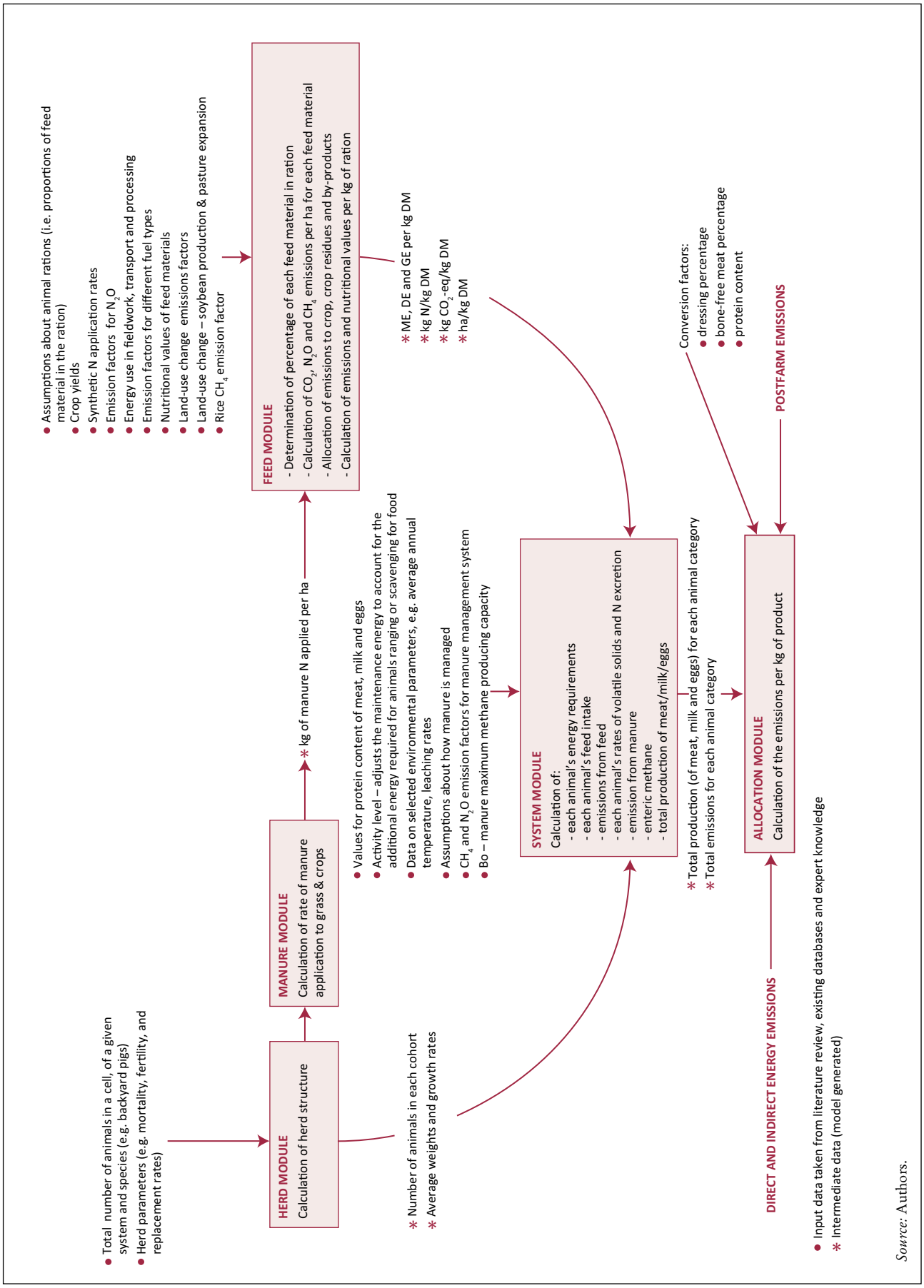
Herd structure. The national herd is disaggregated into six cohorts of distinct animal classes: adult female and adult male, replacement female and replacement male, and male and female surplus or fattening animals which are not required for maintaining the herd. Figure A2 provides an example of a herd structure (in this case for cattle). In this assessment it is assumed that all surplus calves are fattened for meat.[12]

The key production parameters required for herd modeling include data on *mortality, fertility, growth and replacement rates,* also known as "rate parameters". In addition, other parameters are used to define the herd structure. They include:

- the age or weight at which animals transfer between categories e.g. the age at first parturition for replacement females or the weight at slaughter for fattening animals;
- duration of key periods i.e. gestation, lactation, time between servicing; and
- the ratio of breeding females to males.

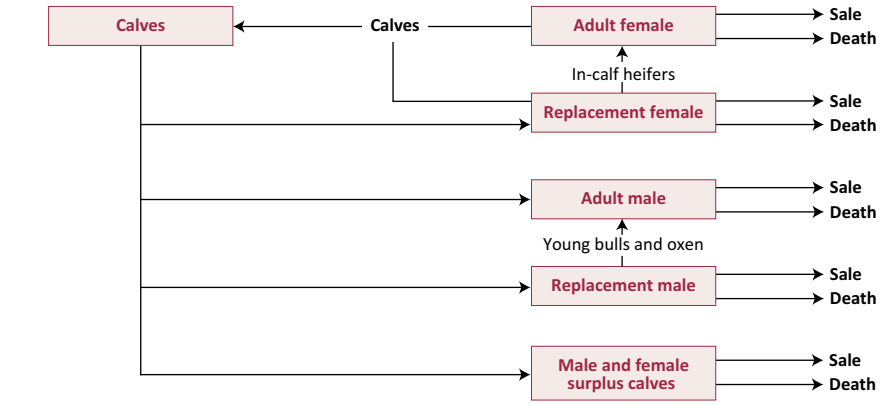
[12] In some intensive dairy systems, surplus calves may be slaughtered within a few days after birth.

Figure A1.
Schematic representation of GLEAM



Source: Authors.

Figure A2.
Structure of herd dynamics for cattle



Source: Authors.

4. MANURE MODULE

The function of the manure module is to calculate the rate at which excreted N is applied to feed crops.

The manure module calculates the amount of manure N collected and applied to grass and cropland in each cell by:

- calculating the amount of N excreted in each cell by multiplying the number of each animal type in the cell by the average N excretion rates;
- calculating the proportion of the excreted N that is lost during manure management and subtracting it from the total N, to arrive at the net N available for application to land; and
- dividing the net N by the area of (arable and grass) land in the cell to determine the rate of N application per ha.

5. FEED MODULE

The functions of the feed module are to:

- Calculate the composition of the ration for each species, system and location;
- Calculate the nutritional values of the ration per kg of feed DM; and
- Calculate of GHG emissions and land use per kg of DM of ration.

The feed module determines the diet of the animal, i.e. the percentage of each feed material in the ration, and calculates the emissions (N_2O, CO_2 and CH_4) arising from the production, processing and transport of the feed. It allocates the emissions to crop co-products such as crop residues or meals) and calculates the emission intensity per kg of feed. It also calculates the nutritional value of the ration, in terms of its energy and N content.

5.1 Determination of the ration

Animal rations are generally a combination of different feed ingredients. For ruminants, three broad categories of feed are considered: roughages, by-products and concentrates. Typically, major feed ingredients include:

- Grass: ranges from natural pasture and roadsides to improved and cultivated grasslands and leys.
- Feed crops: crops specially grown to feed livestock, e.g. maize silage or grains.
- Tree leaves: browsed in forests or collected and carried to livestock.
- Crop residues: plant material left over from food or other crops, such as straw or stover, left over after harvesting.
- Agro-industrial by-products and wastes: by-products from the processing of non-feed crops such as oilseeds, cereals, sugarcane, and fruit. Examples include cottonseed cakes, rapeseed cakes and brans.
- Concentrates: high quality mixtures of by-products and feed that are processed at specialized feed mills into compound feed.

In all livestock production systems, the composition of the feed ration depends on the availability of pasture and fodder, the crops grown and their respective yields. The fraction of concentrates in the ration varies widely, according to the need to complement locally available feed, the purchasing power of farmers, and access to markets. While actual diets will vary depending on what crops are grown locally and the price of feed crops, the balance of forage, crops and by-products must be reasonable in order to match animal performance. The proportion of each feed component is determined differently for industrialized and developing country regions:

- for the industrialized regions, the composition (i.e. feed materials) and relative portions of the feed ration materials are taken from country national inventory reports, literature and targeted surveys.
- for developing countries, due to scanty information, a feed allocation scheme was devised based on literature and expert knowledge. This allocation scheme assumes that in developing regions there is a close relationship between land use and the feed ration.

Feed allocation scheme for developing countries. The feed allocation scheme is based on the availability of feed resources (crops and forage) and animal requirements. The determination of the feed ration is outlined stepwise below:

1. Define the proportion of by-products and concentrates in the ration (based on surveys, literature and expert knowledge) and the difference is considered roughages.
2. Calculate the total roughage availability in each pixel based on the dry matter yields per hectare of pasture, fodder and crop residues and the land area of the respective feeds. Data for this calculation was obtained from a number of sources: FAOSTAT for specific crops (e.g. fodder beet, soybean, rapeseed, cottonseed, sugar beet and palm fruit); You *et al.* (2010) from the Spatial Production Allocation Model (SPAM) for 20 crops; and Haberl *et al.* (2007) to estimate the above-ground net primary productivity for pasture.
3. Feed requirements for all ruminant species were then assessed. This was done by expressing the different ruminant species and categories of animals in cattle equivalent, to take into account the fact that these animals are competing for the same feed resource.
4. To assess the feed availability, a ratio between the total roughage availability (calculated in 2 above) and ruminant species biomass (in cow equivalent calculated in 3 above) was obtained.

5. Total ruminant annual feed requirements are then calculated for the total cow equivalent based on the assumption that an animal consumes about 2 to 3 percent of its bodyweight on a daily basis and hence, on an annual basis, DMI will range between 7.3 and 14 kg DM.
6. The total amount of roughage feed available is then compared with the animal feed requirements within each cell. Comparing the total feed availability with the animal requirements provides an indication of feed adequacy in terms of sufficiency, deficiency or surplus for any given location. An area can be classified based on the dry matter availability and generally a dry matter availability of less than 2 percent of the bodyweight can be considered as a deficit, dry matter availability between 2 and 3 percent can be considered as adequate, and above 3 percent can be considered as surplus. In situations where ample feed is not available to meet the requirements of the animals (i.e. less than 2 percent), the feed ration is supplemented with leaves and hay.
7. The proportion of each roughage material within the feed ration is then obtained by dividing the quantity available of each roughage material by the total available roughage.
8. The proportions of the roughage materials (calculated in 7 above) plus the by-products and concentrate proportions (defined in 1 above) form the total feed ration which sums to 100.

Tables B7 to B12 in Appendix B present the average feed rations and the proportions of the different feed materials within the feed ration for the world's main regions and species.

5.2 Determination of the ration's nutritional values

Nutritional values such as the digestibility and N-content of each individual feed material are used to calculate the nutritional value of animal feed rations. These nutritional values are multiplied by the percentage of each feed material in the ration to arrive at the average energy and N content per kg of DM for the ration as a whole. Table B13 in Appendix B compares regional variation in digestibility of feed rations for ruminant species.

5.3 Determination of the ration's GHG emissions and land use per kg of DM from feed

The categories of GHG emission included in the assessment of each feed material's emissions are:

- direct and indirect N_2O from grass and crop cultivation;
- CO_2 arising from loss of above and below ground carbon brought by land-use change;
- CO_2 from the on-farm energy use associated with field operations (tillage, manure application, etc.) and crop drying and storage;
- CO_2 arising from the manufacture of fertilizer;
- CO_2 arising from crop transport; and
- CO_2 arising from off-farm crop processing.

A brief outline of how the emissions were calculated is provided below.

Determination of feed emissions: N_2O from pasture and crop cultivation. Nitrous oxide emissions from cropping include direct N_2O, and indirect N_2O from leach-

ing and volatilization of ammonia. It was calculated using the IPCC (2006) Tier 1 methodology. Synthetic N application rates were defined for each crop at a national level, based on existing data sets (primarily FAO's fertilizer use statistics, http://www.fao.org/ag/agp/fertistat/index_en.htm) and adjusted down where yields were below certain thresholds. Manure N application rates were calculated in the manure module. Crop residue N was calculated using the crop yields and the IPCC (2006, Volume 4, Chapter 11, p. 11.17) crop residue formulae.

Determination of pasture and crop emissions: CO_2 from land-use change. The approach for estimating emissions from land-use change is presented in Appendix C.

Determination of feed emissions: CO_2 from fertilizer manufacture. The manufacture of synthetic fertilizer is an energy-intensive process, which can produce significant amounts of GHG emissions, primarily via the use of fossil fuels, or through electricity generated using fossil fuels. The emissions per kg of fertilizer N will vary depending on the factors such as the type of fertilizer, the efficiency of the production process, the way in which the electricity is generated, and the distance the fertilizer is transported. Due to the lack of reliable data on these parameters, and on fertilizer trade flow, the average European fertilizer emissions factor of 6.8 kg CO_2-eq per kg of ammonium nitrate N in all regions was used (Jenssen and Kongshaug, 2003), which includes N_2O emissions arising during manufacture.

Determination of feed emissions: CO_2 from field operations. Energy is used on-farm for a variety of field operations required for crop cultivation, such as tillage, preparation of the seed bed, sowing and application of synthetic and organic fertilizers, crop protection and harvesting. The type and amount of energy required per ha, or kg, of each feed material parent crop was estimated. In some countries, field operations are undertaken using non-mechanized power sources, i.e. human or animal labour. The energy consumption rates were adjusted to reflect the proportion of the field operations undertaken using non-mechanized power sources. Table A1 gives an indication of the average level of mechanization per region. From the level of mechanization, we also inferred reliance on animal draught power in the country, and therefore the bull to cow ratio in the herd. The emissions arising from fieldwork per ha of each crop were calculated by multiplying the amount of each energy type consumed per ha, by the emissions factor for that energy source.

Table A1. Estimated average level of mechanization by region

Continent	Estimated rate of mechanisation *(percentage)*
Africa	16
Asia	78
Central and South America	96
Europe	100
North America	100
Oceania	100

Source: FAOSTAT (2009).

Determination of feed emissions: CO_2 from transport and processing. Pasture and crop residues, by definition, are transported minimal distances and are allocated zero emissions for transport. Non-local feeds are assumed to be transported between 100 km and 700 km by road to their place of processing. In countries where more of the feed is consumed than is produced (i.e. net importers), feed that are known to be transported globally (e.g. soybean meal) also receive emissions that reflect typical sea transport distances. Emissions from processing arise from the energy consumed in activities such as milling, crushing and heating, which are used to process whole crop materials into specific products. Therefore, this category of emissions applies primarily to feeds in the by-product category.

Determination of feed emissions: CO_2 from blending and transport of compound feed. Energy is used in feed mills for blending non-local feed materials to produce compound feed and to transport it to its point of sale. It was assumed that 186 MJ of electricity and 188 MJ of gas were required to blend 1 000 kg of DM, and that the average transport distance was 200 km.

5.4 Allocation of emissions between crop and its by-products

In order to calculate the emission intensity of the feed materials, emissions need to be allocated between the crop and its by-products, i.e. the crop residue or by-products of crop processing used as feed. The general expression used is:

$$GHGkgDM = GHGha/(DMYGcrop \cdot FUEcrop + DMYGby \cdot FUEby) \cdot EFA/MFA$$

where:

GHGkgDM	=	emissions (of CO_2, N_2O, or CH_4) per kg of dry matter
GHGha	=	emissions per ha
DMYGcrop	=	gross crop yield (kgDM/ha)
DMYGby	=	gross crop residue or by-product yield (kgDM/ha)
FUEcrop	=	feed use efficiency, i.e. fraction of crop gross yield harvested
FUEby	=	feed use efficiency, i.e. fraction of crop residue or by-product gross yield harvested
EFA	=	economic fraction, crop or co-product value as a fraction of the total value (of the crop and co-product)
MFA	=	mass fraction, crop or co-product mass as a fraction of the total mass (of the crop and co-product)

Dry matter yields and estimated harvest fractions were used to determine the mass fractions. Where crop residues were not used for feed or bedding, they were assumed to have a value of zero, i.e. 100 percent of the emissions were allocated to the crop.

Allocation techniques of feed emissions is summarized in Table A2. Emissions from post-processing blending and transport are allocated entirely to feed. It should be highlighted that emissions that are not allocated to feed do not cease to exist. Rather, they are allocated to other commodities. Failure to follow this approach may lead to incorrect policy conclusions.

Table A2. Summary of the allocation techniques used in the calculation of plant-based feed emissions

Products	Source of emissions	Allocation technique
All feed crops and their by-products	N_2O from manure application N_2O from synthetic fertilizer CO_2 from fertilizer manufacture CO_2 from fieldwork	Allocation between the crop and co-product is based on the mass harvested, and the relative economic values (using digestibility as a proxy)
By-products only	CO_2 from processing CO_2 from LUC (for soybean)	Allocated to the processing by-products based on mass and economic value
Feed produced off-farm	CO_2 from transportation and blending	100 percent to feed material

Source: Authors.

6. SYSTEM MODULE

The functions of the system module are to:

- Calculate the average energy requirement (MJ) and feed intake (kg DM) of each animal cohort;
- Calculate the total feed emissions and land use arising from the production, processing and transport of the feed;
- Calculate the CH_4 and emissions arising during the management of manure;
- Calculate enteric CH_4 emissions.

6.1 Calculation of animal energy requirement

The system module calculates the energy requirements of each animal, which is then used to determine the feed intake (in kg of DM). The model uses the IPCC Tier 2 algorithms (IPCC, 2006 Volume 4, Chapter 10, Equations 10.3 to 10.13) to calculate energy requirements for each animal sub-category. The gross energy requirement is the sum of the requirements for maintenance, lactation and pregnancy, animal activity, weight gain and production.[13] The method estimates a maintenance requirement (as a function of live-weight and energy expended in feeding); a production energy requirement influenced by the level of productivity (e.g. milk yield, live-weight gain, wool production); physiological state (pregnancy and lactation); and the stage of maturity of the animal. Based on production and management practices, the net energy and feed requirements of all animals are first calculated, taking into account the following parameters:

- *Weight*. Larger animals need more energy for maintenance than smaller ones.
- *Production*. The output from animals can be milk and meat, but also non-edible products and services. Data on production of edible and non-edible products is taken from literature and statistical databases. In general terms, a higher production or more labour per day requires more energy and thus more feed per day.

[13] Total production is computed on the basis of herd parameters (reproduction, mortality, etc.) and productivity parameters (such as milk yield and weight gain) used in the analysis. Consequently, total production may not be consistent with total production in the FAOSTAT database.

- *Production/feeding environment (Grazing or stall feeding).* Animals in ranging systems that have to search for their feed (often over long distances) have higher energy requirements than those in grazing systems or stall-fed systems.

6.2 Calculating feed intake, total feed emissions and land use

The feed intake of each animal category (in kg DM/day) is calculated by dividing the animal's energy requirement by the average energy content of the ration from the feed module:

Feed intake (kgDM/animal/day) = total energy requirements (MJ/animal/day)/feed energy content (MJ/kgDM)

where: feed energy content = 18.45 (MJ/kgDM)

The feed intake of each cohort is multiplied by the number of animals in each group to obtain the total daily feed intake for the entire herd. The feed emissions and land use associated with the feed production are then calculated by multiplying the total feed intake for the herd by the emissions or land use per kg of DM taken from the feed module.

6.3 Calculation of CH_4 emissions arising enteric fermentation

Emissions from enteric fermentation (kg CH_4/head) are a function of feed digestibility (DE), i.e. the percentage of gross energy intake that is metabolized. An enteric methane conversion factor, Y_m (percentage of gross energy converted to methane) is used to calculate the methane emissions from enteric fermentation. A Tier 2 approach is applied for the calculation of enteric CH_4 emissions due to the sensitivity of emissions to diet composition and the relative importance of enteric CH_4 to the overall GHG emissions profile in ruminant production. The IPCC (2006) defines the CH_4 conversion factor (Y_m) as 6.5±1 percent, indicating that Y_m is at the high end of the range when digestibility of feed is low and vice versa. The Y_m value of 6.5 is realized at a digestibility of 65 percent. To better reflect the wide-ranging diet quality and feeding characteristics globally, this assessment developed specific Y_m values based on the following formula:

$$Y_{m\ Cattle} = 9.75 - 0.05 \cdot DE$$
$$Y_{m\ mature\ sheep} = 9.75 - 0.05 \cdot DE$$
$$Y_{m\ lamb<1\ year} = 9.75 - 0.05 \cdot DE$$

Y_m is subsequently used in the following formula to estimate the CH_4 emission factor

$$EFCH_4 = (365 \cdot GE \cdot (Y_m / 100) / 55.65)$$

where: $EFCH_4$ is the CH_4 emission factor (kg CH_4 head $^{-1}$ yr $^{-1}$); Y_m corresponds to CH_4 conversion factor; GE is the gross energy intake (MJ head^{-1} day^{-1}) and the factor 55.65 (MJ kg CH_4) represents the energy content of CH_4.

6.4 Calculation of CH_4 emissions arising during manure management

Calculating the CH_4 per head from manure using a Tier 2 approach requires (a) estimation of the rate of excretion of volatile solids per animal, and (b) estimation of the proportion of the volatile solids that are converted to CH_4. The volatile solids excretion rates are calculated using Equation 10.24 from IPCC (2006). Once the volatile solids excretion rate is known, the proportion of the volatile solids converted to CH_4 during manure management per animal per year can be calculated using Equation 10.23 from IPCC (2006).

The CH_4 conversion factor depends on how the manure is managed. In this study, the manure management categories and emission factors in IPCC (2006, Volume 4, Chapter 10, Table 10A-7) were used. The proportion of manure managed in each system is based on official statistics (such as the Annex I countries' National Inventory Reports to the UNFCCC), other literature sources and expert judgement.

6.5 Calculation of N_2O emissions arising during manure management

Calculating the N_2O per head from manure using a Tier 2 approach requires (a) estimation of the rate of N excretion per animal, and (b) estimation of the proportion of the excreted N that is converted to N_2O.

The N excretion rates are calculated using Equation 10.31 from IPCC (2006) as the difference between intake and retention. N-intake depends on the feed dry matter intake and the N content per kg of feed. The feed dry matter intake depends, in turn, on the animal's energy requirement (which is calculated in the system module, and varies depending on weight, growth rate, milk yield, pregnancy, weight gain and lactation rate and level of activity) and the feed energy content (calculated in the feed module). N retention is the amount of N retained in, either as growth, pregnancy live weight gain or milk.

The rate of conversion of excreted N to N_2O depends on the extent to which the conditions required for nitrification, denitrification, leaching and volatilization are present during manure management. The IPCC (2006) default emission factors for direct N_2O (IPCC, 2006 Volume 4, Chapter 10, Table 10.21) and indirect via volatilization (IPCC, 2006 Volume 4, Chapter 10, Table 10.22) are used in this study, along with variable leaching rates, depending on the AEZ.

7. ALLOCATION MODULE

The functions of allocation module are to:

- Sum up the total emissions for each animal cohort;
- Calculate the amount of each commodity (meat, milk, eggs, wool) produced;
- Allocate emissions to each commodity (meat and meat), non-edible outputs (fibre and manure used for fuel), draught and services; and
- Calculate total emissions and emission intensity of each commodity.

7.1 Calculation of the total emissions for each animal cohort

The system module calculates the total emissions arising from feed production, manure management and enteric fermentation. Post farmgate emissions (Appendix D) and direct and indirect on-farm energy use (Appendix E) are calculated separately and incorporated in the allocation module.

7.2 Calculation of the amount of each commodity (meat, milk, fibre) produced

Milk. Total milk production was calculated based on average milk production per animal and number of milking animals. Total milk is then converted to fat and protein milk. Using FPCM as the basis for comparison ensures a comparison between milk produced by different breeds and feeding regimes. All milk was converted to FPCM using the following equations:

Milk yield from cattle was corrected at 4.0 percent fat and 3.3 percent protein using the equation: FPCM (kg) = milk production, kg • [0.337+ 0.116 • fat, (percent) + 0.06 • protein, (percent)]

Milk yield from small ruminants was corrected at 6.5 percent fat and 5.8 percent protein according to Pulina, Macciotta and Nuda (2004) using the equation: FPCM (kg) = milk production, kg • [0.25+ 0.085 • fat, (percent) + 0.035 • protein, (percent)]

Buffalo milk production was expressed was corrected at 4 percent fat and 3.1 percent protein using the following equation (Di Palo, 1992): FPCM (kg) = milk production, kg • [1+ 0.011 • {(fat, (percent) • 10-40) + (10 • protein, (percent)-31)}]

Meat. Total meat production is calculated from the number of live animals (per cohort group) that leave the farm for slaughter and the live weight at which they are sold. Dressing percentages for the conversion of live weight to carcass weight are given in Appendix B, Tables B20 and B21. Conversion of carcass to bone-free meat is obtained by multiplying by 0.75 and 0.70 for large and small ruminants, respectively. The conversion of bone-free meat (BFM) to protein is based on the assumption that BFM is 18 percent protein by weight.

Natural fibre. Total fibre (wool, mohair and cashmere) is estimated by multiplying kg of fibre produced per animal by the number of fibre producing animals in the herd.

7.3 Allocation to co-products and calculation of emission intensity

For ruminant species, emissions are allocated between the edible commodities, i.e. meat and milk. In reality, there are usually significant amounts of other commodities produced during processing, such as skin, feathers and offal. However, the values of these can vary markedly between countries, depending on the market conditions, which, in turn, depend on factors such as food safety regulations and consumer preferences. Allocating no emissions to these can lead to an over-allocation to meat. The potential effect of this assumption is explored in Appendix F. Allocation techniques applied in this assessment are discussed below:

Meat and milk. Emissions related to goods and services other than meat and milk (e.g. fibre, manure used for fuel, draught power) were first calculated separately and deducted from the overall system emissions, before emissions were attributed to meat and milk.

Within the dairy herd, some animals only produce meat (fattened surplus calves), while others contribute to the combined production of meat and dairy products (milked cows, adult reproduction male animals and replacement stock). For the latter group, we chose to allocate GHG emissions on the basis of their protein con-

Table A3. Example of allocation between edible products from dairy production

	Part of herd producing milk and meat *(milking cows, adult male, replacement stock)*	**Part of herd producing meat only** *(surplus males and females)*
Total emissions *(kg CO_2-eq)*	1 700 000	350 000
Total protein *(kg)*	Milk: 18 000 Meat: 1 500	Meat: 2 500
Fraction of milk protein	0.92	NA
Fraction of meat protein	0.08	1
Emission intensity of milk	= (1 700 000 · 0.92)/18 000 **= 87 kg CO_2-eq/kg protein**	
Emission intensity of meat	= [(1 700 000 · 0.08) + 350 000]/(1 500+2 500) **122 kg CO_2-eq/kg protein**	

NA: Not Applicable.
Source: Authors' calculations.

tent. Table A3 provides an illustration of how the technique is applied. This method reflects the fact that a primary function of the livestock sector is to provide humans with edible protein. The advantages of using protein content are that it enables direct comparison with other food products and is also relatively stable in time (as opposed, for example, to the relative prices of meat and milk) and that it can be applied in situations where markets are absent or where they are highly localized and not comparable across regions. However, a disadvantage is that other nutritional properties, such as minerals, vitamins and energy, and essential fatty acids are not captured.

Emissions related to surplus calves fattened for meat production were entirely attributed to meat production. However, the emissions related to the production of calves, i.e. the pregnancy of the dairy cows and female replacement stocks, were allocated to milk because they are an essential input for milk production. No emissions were allocated to the other parts of the slaughtered animal (e.g. skin, horns), although these are utilized and represent an economic yield. This may result in a slight overestimation of the emissions per kg of carcass weight. In beef herds, all emissions were allocated to meat after the deduction of emissions related to draught power (in the case of cattle) and fibre (wool, cashmere and mohair) from small ruminants.

Manure. Manure is another by-product of livestock production. The emissions related to manure were allocated through the subdivision of the production processes:

- *Emissions related to manure storage* were fully allocated to the livestock system.
- *Emission from manure applied on the land used for feed, food and cash crop production* were allocated to livestock in situations where the crop as a whole or in part (e.g. silage, grain, oilseeds) was used for animal nutrition. In situations where manure was entirely deposited on grassland and feed crops, no allocation was required because the manure remained within the livestock system. On the other hand, where parts of the crop (e.g. crop residues) were used for feed, emissions were allocated according to the relative weight of harvested products used as feed, corrected for digestibility. Due to

the absence of an economic value for crop residues, digestibility was used as a proxy for economic value. In cases where the crop was not used for animal nutrition, emissions were not allocated to livestock.

- *Emissions from manure used for fuel at the household level* leave the livestock system and therefore emissions from burning were not allocated to the livestock system.
- *Emissions from manure discharged into the environment* were solely attributed to livestock activities.

Fibre (wool, cashmere and mohair). Fibre is a by-product of sheep and goat production; however in some countries these products can be considered as main products of production due to their price leverage and market value. In this study, the allocation of the carbon footprint to fibre was performed based on the market value of all system outputs – meat, milk, and fibre products. The fractions of the economic value of the co-product within the total economic value of all products produced by a given species were utilized as an allocation factor to partition GHG emissions between fibre and the edible products. This fraction was determined as:

$$F_w = (Wool_{kg} \cdot Price_{wool})/(Meat_{kg} \cdot Price_{meat} + Milk_{kg} \cdot Price_{milk} + Wool_{kg} \cdot Price_{wool})$$

where: F_w is the ratio of economic value of wool to the total economic value of all products produced. Similar calculations were performed for countries producing cashmere and mohair. Wool, meat and milk represent the mass of the product in kg. Table A4 provides an illustration of how the technique is applied. To implement the total economic value, producers prices averaged over five years were taken from the FAOSTAT price domain, reflecting prices that farmers receive at the farmgate. Subsequent to the deduction of emissions for fibre production from the overall emissions, protein content was then used to allocate emissions between meat and milk.

Table A4. Example of allocation between non-edible (wool) and edible products from sheep dairy production

	Part of herd producing milk, meat and wool			Part of herd producing meat and wool only
Total emissions *(kg CO_2-eq)*	80 000			20,000
Total protein *(kg)*	Milk: 500	Meat: 50		Meat: 200
Total economic value *($)*	Milk: 4 000		Meat: 9 000	Wool: 700
Fraction of milk protein	0.9			NA
Fraction of meat protein	0.1			1
Total emission allocated to wool	=80 000 · [700/(4 000+9 000+700)] **= 4 088 kg CO_2-eq**			=20 000 · [700/(4 000+9 000+700)] **= 1 022 kg CO_2-eq**
Total emissions allocated to milk and meat	= 80 000 – 4 088 **= 75 912 kg CO_2-eq**			= 20 000 – 1 022 **= 18 978 kg CO_2-eq**
Emission intensity of milk	= (75 912 · 0.9)/500 **= 138 kg CO_2-eq/kg protein**			
Emission intensity of meat	= [(75 912 · 0.1) + 18 978]/(50+200) **= 104 kg CO_2-eq/kg protein**			

NA: Not Applicable.
Source: Authors' calculations.

Animal draught power. Herd structure, and thus the emissions profile, is affected by the use of animals, usually oxen, for labour. The use of animals for draught power has an influence on the herd's sex and age structure which skews towards higher ratios of male and older animals. Oxen must grow to maturity before they can be used for traction, and this usually takes four years, and therefore they compete with other stock for feed and other resources. The animals are then generally used for a decade before they are slaughtered. The adult male to female ratio is substantially higher than normal when animals are used for draught power because males are slaughtered at a later age.

To allocate emissions to draught power services, we first calculated total emissions and meat output from draught animals alone. In a subsequent calculation step, emissions related to the meat produced from these animals were estimated as being identical to those of meat produced from non-draught animals, slaughtered at an earlier age. The difference (accruing from the extra lifetime and the energy requirements for the labour of draught animals) was then attributed to draught power services.

Capital functions of cattle. In any cattle production system, animals constitute a form of capital, and can be sold or bought according to investment and cash flow requirements. In many pastoral systems, the capital functions of cattle are a particularly important, because they enable the accrual of savings to manage cash needs, insure against risk, and manage crises in the absence of adequate financial institutions. Therefore, low replacement rates are often a feature in these systems, because cattle are often kept even after their productivity drops. While the provision of these capital functions affects the herd structure and emission profiles of these systems, no emissions were allocated to capital services, due to difficulties in obtaining relevant information.

Slaughter by-products. In addition to the production of carcasses, slaughtering processes also produce a whole package of by-products, organs, hide, blood, etc. that are utilized for other purposes, often outside the livestock food chain. Thus, the allocation of emissions to by-products produced at the slaughterhouse can have a major impact on the GHG emission intensity for meat products. This study did not explicitly take into account by-products from slaughter due to the lack of reliable information and data. However, we explored the impact of their inclusion on emission intensity of beef in a selected case study (see Appendix F).

In terms of edible product, ruminants produce both milk and meat. The emissions were allocated between these two commodities, using the following method:

- Quantify the total emissions from animals required for milk and meat production (adult female and adult male, replacement stock and surplus animals).
- Deduct emissions related to draft power (for large ruminants), and manure used for fuel based on the approaches outlines above.
- For the dairy sector, which produces both milk and meat, emissions are allocated on a protein basis (see Tables A3 and A4). For small ruminants, allocation is first performed between the edible and non-edible products based on economic value and subsequently protein content is used to allocate between milk and meat.

REFERENCES

Di Palo, R. 1992. Produzione lattea nella bufala con diete tradizionali e con impiego di acidi grassi. PhD thesis, Università di Napoli.

FAO. 2007. *Gridded livestock of the world 2007* by Wint, W. and Robinson, T. FAO. Rome.

FERTISTAT. 2009. Fertilizer use statistics, FAO. http://www.fao.org/ag/agp/fertistat/index_en.htm.

Haberl, H., Erb, K. H., Krausmann, F., Gaube, V., Bondeau, A., Plutzar, C., Gingrich, S., Lucht W. & Fischer-Kowalski M. 2007. Quantifying and mapping the global human appropriation of net primary production in Earth's terrestrial ecosystem. *Proceedings of the National Academy of Sciences of the USA* 104: 12942-12947.

IPCC. 2006. 2006 IPCC Guidelines for National Greenhouse Gas Inventories, *Volume 4: Agriculture, Forestry and Other Land Use*. Intergovernmental Panel on Climate Change. Prepared by the National Greenhouse Gas Inventories Programme, Eggleston, H.S., Buendia, L., Miwa, K., Ngara, T. & Tanabe K. eds. Published: IGES, Japan.

Jenssen, T.K. & Kongshaug, G. 2003. Energy consumption and greenhouse gas emissions in fertiliser production. IFS Proceedings No.509. International Fertiliser Society. York.

Pulina, G., Macciotta, N. & Nuda, A. 2004. Milk composition and feeding in the Italian dairy sheep. *Ital. J. Anim. Sci.*, 4(SUPPL. 1): 5-14.

You, L., Crespo, S., Guo, Z., Koo, J., Ojo, W., Sebastian, K., Tenorio, T.N., Wood, S. & Wood-Sichra, U. 2010. *Spatial Production Allocation Model (SPAM) 2000, Version 3. Release 2.* Available at http://MapSPAM.info.

APPENDIX B

Data and data sources

This appendix presents the main data utilized in this assessment. The data can be classified into *basic input data* and *intermediate data*. Basic input data can be defined as primary data such as animal numbers, herd parameters, mineral fertilizer application rates, temperature, crop yields, etc. and are data taken from other sources such as literature, databases, and surveys. Intermediate data are an output of the modelling procedure required in further calculation in GLEAM and may include data on growth rates, animal cohort groups, feed rations, animal energy requirements, feed intake, etc.

1. DATA RESOLUTION AND DISAGGREGATION

Data availability, quality and resolution vary according to the parameter and the country in question. In OECD countries, where farming tends to be more regulated, there are often comprehensive national or regional data sets, and in some cases sub-national data (e.g. for manure management in U.S. dairy). Conversely, in many non-OECD countries, data are unavailable, necessitating the use of regional default values (e.g. herd parameters). Examples of the spatial resolution of some key parameters are given in Table B1.

2. HERD

Livestock distributions. Maps of the spatial distribution of each animal species and production systems are one of the key inputs into the GLEAM model. Total ruminant numbers at a national level are reported in FAOSTAT. The spatial distributions used in this study were based on maps developed in the context of FAO's Gridded Livestock of the World (FAO, 2007).

Herd parameters. The national herd is disaggregated into cohorts according to six animal classes: adult female and male, replacement female and male, and male and female surplus or fattening animals that are not required for maintaining the herd and are kept for meat production only. The key biological parameters required for herd modelling incorporate data on mortality, fertility and growth rate, also known as "rate parameters".

- *Fertility parameters:* data on fertility are usually incorporated in the form of parturition rates (e.g. calving, kidding, lambing rates), and are normally defined as the number of births occurring in a specified female population in a year. For cattle, the number of births per year is assumed to be one. However, in the case of small ruminants, litter size is taken into account. The model utilizes age-specific fertility rates for adult and young replacement females. The proportion of breeding females that fail to conceive is also included.
- *Mortality rates:* data on mortality are incorporated in the form of death rates. In the modelling process, age specific death rates are used; mortality rate in calves and mortality rate in other animal categories. The death rate of

Table B1. Spatial resolution of the main input variables

Parameters	Cell[1]	Subnational	National	Regional[2]	Global
Herd					
Animal numbers	X				
Weights		X →		X	
Mortality, fertility and replacement data		X →		X	
Manure					
N losses rates					X
Management system		X →		X	
Leaching rates				X	
Feed					
Crop yields	X				
Harvested area	X				
Synthetic N fertilizer rate			X		
N residues	X[3]			X[4]	
Feed ration			X[5] →	X	
Digestibility and energy content			X →		X
N content				X →	X
Energy use in fieldwork, transport and processing					X
Transport distances					X
Land-use change					
Soybean (area and trade)			X		
Pasture (area and deforestation rate)			X		
Animal productivity					
Yield (milk, eggs, and fibers)			X →	X	
Dressing percentage			X →	X	
Fat and protein content			X →		X
Product farmgate prices[6]			X →	X	
Postfarm					
Transport distances of animals or products			X		
Energy (processing, cooling, packaging)			X		
Mean annual temperature	X				
Direct and indirect energy			X →	X	

→ The spatial resolution of the variable varies geographically and depends on the data availability. For each input variable, the spatial resolution of a given area is defined as the finest available.

[1] Animal numbers and mean annual temperature: ~ 5 km x 5 km at the equator; crop yields, harvested area and N residues: ~ 10 km x 10 km at the equator.

[2] Geographical regions or agro-ecological zones.

[3] For monogastrics.

[4] For ruminants.

[5] Ruminants: rations in the industrialized countries; Monogastrics: rations of swill and concentrates.

[6] Only for allocation in small ruminants.

calves reflects the percentage of pregnancies that end with a dead calf. This may occur by abortion, still birth or death in the first 30 days after birth.

- *Growth rates:* the growth rate of animals is based on the age at which they attain adult weight. For females, this depends on the age at first parturition, although some growth takes place after this. The age at which animals are sold for slaughter is based on the defined slaughter weight and the calculated growth rate.
- *Replacement rates:* these represent the number of adult animals replaced by younger adult animals per year. The replacement rate of female animals is taken from the literature. Literature reviews did not reveal any data on the replacement rate of male animals, so the replacement rate was defined as the reciprocal value of the age at first parturition, on the assumption that farmers will prevent in-breeding by applying this rule. For small ruminants, adult males are usually exchanged twice by farmers and therefore have three service periods.

Tables B2-B6 present input herd parameter data used in this analysis.

Table B2. Herd parameters for dairy cattle, regional averages

Parameters	N. America	Russian Fed.	W. Europe	E. Europe	NENA	E & SE Asia	Oceania	South Asia	LAC	SSA
	Weights *(kg)*									
Adult cow	747	500	593	518	371	486	463	346	551	325
Adult bull	892	653	771	673	477	326	601	502	717	454
Calves at birth	41	33	38	36	20	28	31	23	38	20
Slaughter female	564	530	534	530	329	256	410	87	540	274
Slaughter male	605	530	540	530	367	243	410	141	540	278
	Rate *(percentage)*									
Replacement adult cow	35	31	31	27	15	28	22	21	21	10
Fertility	77	83	83	84	73	80	80	75	80	72
Death rate female calves	8	8	8	8	20	15	10	22	9	20
Death rate male calves	8	8	8	8	20	15	10	50	9	20
Death rate other animals	3	4	4	4	6	6	4	8	9	6
Age at first calving (years)	2.1	2.3	2.3	2.2	3.4	2.5	2.1	3.1	2.6	4.0

Source: Input data based on literature, surveys and expert knowledge.

Table B3. Herd parameters for beef cattle, regional averages

Parameters	N. America	Russian Fed.[1]	W. Europe	E. Europe	NENA	E & SE Asia	Oceania	South Asia	LAC	SSA
	Weights *(kg)*									
Adult cow	649	0	529	530	431	501	403	350	419	271
Adult bull	843	0	688	689	563	542	524	505	545	347
Calves at birth	40	0	35	35	29	33	27	23	28	20
Slaughter female	606	0	529	530	445	223	403	73	392	349
Slaughter male	565	0	529	530	478	218	403	68	400	288
	Rate *(percentage)*									
Replacement adult cow	14	0	15	15	21	16	22	21	14	11
Fertility	93	0	93	93	75	90	93	75	73	59
Death rate female calves	11	0	10	10	18	15	10	22	14	19
Death rate male calves	11	0	10	10	18	15	10	50	14	19
Death rate other animals	4	0	3	3	7	7	3	8	6	7
Age at first calving (years)	2.0	0	2.3	2.3	2.8	2.5	2.1	3.1	3.4	3.9

[1] Based on our estimates, the Russian Federation has no specialized beef herd.

Source: Input data based on literature, surveys and expert knowledge.

Table B4. Herd parameters for goats, regional averages

Parameters	N. America	Russian Fed.	W. Europe	E. Europe	NENA	E & SE Asia	Oceania	South Asia	LAC	SSA
	Weights *(kg)*									
Adult female	64	55	59(61)	50	37(40)	44(34)	50	32(31)	35(37)	29(31)
Adult male	83	100	88(91)	100	53(56)	60(43)	81	42(39)	50(60)	36(40)
Kids at birth	6.4	2.2	4.0(4.6)	5.0	2.7(3.2)	3.9(2.1)	3.6	2.7(2.4)	3.5(3.7)	2.2(2.3)
Slaughter female	36	30	26	30	32	27	38	25	27	19
Slaughter male	36	30	26	30	32	27	38	25	28	19
	Rate *(percentage)*									
Replacement female	30	18	17	18	19	24	21	19	24	16
Fertility	85	90	87	90	87	88	87	81	80	87
Death rate kids	18	5	4	5	31	37	12	15	14	27
Death rate other	9	2	2	2	7	16	6	5	5	7
Age at first kidding (years)	1.4	1.3	1.3	1.3	1.6	1.1	1.4	1.8	1.5	2.0

Note: Numbers in brackets refer to parameters for meat animals.

Source: Input data based on literature, surveys and expert knowledge.

Table B5. Herd parameters for sheep, regional averages

Parameters	N. America	Russian Fed.	W. Europe	E. Europe	NENA	E & SE Asia	Oceania	South Asia	LAC	SSA
	Weights *(kg)*									
Adult female	80	49	62	44	41	47	70	35	59	38
Adult male	108	101	82	85	55	65	98	45	81	51
Lambs at birth	4	3	4	3	3	4	4	3	3	3
Slaughter female	27	21	29	21	26	26	35	24	29	24
Slaughter male	27	21	29	21	26	26	35	24	29	24
	Rate *(percentage)*									
Replacement female	21	23	29	22	21	16	24	18	20	17
Fertility	92	95	91	90	83	77	100	81	91	76
Death rate lambs	19	17	18	18	25	31	9	24	18	33
Death rate other	8	2	3	5	12	14	4	12	12	13
Age at first lambing (years)	2.1	1.9	1.6	1.8	1.4	1.6	1.8	1.6	2.0	1.5

Source: Input data based on literature, surveys and expert knowledge.

Table B6. Herd parameters for buffalo, regional averages

Parameters	LAC	E & SE Asia	E. Europe	N. America	Russian Fed.	South Asia	NENA	W. Europe
	Weights *(kg)*							
Adult female	650	380	559	650	650	485	500	648
Adult male	900	398	700	800	800	532	610	800
Calves at birth	38	24	38	38	38	31	32	38
Slaughter female	400	190	481	350	440	215	310	352
Slaughter male	475	190	380	350	440	135	309	352
	Rate *(percentage)*							
Replacement female	10	20	20	10	20	20	16	10
Fertility	75	57	68	76	68	53	69	76
Death rate female calves	7	29	8	8	8	24	18	8
Death rate male calves	7	28	8	8	8	44	18	8
Death rate others	2	6	4	4	4	9	6	4
Age at first calving (years)	3.0	4.0	3.2	2.5	3.6	4.0	3.1	2.5

Note: Based on this analysis, SSA and Oceania have no buffalo herd.
Source: Input data based on literature, surveys and expert knowledge.

3. FEED

Animal rations are generally a combination of different feed ingredients. For ruminants, three broad categories of feed are considered: roughages, by-products and concentrates. Feed is defined by a feed ration which differs among animal categories as defined in the herd module. Three separate feed rations are formulated for the following categories: adult females; replacement males and females and adult males; and surplus (meat) animals for fattening. Tables B7 to B12 present the average feed rations and proportions of different feed materials within the feed basket by region and ruminant species.

In this assessment, all plant-based feed materials are identified by three key parameters: dry-matter yield per hectare; net energy content (or digestibility); and nitrogen content. These three parameters are data input in the calculation of the feed ration and its nutritive value. The dry matter yield determines the type of feed ingredients that make up the feed ration as well as the potentially available feed in a region. The digestibility and N-content of feed define the quality properties of feed and determine the efficiency with which feed is digested and eventual GHG emissions. Table B13 presents regional average feed ration digestibility values.

Emission factors for key data inputs into feed production. Emissions of fossil CO_2 from feed production, transport and processing are dependent on the amounts and types of fuels used. Table B14 presents emission factor data used in the calculation of the feed emission intensity.

Emissions of CO_2 and N_2O occurring during the production of nitrogenous fertilizers. The most commonly occurring mineral fertilizer, ammonium nitrate, which consists of equal parts of ammonium- and nitrate-nitrogen, currently releases ~6.8 kg CO_2-equivalents in production (Jenssen and Kongshaug , 2003). Due to the lack of reliable data on these parameters, and on fertilizer trade flow, the average European fertilizer emissions factor of 6.8 kg CO_2-eq per kg of ammonium nitrate N in all regions was used.

4. MANURE

There are considerable differences in emissions from MMS. Data requirements for the estimation of GHG emissions from MMS include: information on how manure is managed, the types of MMS, and the proportion of manure managed in these systems. Additionally, climatic information (e.g. temperature) is important because emission factors are climate dependent. It was thus necessary to consider the climate under which livestock is managed in each country.

On a global scale, there is limited data available on how manure is managed and the proportion of the manure managed in each system. Consequently, this study relied on various data sources such as national inventory reports, literature and expert knowledge to define the proportions of manure management systems. It uses the IPCC (2006) classification of MMSs (definition in Table 10.18, IPPC guidelines). Regional variations manure management practices are presented in Tables B15 to B19.

Table B7. Dairy cattle feed ration, regional averages

	N. America	Russian Fed.	W. Europe	E. Europe	NENA	E & SE Asia	Oceania	South Asia	LAC	SSA
	percentage									
Roughage										
Fresh grass	14.4	23.8	33.2	22.5	41.4	22.4	68.3	10.7	54.9	56.8
Hay	17.0	23.8	16.6	22.8	17.8	19.2	5.6	14.2	15.4	18.1
Legumes and silage	30.6	34.3	22.6	33.2	0.3	2.7	10.4	-	-	-
Crop residues	-	1.8	2.5	1.8	31.7	38.4	-	60.1	8.7	17.0
Sugarcane tops	-	-	-	-	1.6	0.6	-	3.5	2.6	1.9
Leaves	-	-	-	-	3.6	2.3	-	6.1	6.5	3.0
By-products and concentrates										
Bran	4.4	2.9	2.0	3.0	0.6	0.5	2.5	0.2	0.4	0.1
Oilseed meals	6.4	4.6	8.5	5.7	2.3	6.7	1.3	5.2	6.4	3.1
Wet distillers grain	4.3	-	-	-	-	-	-	-	-	-
Grains	22.8	7.2	13.2	9.1	0.2	7.2	11.8	-	4.9	0.1
Molasses	-	-	0.1	-	0.5	-	-	-	0.1	0.1
Pulp	-	1.8	1.3	1.8	-	-	-	-	-	-

Source: GLEAM based on input data from literature, national inventory reports, expert knowledge and databases (SPAM, FAOSTAT).

Table B8. Beef cattle feed ration, regional averages

	N. America	W. Europe	E. Europe	NENA	E & SE Asia	Oceania	South Asia	LAC	SSA
	percentage								
Roughage									
Fresh grass	35.2	36.0	21.0	24.9	23.6	63.5	8.0	65.1	61.1
Hay	39.4	14.8	21.9	36.7	18.7	6.8	12.5	9.4	12.6
Legumes and silage	7.8	23.1	32.3	2.1	0.7	10.7	-	-	-
Crop residues	-	3.8	2.1	24.2	46.2	-	68.0	10.2	19.4
Sugarcane tops	-	-	-	0.1	0.8	-	3.6	2.5	3.7
Leaves	-	-	-	9.2	2.8	-	5.9	4.1	1.6
By-products and concentrates									
Bran	0.9	1.7	3.5	0.3	0.2	3.8	0.1	0.1	-
Oilseed meals	0.6	7.6	6.6	1.9	2.7	1.5	1.9	3.9	1.4
Wet distillers grain	1.0	-	-	0.0	-	-	-	-	-
Grains	15.1	10.6	10.5	0.6	4.2	13.7	-	4.7	0.1
Molasses	-	0.7	-	-	-	-	-	-	-
Pulp	-	1.7	2.1	-	-	-	-	-	-

Source: GLEAM based on input data from literature, national inventory reports, expert knowledge and databases (SPAM, FAOSTAT).

Table B9. Dairy buffalo feed ration, regional averages

	N. America	W. Europe	E. Europe	NENA	E & SE Asia	South Asia	LAC
	percentage						
Roughage							
Fresh grass	-	1.7	38.9	3.4	35.7	5.2	65.3
Hay	15.6	16.1	25.9	10.7	13.7	20.1	12.2
Legumes and silage	34.4	33.7	17.3	-	-	-	-
Crop residues	5.2	5.0	-	72.8	39.5	54.8	8.4
Sugarcane tops	-	-	-	5.8	2.2	4.7	2.2
Leaves	-	-	-	4.0	2.3	8.1	5.2
By-products and concentrates							
Bran	4.7	0.8	4.6	1.6	3.3	3.6	3.4
Oilseed meals	10.9	11.5	5.2	1.6	3.3	3.6	3.4
Wet distillers grain	7.3	7.0	-	-	-	-	-
Grains	15.6	18.2	8.1	-	-	-	-
Molasses	-	-	-	-	-	-	-
Pulp	6.2	6.0	-	-	-	-	-

Source: GLEAM based on input data from literature, national inventory reports, expert knowledge and databases (SPAM, FAOSTAT).

Table B10. Buffalo meat feed ration, regional averages

	Russian Fed.	NENA	E & SE Asia	South Asia	LAC
	percentage				
Roughage					
Fresh grass	41.1	38.9	37.8	5.9	68.0
Hay	27.4	27.7	12.0	19.8	13.2
Legumes and silage	18.3	-	-	-	-
Crop residues	-	29.8	43.5	60.1	8.9
Sugarcane tops	-	-	2.1	4.7	2.3
Leaves	-	2.2	2.5	7.5	5.3
By-products and concentrates					
Bran	4.7	0.7	1.1	1.0	1.1
Oilseed meals	3.3	0.7	1.1	1.0	1.1
Wet distillers grain	-	-	-	-	-
Grains	5.2	-	-	-	-
Molasses	-	-	-	-	-
Pulp	-	-	-	-	-

Source: GLEAM based on input data from literature, national inventory reports, expert knowledge and databases (SPAM, FAOSTAT).

Table B11. Small ruminant milk feed ration, regional averages

	N. America	Russian Fed.	W. Europe	E. Europe	NENA	E & SE Asia	Oceania	South Asia	LAC	SSA
	percentage									
Roughage										
Fresh grass	29.7	32.0	24.9	32.5	46.4	23.0	62.2	23.9	74.9	58.8
Hay	37.5	24.6	19.3	25.0	7.0	33.8	6.9	6.3	11.9	4.9
Legumes and silage	2.6	9.8	6.6	10.0	0.7	-	7.8	-	-	-
Crop residues	-	11.5	16.4	11.8	38.4	26.9	1.1	53.9	8.7	31.1
Sugarcane tops	-	-	-	-	2.2	0.3	-	2.3	2.1	3.9
Leaves	-	-	-	-	0.9	2.1	-	1.6	0.3	0.2
By-products and concentrates										
Bran	5.8	8.6	11.3	8.2	2.1	6.9	9.8	6.0	1.0	0.6
Oilseed meals	2.1	2.3	4.3	2.1	1.7	6.9	0.6	6.0	1.0	0.6
Wet distillers grain	-	-	-	-	-	-	-	-	-	-
Grains	17.2	3.6	5.4	3.3	0.2	-	5.5	-	-	-
Molasses	0.2	-	0.7	-	-	-	-	-	-	-
Pulp	4.9	7.6	11.1	7.2	0.3	-	6.1	-	-	-

Source: GLEAM based on input data from literature, national inventory reports, expert knowledge and databases (SPAM, FAOSTAT).

Table B12. Small ruminant meat feed ration, regional averages

	N. America	Russian Fed.	W. Europe	E. Europe	NENA	E & SE Asia	Oceania	South Asia	LAC	SSA
	percentage									
Roughage										
Fresh grass	34.8	38.2	45.4	37.0	34.9	19.7	75.4	25.7	68.9	57.9
Hay	44.0	29.4	21.6	29.0	22.2	32.6	7.5	6.6	18.8	8.8
Legumes and silage	3.0	11.8	9.7	12.0	0.6	-	9.3	-	-	-
Crop residues	-	13.7	13.0	13.9	37.4	39.2	1.2	55.9	9.9	27.9
Sugarcane tops	-	-	-	-	1.8	0.3	-	4.2	1.4	5.2
Leaves	-	-	-	-	2.2	1.5	-	1.7	0.2	0.2
By-products and concentrates										
Bran	0.2	3.6	2.8	4.3	0.5	3.3	4.7	3.0	0.4	-
Oilseed meals	0.5	0.2	2.2	0.3	0.3	3.3	0.1	3.0	0.4	-
Wet distillers grain	-	-	-	-	-	-	-	-	-	-
Grains	17.3	0.4	0.7	0.5	-	-	0.9	-	-	-
Molasses	0.2	-	1.3	-	-	-	-	-	-	-
Pulp	-	2.6	3.4	3.1	-	-	1.0	-	-	-

Source: GLEAM based on input data from literature, national inventory reports, expert knowledge and databases (SPAM, FAOSTAT).

Table B13. Calculated feed digestibility, regional averages

Region	Dairy	Beef	Small Ruminants	Buffalo
	percentage			
N. America	71.8	68.3	66.2	73.4
Russian Fed.	72.6	-	65.4	70.7
W. Europe	77.0	76.1	69.7	75.5
E. Europe	73.5	73.8	67.4	72.8
NENA	56.1	57.7	55.5	52.0
E & SE Asia	59.0	57.4	56.3	56.0
Oceania	72.9	72.9	69.8	-
South Asia	52.6	50.7	54.1	52.1
LAC	62.2	62.7	58.9	60.5
SSA	57.3	57.2	55.5	-

Source: GLEAM based on input data from literature, national inventory reports, expert knowledge and databases (SPAM, FAOSTAT).

Table B14. Emissions factors for fuel consumption

Fuel	Emission factor	Source
Diesel	3.2 kg CO_2-eq/litre diesel	Berglund *et al.* (2009)
Oil	5.7 kg CO_2-eq/kg oil	de Boer (2009)
Coal	17.8 kg CO_2-eq/kg coal	de Boer (2009)
Gas	7.6 kg CO_2-eq/m^3 gas	de Boer (2009)

Table B15. Dairy cattle manure management systems, regional averages

MMS	Burned for fuel	Daily spread	Drylot	Uncovered anaerobic Lagoon	Liquid slurry	Pasture, range, pad-dock	Solid storage
			percentage				
N. America	-	9.5	-	27.2	26.3	11.8	25.2
Russian Fed.	-	-	-	-	-	22.5	77.5
W. Europe	-	2.3	-	0.1	41.6	26.6	29.5
E. Europe	-	1.4	-	-	10.2	17.0	71.3
NENA	3.6	-	39.4	-	-	46.1	10.9
E & SE Asia	1.5	-	29.1	-	3.1	30.7	35.7
Oceania	-	1.2	-	4.6	0.1	94.2	-
South Asia	20.0	-	54.4	-	-	23.5	2.0
LAC	0.4	-	41.5	-	-	53.5	4.7
SSA	6.9	-	34.8	-	-	39.7	18.5

Source: Input data from literature, national inventory reports and expert knowledge.

Table B16. Beef cattle manure management systems, regional averages

MMS	Burned for fuel	Daily spread	Drylot	Uncovered anaerobic Lagoon	Liquid slurry	Pasture, range, paddock	Solid storage
				percentage			
N. America	-	-	12.8	-	0.7	43.4	43.2
Russian Fed.	-	-	-	-	-	-	-
W. Europe	-	4.2	0.1	-	22.1	47.6	25.9
E. Europe	-	-	-	-	65.0	33.0	2.0
NENA	9.3	-	34.9	-	-	42.8	12.9
E & SE Asia	0.6	-	33.9	-	-	27.7	37.8
Oceania	-	-	-	-	-	100.0	-
South Asia	20.0	-	58.2	-	-	20.3	1.4
LAC	0.2	-	4.8	-	-	91.8	3.2
SSA	6.2	-	34.3	-	-	46.5	13.0

Source: Input data from literature, national inventory reports and expert knowledge.

Table B17. Buffalo milk production manure management systems, regional averages

MMS	Burned for fuel	Daily spread	Drylot	Liquid slurry	Pasture, range, paddock	Solid storage
			percentage			
N. America	17.4	40.2	42.4	-	-	-
W. Europe	3.4	61.9	34.7	-	-	-
E. Europe	13.0	67.8	18.2	-	1.0	-
NENA	50.8	9.2	-	38.9	-	1.1
E & SE Asia	31.0	13.3	-	53.6	-	2.0
South Asia	37.8	1.3	-	40.4	-	19.9
LAC	50.7	1.2	-	48.0	-	-

Source: Input data from literature, national inventory reports and expert knowledge.

Table B18. Buffalo meat production manure management systems, regional averages

MMS	Burned for fuel	Daily spread	Drylot	Liquid slurry	Solid storage
			percentage		
Russian Fed.	27.8	66.6	5.6	-	-
NENA	48.7	22.9	-	13.4	14.5
E & SE Asia	28.6	9.1	-	61.2	0.8
South Asia	38.6	1.5	-	39.7	2-
LAC	93.8	1.2	-	4.9	-

Source: Input data from literature, national inventory reports and expert knowledge.

Table B19. Small ruminant manure management systems, regional averages

MMS	Drylot	Pasture, range, paddock	Solid storage
	percentage		
N. America	-	47.4	53.0
Russian Fed.	-	18.0	82.0
W. Europe	-	83.8	16.2
E. Europe	-	64.6	35.2
NENA	37.5	57.2	5.2
E & SE Asia	0.8	56.7	42.3
Oceania	-	100.0	-
South Asia	12.8	85.0	2.0
LAC	3.7	83.3	12.7
SSA	9.3	84.4	6.2

Source: Input data from literature, national inventory reports and expert knowledge.

Table B20. Dressing percentages for large ruminants

	N. America	Russian Fed.	W. Europe	E. Europe	NENA	E & SE Asia	Oceania	South Asia	LAC	SSA
	percentage									
Dairy cattle										
Adult and replacement females	50	50	50	50	48	50	50	50	50	47
Adult and replacement male	50	50	50	50	48	50	50	50	50	47
Surplus female and male	52	52	52	52	50	55	52	55	52	47
Beef cattle										
Adult and replacement females	55	55	55	55	50	50	50	50	50	47
Adult and replacement male	55	55	55	55	50	50	50	50	50	47
Surplus female and male	60	60	60	60	55	55	55	55	55	47
Buffalo										
Adult and replacement females	49	49	49	49	49	49	49	49	49	49
Adult and replacement male	50	50	50	50	50	50	50	50	50	50
Surplus female and male	55	55	55	55	55	55	55	55	55	55

Source: Input data from literature, surveys and expert knowledge.

Table B21. Dressing percentages for small ruminants

Region	Goats	Sheep
	percentage	
N. America	52	52
Russian Fed.	43	45
W. Europe	43	48
E. Europe	43	45
NENA	44	45
E & SE Asia	48	49
Oceania	45	50
South Asia	43	48
LAC	44	49
SSA	48	45

Source: Input data from literature, surveys and expert knowledge.

5. PRODUCTION AND ALLOCATION

Dressing percentage. Dressing percentage can be defined as the percent of the live animal that ends up in the carcass. The LW:CW ratio varies substantially depending on a range of factor including breed, gender, diet, age, diet, cold versus warm carcass weight, and distance trucked. Tables B20 and B21 present the dressing percentages used for large and small ruminants.

Emission allocation factors. Table B22 presents a comparison of dairy and beef herds in total cattle population across world regions, their contribution to total beef production and the allocation factors used in this assessment for the allocation of emissions between milk and meat from the dairy herd. Emission allocation factor for wool, yield and total economic value (for meat, milk and wool produced by sheep) are presented in Table B23. See Appendix A for more details on allocation techniques applied.

Table B22. Percentage of dairy and beef herds, ratio of beef production from cattle herds and emission allocation factor for milk and meat from the dairy herd

	Percentage of cattle		Ratio of beef production from dairy and specialized beef herd		Allocation factor between milk and meat from the dairy herd
Region	Dairy herd	Beef herd	Dairy herd	Beef herd	Fraction
LAC	24.8	75.2	0.31	0.69	0.92
E & SE Asia	20.9	79.1	0.23	0.77	0.93
E. Europe	99.2	0.80	0.99	0.01	0.94
N. America	23.8	76.2	0.24	0.76	0.94
Oceania	38.1	61.9	0.38	0.62	0.96
Russian Federation	100.0	-	1.00	-	0.91
South Asia	56.9	43.1	0.60	0.40	0.90
SSA	57.5	42.5	0.59	0.41	0.90
NENA	98.9	1.1	0.98	0.02	0.92
W. Europe	70.5	29.5	0.70	0.30	0.95

Source: GLEAM.

Table B23. Emission allocation factors for sheep

Country*	Total economic value *('000 US$)*	Wool allocation factor	Wool *(kg/animal)*
Afghanistan	78 513	0.14	2.6
Albania	169 530	0.03	3.1
Algeria	519 567	0.08	2.4
Argentina	980 205	0.28	6.2
Armenia	18 138	0.09	2.1
Australia	4 967 220	0.38	6.4
Austria	31 346	0.02	3.5
Azerbaijan	79 042	0.13	2.1
Bangladesh	16 262	0.16	2.6
Belarus	1 797	0.06	5.0
Belgium	8 128	0.21	3.5
Bhutan	292	0.50	2.6
Bolivia	137 832	0.32	5.3
Bosnia and Herzegovina	41 272	0.09	3.1
Brazil	278 548	0.30	6.1
Bulgaria	44 497	0.09	5.0
Canada	24 881	0.11	5.5
Chile	88 762	0.26	6.0
China	1 797 202	0.17	2.1
Colombia	38 411	0.80	6.0
Croatia	91 675	0.01	3.1
Cyprus	26 049	0.01	2.1
Czech Republic	10 792	0.23	5.0
Denmark	9 372	0.26	5.0
Ecuador	45 468	0.51	4.3
Egypt	190 515	0.08	2.4
Eritrea	53 231	0.05	2.0
Estonia	1 554	0.08	2.8
Ethiopia	62 025	0.42	2.0
Finland	3 064	0.15	2.8
France	792 773	0.04	3.5
Georgia	28 259	0.20	2.1
Germany	144 509	0.04	3.5
Greece	1 368 750	0.01	3.1
Hungary	84 145	0.04	5.0
India	875 770	0.16	2.6
Indonesia	181 290	0.11	1.0
Iran (Islamic Republic of)	1 099 145	0.05	2.6
Iraq	149 159	0.19	2.1
Ireland	243 544	0.20	2.0
Israel	31 197	0.02	2.1

(Continued)

Table B23. *(Continued)*

Country*	Total economic value *('000 US$)*	Wool allocation factor	Wool *(kg/animal)*
Italy	1 022 570	0.02	3.1
Jordan	83 719	0.03	2.1
Kazakhstan	149 923	0.09	2.1
Kenya	103 366	0.11	2.0
Kuwait	24 814	0.21	2.1
Kyrgyzstan	46 492	0.06	2.1
Latvia	914	0.15	2.8
Lebanon	18 130	0.12	2.1
Lesotho	20 706	0.49	3.8
Lithuania	863	0.08	2.8
Luxembourg	911	0.09	3.5
Macedonia	62 263	0.02	3.1
Malaysia	1 475	0.15	1.0
Mali	158 637	0.13	2.0
Malta	1 382	0.04	3.1
Mexico	342 445	0.02	2.0
Moldova, Republic of	15 252	0.10	5.0
Mongolia	79 706	0.06	2.1
Montenegro	8 935	0.02	3.1
Morocco	674 549	0.12	2.4
Myanmar	14 162	0.03	1.0
Namibia	36 361	0.07	3.8
Nepal	15 740	0.12	2.6
Netherlands	74 491	0.03	3.5
New Zealand	1 699 390	0.23	5.5
Norway	143 600	0.18	2.8
Pakistan	250 607	0.14	2.6
Paraguay	12 046	0.29	5.3
Peru	305 378	0.26	6.0
Poland	13 963	0.07	5.0
Portugal	315 014	0.02	3.1
Republic of Serbia	58 074	0.02	3.1
Romania	370 170	0.05	5.0
Russian Federation	321 514	0.18	5.0
Saudi Arabia	412 672	0.13	2.1
Slovakia	9 059	0.09	5.0
Slovenia	8 112	0.02	3.1
South Africa	1 048 040	0.23	3.8
Spain	1 659 448	0.02	4.5
State of Libya	196 954	0.09	2.4
Sudan	1 310 660	0.03	2.4

(Continued)

Table B23. *(Continued)*

Country*	Total economic value *('000 US$)*	Wool allocation factor	Wool *(kg/animal)*
Sweden	20 060	0.09	2.8
Switzerland	42 600	0.02	3.5
Syrian Arab Republic	2 711 860	0.02	2.1
Tajikistan	26 784	0.24	2.1
Tunisia	277 587	0.11	2.4
Turkey	1 792 952	0.04	2.1
Turkmenistan	171 606	0.77	2.1
Ukraine	24 660	0.10	5.0
United Arab Emirates	28 401	0.13	2.1
U.K. of Great Britain and Northern Ireland	1 110 150	0.05	2.8
United Republic of Tanzania	49 968	0.09	2.0
United States of America	174 326	0.22	4.8
Uruguay	258 626	0.41	6.2
Uzbekistan	130 762	0.51	2.1
Yemen	268 873	0.09	2.1

* Represents 95 percent of the global sheep population.

Source: GLEAM based on input data from literature, national inventory reports, expert knowledge and databases (FAOSTAT).

REFERENCES

Berglund, M., Cederberg, C., Clason, C. & och Lars Törner, M.H. 2009. Jordbrukets klimatpåverkan – underlag för att beräkna växthusgasutsläpp på gårdsnivå och nulägesanalyser av exempelgårdar. *Delrapport i JoKer-proJeKtet, Hushållningssällskapet Halland.*

IPCC. 2006. *2006 IPCC Guidelines for National Greenhouse Gas Inventories prepared by the National Greenhause Gas Inventories Programme,* Eggleston, H.S., Buenida, L., Miwa, K., Nagara, T. & Tanabe, K. (eds). Published: IGES, Japan.

You, L., Crespo, S., Guo, Z., Koo, J., Ojo, W., Sebastian, K., Tenorio, T.N., Wood, S. & Wood-Sichra, U. 2010. *Spatial Production Allocation Model (SPAM) 2000, Version 3. Release 2.* Available at http://MapSPAM.info.

Jenssen, T.K. & Kongshaug, G. 2003. Energy consumption and greenhouse gas emissions in fertiliser production. *The International Fertiliser Society*, York, U.K. Proceedings No. 509.

APPENDIX C

Changes in carbon stocks related to land use and land-use change

1. INTRODUCTION

This appendix discusses GHG emissions and changes in carbon stocks that result from land use and LUC. Land uses and LUCs are defined; the relevant carbon pools and emission sources are discussed in the context of these categories; the approaches to estimating emissions and changes in carbon stocks are outlined; and finally, justification for and an explanation of the selected estimation methods used in this study is also provided.

Land use, LUC and forestry (LULUCF) is defined by the United Climate Change Secretariat as: *a greenhouse gas inventory sector that covers emissions and removals of greenhouse gases resulting from direct human-induced land use, land-use change and forestry activities*. Six land use categories are defined in the 2006 IPCC Guidelines for National Greenhouse Gas Inventories: 1. Forest Land; 2. Cropland; 3. Grassland; 4. Wetlands; 5. Settlements; and 6. Other Land.

Land may remain in any of these categories or, in the case of LUC, its use may change to another category (e.g. from forest to grassland). Thus, each land use category can be further subdivided into land that is converted from one land use category to another, and land that remains in the same category. While this study focuses on the emissions from LUC, emissions from land use are also discussed.

1.1 GHG emissions from land-use change

Most LUCs alter the soil and vegetation of the land, thus changing the amount of carbon stored per unit area. These changes may be positive or negative, and may occur in each carbon pool: biomass (above- and below-ground); dead organic matter (dead wood and litter); and soil (soil organic matter).

LUC can significantly alter the carbon stored in biomass, by replacing the vegetation of the existing land use category with the vegetation of another land use category. Conversion of forest land to either grassland or cropland can lead to large and rapid losses of the typically large stores of carbon in forest vegetation, when this vegetation is replaced with herbaceous grasses or annual crops.

While most of the carbon stored in forest biomass is lost following conversion, some carbon will be transferred from one pool to another; e.g. when trees are felled, a portion of the above-ground biomass is transferred to the dead organic matter pool, and a portion of the below-ground biomass is transferred to the soil organic matter pool.

The drainage and cultivation or grazing of organic soils is also an important cause of the oxidation and loss of SOC for both croplands and grasslands (Armentano and Menges, 1986). While the most important GHG emission flux is CO_2, the oxidization of the various organic carbon pools as a consequence of LUC can also release N_2O.

Land conversion often results in an abrupt change where most biomass is lost, followed by a longer period where biomass is oxidized at a much slower pace. The IPCC (2006) assumes a default 20-year transition period following conversion over which all losses are accounted for.

The conversion of forest land to agricultural land may also lead to losses from the SOC pool. When forest land is converted to cropland, there is an average reduction in soil carbon of between 25 and 30 percent in the upper metre of soil (Houghton and Goodale, 2004).[14] These soil carbon losses are due, in part, to a lower fraction of non-soluble material in the more easily decomposed crop residues, and to the breaking up of aggregates and subsequent exposure of organo-mineral surfaces to decomposers following tillage (Post and Kwon, 2000). On the other hand, because grasslands, unlike crops, are not ploughed (temporary cultivated pastures are classified to be crops), little change in soil carbon is expected following the conversion of forests to grasslands (Houghton and Goodale, 2004).

When either cropland or grasslands are abandoned, there is a re-accumulation of carbon in vegetation as the land returns to its natural state, and the greater the biomass of the returning vegetation the larger is the long-term carbon sink due to the recovery. Post and Kwon (2000) note relatively low rates of accumulation in mineral soil following the abandonment of cropland. Considering all LUCs during the 1990s, Houghton & Goodale (2004) estimate that the average annual emissions from LUC were estimated to be 2.2 petagram C yr^{-1}, with almost all of this emanating from deforestation in the tropics.

1.2 Land use and its effects on emissions and carbon stocks

Agricultural lands hold substantial carbon stocks, mostly in soil organic matter. Carbon stock changes in agricultural lands are closely tied to management practices, which can either enhance or erode carbon stocks. Practices which raise (lower) the photosynthetic input of carbon and/or slow (accelerate) the release of stored carbon through respiration, erosion or fire will increase (decrease) carbon stocks (Smith *et al*., 2007). While it is possible for substantial biomass carbon to be stored through perennial plantings on agricultural lands (e.g. silvopastoral systems), carbon accumulation and losses occur mostly in the SOC pool. This below-ground carbon pool also has slower rates of turnover than above-ground pools, because most of the organic carbon in soils comes from the conversion of plant litter into more persistent organic compounds (Jones and Donnelly, 2004).

Smith *et al.* (2007) estimated that 89 percent of the agriculture sector's total mitigation potential is from SOC sequestration. For grasslands, practices such as the optimization of grazing intensities to maximize grass production, moderate intensification of nutrient-poor grasslands, and the restoration of degraded pastures are known to improve sequestration rates (Conant and Paustian, 2002; Sousanna *et al.*, 2010). Conversely, the overgrazing of grasslands reduces vegetation and the amount of litter returned to soils, and it leads to erosion and degradation contributing to CO_2 losses from the SOC pool. For croplands, significant changes in SOC stocks are associated with management practices including tillage, residue management, nutrient management and the use of organic amendments (Smith *et al.*, 2007).

[14] While there is some variation around this range, it has been documented in numerous studies, and has been found to be broadly robust across all ecosystems (Houghton and Goodale, 2004).

Historically, while agricultural management practices can result in either reductions or accumulations in the SOC pool, agricultural lands are estimated to have released more than 50 petagram C (Paustian *et al*., 1998; Lal, 1999, 2004), some of which can be restored via better management. Currently, however, the net flux of CO_2 between the atmosphere and agricultural lands is estimated to be approximately balanced (Smith *et al*., 2007). For the estimation of net livestock sector GHG emissions, which is the main purpose of this report, measures of net CO_2 current fluxes by region are of greater interest than the sequestration/mitigation potential.

The lack of a globally consistent and regionally detailed set of net CO_2 flux estimates make it difficult to quantify these potential emission sources and sinks by region in this study, although there are some relevant studies that provide useful estimates of these net fluxes for specific regions and agricultural land use categories. For example, based on literature observations for temperate grasslands mainly from Western Europe, Soussana *et al*. (2010) estimate that grasslands SOC sequestration rates averaged 5 ± 30 gC/m^2 per year. Nevertheless, Soussana *et al*. (2010) concede that the uncertainties associated with SOC stock changes following changes in management are very high. Further, stocks of SOC are very vulnerable to disturbances, including tillage, fire, erosion, and droughts that can lead to rapid reversals of accumulated stocks. Moreover, the authors recommend that further research is needed to separate the influence of management factors from other climate-related factors such as average temperature increase and CO_2 fertilization, in order to be able to attribute sequestration to direct anthropogenic causes.

There is also considerable potential to sequester carbon in croplands through a range of options available that include reduced and zero tillage, set-aside, perennial crops, deep rooting crops, more efficient use of organic amendments, improved rotations, irrigation, etc. In Brazil, for example, long-term field experiments (Costa de Campos *et al*., 2011; Dieckow *et al*., 2010; Vieira *et al*., 2009; Sisti *et al*., 2004) have evaluated the impact of conservation tillage and crop rotations on SOC. The results from these studies confirm that non-tillage and crop rotations can enhance the conservation of SOM and increase C accumulation. For example, Dieckow *et al*. (2010) who assessed the 17-year contribution of no-tillage crop rotations to C accumulation in subtropical Ferralsol of Brazil concluded that crop-forage systems and crop-based systems with legume represent viable strategies to increase soil organic C stocks. They found that the alfalfa system with maize at each three years showed the highest C accumulation (0.44 tonnes C/ha/yr). The bi-annual rotation of ryegrass (hay)-maize-ryegrass-soybean sequestered 0.32 tonnes C/ha/yr. However, an assessment of realistically achievable potentials for carbon sequestration in croplands needs to take into account economic, political and cultural constraints and other environmental impacts (such as non-CO_2 GHG emissions) also need to be accounted for.

2. QUANTIFICATION OF CARBON EMISSIONS AND SEQUESTRATION

2.1 Changes of carbon stocks related to land-use change

The most fundamental step in assessing emissions from LUC is the tracking of changes in areas of land use and conversions from one land use category to the next. This requires a time series of data, or at least two points in time, to capture changes in the area of land for each category.

Comprehensive guidance on methodological approaches for estimating LUCs as well as emissions and removals from LULUCF is provided in the 2006 IPCC Guidelines for National Greenhouse Gas Inventories (IPCC, 2006). Three different approaches are suggested with differing degrees of accuracy to best ensure the consistent representation of LUCs for given data quality and availability. The most accurate of these, Approach 3, requires the use of spatially-explicit data for land use categories and conversions, and includes the use of gridded map products derived from remote sensing imagery. At the other extreme is Approach 1, which relies on non-spatially explicit data from census and survey data, often reported at country or province level, and which only permits net changes in land use categories over time, and cannot specify inter-category conversions. Finally, Approach 2 enables the tracking of conversions between land use categories without the spatially-explicit location data. Naturally, the choice among the simple and more sophisticated approaches involve big trade-offs between the data and analytical resource requirements, and the accuracy with which LUCs and their attendant emissions and carbon removals are estimated.

For grassland remaining grassland, cropland remaining cropland, and conversion from forestland to either of these land use categories, the 2006 IPCC Guidelines require that changes in carbon stocks from each carbon pool (i.e. above-ground biomass, below-ground biomass, dead wood, litter and soil organic matter), as well as emissions of non-CO_2 gases, are estimated. The guidelines do, however, provide flexibility in the use of methods that range from very simple approaches that rely on default emission factors to more sophisticated approaches that use detailed location-specific data and process models that fully characterize the fluxes between carbon pools.

2.1.1 Biomass and dead organic matter (DOM) pools

As mentioned, land-use conversions are often associated with an initial abrupt change and subsequent transition period following conversion. The 2006 IPCC Guidelines provide separate equations for these two phases when using Tier 2 and 3 approaches. Where country-specific emission factors are available and comprehensive national data are available, country-defined Tier 3 methodologies based on either process models or detailed inventories, stratified by climate and management regime can be recommended. These methods can also use non-linear loss and accumulation response curves during the transition phase.

At the other extreme, Tier 1 methods assume that both biomass and DOM pools are lost immediately after conversion from forestland to agricultural land, and that agricultural land reaches its steady-state equilibrium in the first year following conversion. While the IPCC provides default values to quantify biomass levels prior to and after conversion, there is assumed to be no accumulation in the DOM pool in the transition phase on agricultural land following conversion from forestland.

The Tier 2 methods represent a compromise, better capturing the dynamics of land-use conversion, by specifying separate equations for the abrupt change and transition phases, accounting for biomass accumulation during the latter phase. They also rely on some country-specific estimates of initial and final biomass stocks, instead of relying solely on default values.

Further, both Tier 2 and Tier 3 methods account for transfers between carbon pools and can estimate carbon pool changes using either the gain-loss or stock-

difference methods**.** The former method includes all processes that cause changes in a carbon pool, including biomass growth and the transfer of carbon from one pool to another. Alternatively, the stock-difference method can be used where carbon stocks are measured at two points in time. Both methods are valid, providing they can represent disturbances and continuously varying trends, and can be verified with actual measurements (IPCC, 2006).

2.1.2 Soil organic carbon (SOC) stocks

Changes in the SOC pools in both mineral and organic soils should be taken into account when estimating emissions and carbon accumulation resulting from LUC (IPCC, 2006). This requires that the areas of converted land be stratified by climate region, management and major soil type. Simple Tier 1 methods, which rely on default reference SOC stock change factors, can be used, or more country- or region-specific reference C stocks and stock change factors can be combined with more disaggregated land use activity data to use either Tier 2 or Tier 3 methods. Some of the process models suited to Tier 3 methods are discussed in the following section.

In this study, LUC emissions are estimated for each major carbon pool, including the biomass, DOM and SOC pools are estimated using Tier 1 methods. While Tier 2 and Tier 3 methods are recommended, the Tier 1 approach was deemed to be appropriate given the global nature of the assessment combined with the absence of country-specific emission factors, inventory data and/or a suitable global process model.

2.2 Changes in carbon stocks for agricultural land remaining in the same land use category

As with LUCs, the estimation of emissions and carbon accumulation from management practices on land that remains in the same land use category requires that changes in carbon stocks from each major carbon pool (i.e., above-ground biomass, below-ground biomass, dead wood, litter and soil organic matter), as well as emissions of non-CO_2 gases, are estimated.

For agricultural lands, changes in these carbon pools and non-CO_2 emission fluxes depend on management practices such as grazing, burning, pasture management, tillage and residue management. Tier 2 and Tier 3 methods are able to estimate changes in each carbon pool and in emissions resulting from management practices, while Tier 1 methods can only be used to estimate these changes for the SOC pool (and non-CO_2 emissions from burning), but not for the other carbon pools. As with the measurement of emissions and carbon storage under LUC, the same gain-loss and/or stock-difference methods can be employed.

As discussed, Tier 3 methods can be used to more accurately assess changes in these carbon pools and non-CO_2 emission sources, using dynamic process models and/or detailed inventory measurements to estimate carbon stock changes. Process model-based approaches simultaneously solve multiple equations to estimate net changes in carbon stocks. These models can incorporate management effects such as grazing intensity, fire, fertilization, tillage and residue management, and they can be combined with regionally representative sampling-based estimates to validate and extrapolate to other agricultural lands. According to IPCC (2006), important criteria for selecting these models include: their ability to represent all relevant management practices and production systems, the compatibility of model's driving variables (inputs) with available country data, and validity gauged by the model's ability

to represent stock change dynamics reported in empirical assessments. Well-known biogeochemical models that can satisfy these criteria include the Century model (and the daily time-step version, Daycent), DNDC and RothC.

The RothC (Hart, 1984; Jenkinson *et al.,* 1987; Coleman *et al*., 1997; Smith *et al.,* 2006) and Century (Parton *et al.*, 1987; Falloon and Smith, 2002; Kirschbaum and Paul, 2002) models can be used to simulate GHG gas exchange and carbon cycling dynamics of cropland, grassland and forestland land use categories, and both operate on monthly time-steps. Soil texture and weather data are the major input variables. While the Century model can simulate the dynamics of carbon in biomass, DOM and SOC pools, as well as nitrogen, phosphorous, and sulphur dynamics, RothC only estimates SOC stocks and CO_2 losses from decomposition of SOC.

The Daycent model is the daily time-step version of the Century model (Del Grosso *et al.*, 2001; Parton *et al.*, 1998), which is well suited to capturing N mineralization and N gas production in non-waterlogged soils, along with the same carbon pool dynamics modelled in Century. As with Daycent, the denitrification-decomposition (DNDC) model (Li, 1996; Li *et al.*, 1992 and 1994) simulates soil carbon and nitrogen fluxes using a daily time-step but, unlike Daycent, it is also able to represent N gas and CH_4 fluxes from waterlogged soils, such as found in rice paddies. Both Daycent and DNDC have higher data demands than either Century or RothC, due their short time-steps and wider range of biogeochemical dynamics. Since none of these models has been validated on a global scale, they have not been applied in this analysis.

3. QUANTIFICATION OF CARBON STOCK CHANGES FROM LAND USE AND LAND-USE CHANGE IN THIS REPORT

In this study, LUC emissions are estimated for three major carbon pools, including the biomass, DOM and SOC pools. It could be argued that Tier 2 and Tier 3 methods, including process-based modelling approaches, should have been used to capture variability and possibly to reduce uncertainty in the emission and carbon accumulation estimates. However, given the global nature of the assessment, and the absence of country-specific EFs, carbon stock/flux inventory data and/or a suitable global process model (cf. previous section), the Tier 1 approach was deemed a suitable option to develop preliminary estimates and shed light on the potential magnitude of the LUC emissions for the sector.

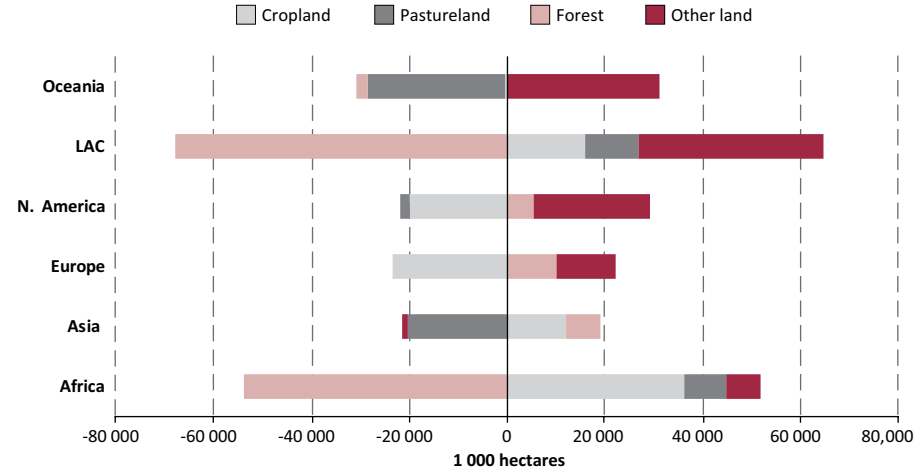
For the reasons outlined above, this assessment does not cover changes in C stocks occurring under constant land use management. This may be done in future updates once global datasets are available and/or models have been calibrated for global studies.

This section presents the approach applied in this study to quantify LUC emissions, discussing the rationale for the approach chosen, and the results from the analysis. It also explores the implications of alternative approaches to quantifying LUC emission.

3.1 Approach for feed crops

The analysis focuses on one specific feed product – soybean – in specific countries in Latin America. This assessment is based on observed land use trends, feed crop expansion trends and trade flow patterns as well as findings from previous studies such as Wassenaar *et al.* (2007) and Cederberg *et al.* (2011).

Figure C1.
Net land conversion between 1990 and 2006, by region



Source: FAOSTAT (2012).

This study uses IPCC guidelines as a basis for the quantification of LUC emissions. This choice is largely based on the fact that the IPCC approach meets the UNFCCC requirements for calculating and reporting of GHG emissions from LUC. The cropland part of this assessment also relies on other guidelines such as the PAS 2050 (also based on IPCC guidelines) for input data. According to IPCC guidelines, emissions arising from LUC are allocated over a 20-year period (the "amortization" period). Because of data availability (forestry inventories are only available from 1990),[15] in this assessment, the rates of LUC are taken as the average over the 16-year period (1990–2006). This practically discounts four years of emissions.

Agriculture has been a major driving force behind land transformation; globally, the area of land used for agriculture increased by 83 million ha over the period 1990–2006. In most regions, cropland has increased whereas pasture and forest land decreased (Figure C1). The most affected regions in terms of crop expansion are Latin America, Asia and Africa. Declining agricultural land (i.e. cropland and pastureland) is observable in Europe and North America where agricultural land abandonment has resulted in reforestation. During the period considered (1990-2006), deforestation occurred mainly in Africa and Latin America. More recent trends in deforestation, in particular in Asia, and their association with feed production are therefore not considered in this study.

Between 1990 and 2006, crop expansion was mainly driven by major oil crops (e.g. soybeans, rapeseed, sunflower and oil palm) the demand for which was fuelled by demand for vegetable oil, feed and, more recently, biofuel policies. The expansion of soybean production is argued to be one of the major drivers of LUC, par-

[15] The FAOSTAT forest area dataset (based on the Global Forest Resource Assessment) used in this study is only available from 1990 and in order to align the C stocks assessment with the livestock input data which is based on 2005 statistics, land use conversion trends were assessed for the period 1990 to 2006.

Table C1. Global area expansion for selected crops with highest area expansion (1990-2006)

Crop	Area expansion *(1 000 ha)*	Share of global gross crop expansion *(percentage)*
Soybeans	38 110	22.6
Maize	15 620	9.2
Rapeseed	9 815	5.8
Rice, paddy	8 650	5.1
Sunflower seed	7 237	4.3
Oil palm fruit	7 205	4.3

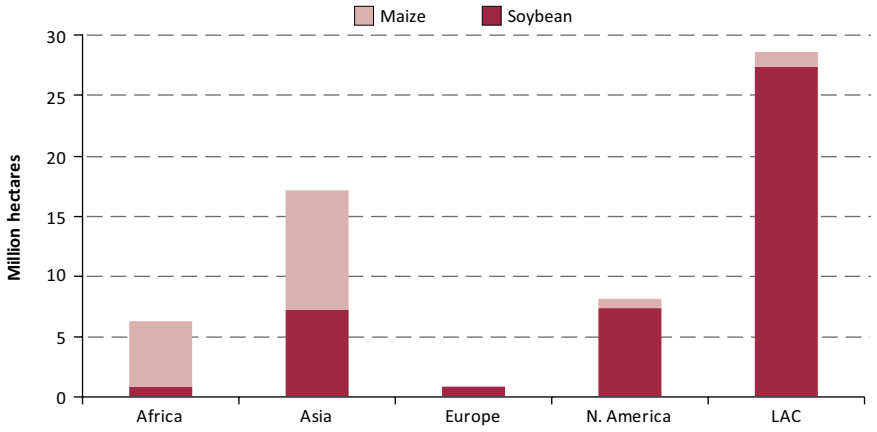
Source: FAOSTAT (2012).

ticularly deforestation (Pacheco, 2012; Nepstad *et al.*, 2006; Fearnside, 2005; Bickel and Dros, 2003; Carvalho *et al.*, 2002). The global area under cultivation of soybean has increased rapidly in recent decades; between 1990 and 2006, the global soybean area increased faster than any other crop (Table C1). Maize expansion is also important, representing 9.2 percent of global crop expansion. At the same time, crops such as wheat, barley and oats, have strongly declined, which explains the apparent discrepancies with the net land conversion trends in Figure C1.

A comparison of the two major crops driving agricultural expansion reveals key regional differences with regard to their importance (Figure C2). The expansion of soybean area has been significant in North and South America, while maize expansion is more important in Africa and Asia.

Deforestation for crop expansion has been an important LUC process in Africa, however crop expansion in the region has been mainly driven by sorghum and millet, with maize and soybeans only accounting for 5 percent and 0.5 percent of total gross cropland expansion respectively. In Africa, pasture expansion has also occurred largely at the expense of forest area. However, due to lack of reliable data and information it is difficult to draw conclusions on the land-use conversion trends in this region.

Figure C2.
Maize and soybean area expansion between 1990 and 2006, by region



Source: FAOSTAT (2012).

Table C2. Average annual land-use change rates in Argentina and Brazil (1990-2006)

Land-use type	Argentina	Brazil
	(1 000 ha)	
Agricultural area	+351	+1 288
Grasslands	-7	+753
Arable land & permanent crops	+358	+535
Soybean area	+648	+534
Forest area	-149	-2 855
Other land	-201	+1 567

Source: FAOSTAT (2009).

In North America, soybean expansion is responsible for 37 percent of total crop expansion and maize 7 percent. However in this region the overall trend has been a decrease of total cropland (due to sharp decreases in wheat and barley areas) and pastures and an increase of forest area.

In Asia, soybean expansion is responsible for 7 percent of total crop expansion and maize 8 percent. At the same time, forest land has increased overall in Asia and pastureland has decreased. But the two trends occurred in different subregions within Asia. Pasture decrease mainly occurred in Mongolia and Iran, where maize and soybean expansion were null or limited. On the contrary, expansion of soybean and maize area has largely occurred in India and China (77 percent of gross maize expansion and 96 percent of gross soybean expansion), however, forest area increased in these two countries. Pastures decreased in India but to a limited extent of 1.2 million ha, compared to the 5.8 and 3.0 million ha of soybean and maize expansion in the country, respectively.

In Latin America, most of the decrease in forest area occurred in countries with soybean expansion. Trends in land conversion, particularly deforestation, are therefore closely linked to the expansion of soybean.

Based on these observations the scope of our assessment was narrowed to the soybean expansion in Latin America. Within Latin America, Brazil and Argentina account for 91 percent of the total soybean area. In the period 1990–2006, 90 percent of the soybean area expansion in Latin America took place there, further narrowing the scope to these two countries. An assessment of land use trends in these key producing countries shows that the expansion in soybean area has been largely gained at the expense of forest area (Table C2).

In Argentina, the annual increase of area dedicated to soybean is much larger than the increase of total arable land (Table C2), indicating that there has been a shift in land use from other crops to soybean. According to FAOSTAT statistics, 44 percent of the new soybean area was gained against other crops, while the rest was gained against forest (22 percent) and other land (31 percent). The latter category covers natural vegetation that does not include forest and grazed natural grasslands.

The reported annual increase of soybean area in Brazil is 534 000 ha (Table C2). We assumed a simplified pattern of deforestation in the Amazon, in which cleared land is first used as pasture and/or crop land, and then left as fallow land. The latter, classified as "other land" in FAOSTAT, is occupied by weeds, grasses, shrubs and,

Table C3. Net changes in area for main land-use categories (1990–2006)

Region	Arable land & permanent crops	Pasture	Forest area	Other land
		(1 000 ha)		
Africa	36 025	8 863	-53 700	7 001
Asia* (*South, East and SE Asia*)	12 149	-20 506	6 855	-1 068
Europe	-55 646	-152 441	261	-96 796
North America	-20 073	-1 954	5 387	23 811
Latin America and the Caribbean	15 753	11 069	-67 870	37 973
Oceania	-263	-28 408	-2 112	30 926

* Central Asia excluded due to incomplete dataset.
Source: FAOSTAT (2012).

partly, by secondary forest. Under this assumption, every year roughly 2.9 million ha are converted to arable land and grassland. At the same time, agricultural land is abandoned at a rate of 1.6 million ha per year. The annual net increase of arable land and grassland is 0.53 and 0.75 million ha, respectively. We thus assume that all incremental soybean area is gained at the expense of forest area.

Rates of C loss/gain arising from specific land-use transitions were taken from PAS 2050 guidelines (BSI, 2008), which are based on IPCC (2006). The PAS 2050 guidelines estimate deforestation (conversion of forest to annual cropland) releases in Brazil at an average 37 tonnes CO_2-eq/ha, and conversion of forest and shrub land to annual crop in Argentina at 17 and 2.2 tonnes CO_2-eq per ha, respectively. GHG emissions from soybean-driven LUC were calculated as the accumulated emissions for one year resulting from the total area deforested during the period 1990–2006 divided by the total soybean production in 2006. Based on this data, two LUC emission intensities were estimated for soybean cake produced in Brazil and Argentina, respectively: **7.69 and 0.93 kg CO_2-eq/kg soybean cake**. Soybeans and soybean cake produced elsewhere were assumed not to be associated with LUC.

3.2 Pasture expansion and land-use change

It has been argued that while forest conversion to soybean cultivation is occurring, the majority of deforested area is destined to pasture formation (Morton *et al*., 2006; Brown *et al.*, 2005). Wassenaar *et al.* (2007) developed a spatial and temporal model framework to analyse the expansion of pasture into forest in Latin America. The analysis predicted that, on average, 76 percent of deforested land would become pasture. Table C3 presents the net changes for different land use categories across regions; pasture expansion has been notable in Latin America and Africa while, at the same time, forest area in Latin America and Africa during the same period declined substantially.

3.2.1 Approach

The approach is based on the IPCC stock-based approach termed the *Stock-Difference Method*, which can be applied where carbon stocks are measured at two points in time to assess carbon stock changes (IPCC, 2006). The following emissions from deforestation were considered:

- CO_2 emissions from changes in biomass stocks (above-and below-ground biomass);
- CO_2 emissions from changes in dead organic matter (litter and deadwood);
- CO_2 emissions from changes in soil carbon stocks.

For each of the carbon pools mentioned above, several factors such as land use (forest, croplands, pasture), climatic zone, ecotype (tropical moist or tropical dry forest), soil type (mineral or organic soils), forest type, etc., were taken into consideration. Since data from forestry inventories are only available from 1990, the changes in carbon stocks due to deforestation could only be calculated for the period 1990-2006.

The calculations of land-use change were accomplished in two steps: first, the assessment of land use dynamics; and second, the carbon emissions based on land use dynamics and biophysical conditions. A complete assessment of carbon emissions from LUC involves the quantification of several key elements including deforestation rates, land use dynamics, and initial carbon stocks in biomass and soil. Two types of information are fundamental to enable emissions to be calculated: rates of deforestation and per hectare changes in carbon stocks in the different carbon pools. The following sections provide a detailed description of the applied methodology and assumptions made.

Determining total land area converted from forest to grassland. To accurately estimate carbon fluxes from LUC, it is critical to understand LUC dynamics following deforestation. With regard to land-use transition matrices, a simplified approach was adopted. Changes in land use area were estimated on the basis of the Tier 1 approach outlined in Chapter 3 of the IPCC guidelines, which estimates the total change in area for each individual land use category in each country.

FAOSTAT statistics on total land area (classified by land use category) were used to calculate the annual net change in the area of each land use category.

Table C4 presents the countries in which the increase in pasture area was largely facilitated by a decrease in forest area, and our estimates show that about 13 million hectares were deforested for pasture establishment.

Table C4. Pasture expansion against forestland in Latin America (1990-2006)

Countries	Pasture area change *(1 000 ha)*	Share of regional expansion *(percentage)*
Brazil	10 212.3	77.2
Chile	1 150.0	8.7
Paraguay	1 040.0	7.9
Nicaragua	454.3	3.4
Other*	365.0	2.8
Total	**13 221.6**	100

* 'Other' category includes: Honduras, Ecuador, Panama, El Salvador and Belize.
Source: Authors' calculations based on FAOSTAT data.

Table C5. Country specific estimates of above-and below-ground biomass

Countries	Above-ground biomass[1] *(tonnes DM/ha)*	Ratio of below- to above- ground biomass[2]	Below-ground biomass *(tonnes DM/ha)*	Total biomass[3] *(tonnes DM/ha)*
Brazil	220	0.24	52.8	272.8
Chile	220	0.24	52.8	272.8
Paraguay	210	0.24	50.4	260.4
Nicaragua	210	0.24	50.4	260.4
Ecuador	300	0.37	111	411.0
Other*	220	0.24	52.8	272.8

[1] Derived from IPCC, Volume 4, Chapter 4, Table 4.4.

[2] Ratio of above-below ground factors are derived from IPCC guidelines, Table 4.7.

[3] Total biomass is the sum of above-and below-ground biomass.

* 'Other' category includes: Honduras, Ecuador, Panama, El Salvador and Belize.

Changes in carbon stocks from above- and below-ground biomass. The method applied here focuses on stock changes in biomass associated with woody vegetation which are capable of accumulating large quantities of carbon over a long period of time. The Tier 1 method necessitates the estimation of biomass before and after conversion using IPCC equation 2.16 (Volume 4, Chapter 2).

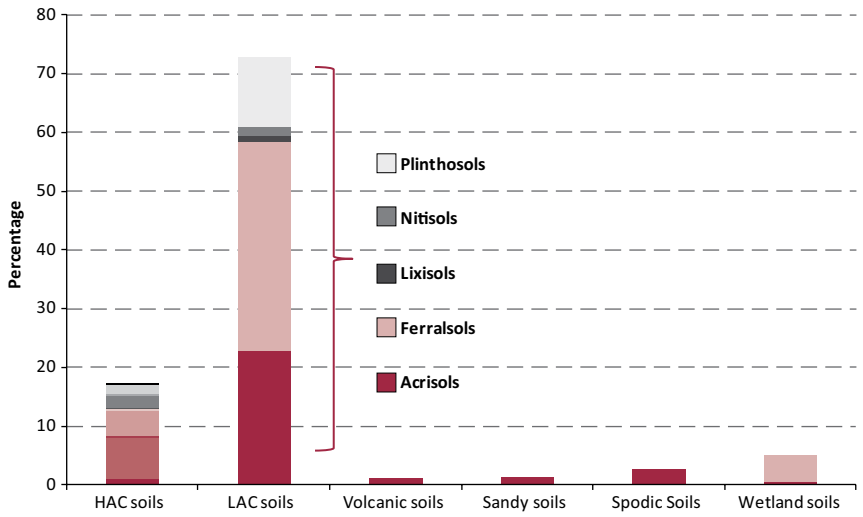
Biomass in forests is determined by ecological zone, type of native vegetation and geographical location of forests. Based on the IPCC Tier 1 approach, in the conversion of forest to grassland it is assumed that all biomass is cleared and therefore the default biomass after conversion is 0 tonnes DM ha^{-1}. The IPCC guidelines (Chapter 4, Volume 4, Table 4.7) provide average default values for above-ground biomass in forests. Due to the lack of data on below-ground biomass, the ratio of below-to-above ground biomass (root-to-shoot ratio) was used to estimate the below-ground component of biomass and the total biomass (tonnes DM/ha) given in Table C5. A default factor of 0.50 tonnes C per tonnes DM (carbon fraction for woody biomass was used to convert biomass into carbon stocks per hectare.

Changes in carbon stocks from dead organic matter (DOM) pools. The conceptual approach to estimating changes in C stocks in dead wood and litter pools is to estimate the C stocks in the old and new land use categories and apply this change in the year of conversion. Equation 2.23 (IPCC, 2006, Volume 4, Chapter 2) was used to estimate changes in C stocks from DOM.

According to the IPCC Tier 1 approach, DOM pools in non-forest land categories after the conversion are zero and this is based on the assumption that all DOM carbon losses occur entirely in the year of land-use conversion. Tier 1 also assumes that carbon contained in biomass killed during the conversion of land is emitted to the atmosphere and none is added to the dead wood and litter pools. Tier 1 default factors for dead wood and litter were taken from IPCC (2006, Volume 4, Chapter 2, Table 2.2).

Changes in soil carbon stocks. SOC stock changes do not occur instantaneously but over a period of years to decades. The current IPCC good practice guidance for GHG inventories assumes a period of 20 years for a new equilibrium to occur after conversion (IPCC, 2006). The change in the amount of SOC depends on factors such as climate region, native soil type, management system after conversion

Figure C3.
Main soil classes in Latin American forested areas based on the World Reference Base for Soil Resources classification



LAC: low activity clay; HAC: high activity clay.
Source: Authors.

and input use. The calculation of SOC losses per hectare of area transformed from forest to grassland is based on equation 2.25 in IPCC (2006, Volume 4, Chapter 2), which takes into account changes in soil carbon stocks associated with type of land use, management practices and input of organic matter (fertilization, irrigation, liming and grazing intensity) in the soil.

The approach makes a distinction between organic and mineral soil carbon pools, and the focus is on the impacts of LUC on the organic pool, because inorganic soil carbon is assumed to be insensitive to land-use change and management. Land converted to grassland was stratified according to climatic region, management and major soil types based on country specific classifications. The starting point was to derive a soil type classification of areas under forest in the selected countries in order to determine SOCs. This was accomplished with overlays of suitable climatic and soil maps coupled with spatial data on forest land area[16,17]. Figure C3 presents the mapping results of country-specific soil types on forested land and provides information on the dominant soil groups in forested areas in Latin America.

To establish SOC stocks, the soil divisions were further aggregated into dominant soil type classes (Figure C3) defined in IPCC guidelines based on the World Reference Base (WRB) for Soil Resources classification. Based on this aggregation, at a regional level, soils with low activity clay cover nearly 73 percent of the forested area in the nine countries. The remaining forested area is made up of the other five dominant soil types of which the high activity clay soil types cover 17 percent of the area (Figure C3).

[16] FAO/IIASA/ISRIC/ISS-CAS/JRC. 2009. Harmonized World Soil Database (version 1.1). FAO, Rome, Italy and IIASA, Laxenburg, Austria.

[17] Arino, O., Ramos, J., Kalogirou, V., Defourny, P. & Achard, F. 2010. "GlobCover 2009", Proceedings of the Living Planet Symposium, SP-686, June 2010. Data downloaded from http://ionia1.esrin.esa.int/ in August 2011.

Table C6. Default soil organic C stocks for mineral soils

Climate region	High activity clay soils	Low activity clay soils
	(tonnes C.ha^{-1} in 0-30 cm depth)	
Boreal	68	NA
Cold temperate, dry	50	33
Cold temperate, moist	95	85
Warm temperate, dry	38	24
Warm temperate, moist	88	63
Tropical, dry	38	35
Tropical, moist	65	47
Tropical, wet	44	60
Tropical, montane	88	63

NA: Not Applicable because these soils do not normally occur in some climatic zones.
Source: IPCC (2006).

Table C7. Soil organic carbon pool at 0-30 cm depth

Countries	Soil C stocks under forest	Soil C stocks under grassland	Net change in carbon stocks	Net annual change
	tonnes C.ha^{-1}		*tonnes C.ha^{-1}*	*tonnes C.ha^{-1} yr^{-1}*
Brazil	60	58.20	-1.8	- 0.11
Chile	44	42.68	-1.3	- 0.08
Paraguay	65	63.05	-2.0	- 0.12
Nicaragua	35	33.95	-1.1	- 0.07
Honduras	56	54.32	-1.7	- 0.11
Ecuador	78	75.66	-2.3	- 0.15
Panama	65	63.05	-2.0	- 0.12
El Salvador	50	48.50	-1.5	- 0.09
Belize	65	63.05	-2.0	- 0.12

Source: Authors' calculations based on IPCC (2006).

The 2006 IPCC guidelines provide average default SOC stocks for the dominant soil classes clustered by eco-region reproduced in Table C6. The default reference soil organic C stocks are for the top 30 cm of the soil profile because different land use management methods mostly affect soil carbon in the surface layer.

For Tier 1, all stock change factors (F_{lu}, F_{mg}, F_I) were assumed to be equal to 1 for forest land, corresponding to the default values in IPCC guidelines. For grasslands, stock change factors used for land use and input (G_{lu}, *and* F_I) were assigned a value of 1.

The quality of management of tropical pastures after conversion is critical in understanding whether the soils under this land use represent a source or a sink of atmospheric carbon. Differences in management practices could significantly affect subsequent trends in soil carbon. Due to the limited data on management and input, default values were used.

It was assumed that pastures are moderately degraded and therefore a coefficient of 0.97 (IPCC, 2006 Volume 4 , Chapter 6, Table 6.2) for F_{mg} stock factor was applied, which represents overgrazed or moderately degraded grasslands with reduced productivity and receiving no management inputs. This assumption is based

on the findings of studies (Hernandez *et al*., 1995; Murty *et al*., 2002; De Oliveira *et al*., 2006; Cerri *et al*., 2005;) which inferred that most of the pastures in LAC are in some process of degradation caused by poor management methods, low input fertilization and no maintenance. The results (Table C7) show a net decrease in SOC with losses ranging between 1.1 to 2.3 tonnes C ha^{-1}.

3.3 Sensitivity analysis and the influence of LUC method

Modelling of land use and LUC emissions is subject to great uncertainties mainly because of the complexity of LULUCF processes, the challenges of obtaining reliable global data and the absence of validated approaches to estimate carbon stock changes. In particular, uncertainty regarding the magnitude of LUC emissions arises due to uncertainties in: (a) the rates of land use; (b) the carbon storage capacity of different forests, initial carbon stocks and the modes of C release; and (c) the dynamics of land use not normally tracked. In addition, a value judgment has to be made regarding what drives LUC and, consequently, how the emissions should be allocated. In order to explore the potential effect that different methodologies can have, the results obtained with the GLEAM approach are compared to three alternative approaches: (a) PAS 2050-1:2012; (b) One-Soy; and (c) reduced time-frame approach. These approaches are summarized in Table C8.

3.3.1 Alternative approaches

PAS 2050-1: 2012 approach. Several studies suggest that deforestation is related to the expanding soybean sector (Fearnside, 2005; Bickel and Dros 2003; Carvalho *et al.*, 2002), but others dispute this claim, and argue that soybean is expanding into land previously under pasture, and is not causing new deforestation (Mueller, 2003; Brandao *et al.*, 2005). Due to the lack of knowledge of the origin of the converted

Table C8. Alternative approaches for soybean LUC emissions calculations

Method	Spatial allocation	Temporal allocation of LUC emissions	Quantification of rates of LUC	Quantification of rates of C loss/gain
GLEAM approach (current study)	To all soybean produced within the country	20 years	FAOSTAT average LUC rates 1990-2006 Brazil: forest→crops (100%) Argentina: other crops (44%), forest (22%) and other land (31%)→soybean	IPCC (2006) Tier 1
PAS 2050-1:2012	To all soybean produced within the country	20 years	Average rates over 20 years. LUC rates based on (a) or (b) - whichever results in the highest emission factor. (a) from grassland forest and perennial arable in equal proportion (b) from grassland, forest and perennial arable in proportion to their rates of change	IPCC (2006) Tier 1
One-Soy	To traded soybean	20 years	FAOSTAT average LUC rates 1990-2006 Brazil: forest→crops (100%) Argentina: other crops (44%), forest (22%) and other land (31%)→soybean	IPCC (2006) Tier 1
Reduced time-frame	To all soybean produced within the country	20 years	FAOSTAT average LUC rates 2002-2007 Brazil: forest→crops Argentina: other crops (44%), forest (22%) and other land (31%)→soybean	IPCC (2006) Tier 1

Source: Authors.

land, the GLEAM results were compared with PAS 2050-1:2012 (BSI, 2012), which provides a way of quantifying LUC emissions when previous land use is not known and only the crop and country are known. The PAS 2050-1:2012 calculations of emissions related to land-use change are accomplished in two steps.

First, rates of land-use change need to be calculated based on the PAS 2050-1: 2012. To calculate these, four categories of land are considered: forest, pasture, annual cropland and perennial cropland. Time series data on land area for forest, pasture, annual and perennial crops taken from FAOSTAT were used to: (i) determine whether the crop in question was associated with LUC by quantifying the rate of expansion over a 20-year period; and (ii) determine the share of LUC associated with each land category. In a second step, carbon losses based on land dynamics and biophysical conditions (climate, soil type, forest type, crop management, etc.) were computed based on the IPCC (2006) Tier 1 approach. The two sources of carbon taken into account in this approach are vegetation and soil. Two LUC EFs were calculated, based on different assumptions regarding where land for soybean expansion is derived from: (i) assuming that land for soybean production is gained in equal proportions from grassland, forest and perennial cropland; (ii) assuming that land for soybean is gained from other land use categories in proportion to their relative rates of change. The highest of the two EF's was then selected, in accordance with the guidelines. BSI (2012) present a detailed account of methodology and data sources.

One-Soy approach. In this approach it is assumed that all soybeans, irrespective of where they have been produced, are associated with LUC. The central argument for this scenario is that the global demand for soybeans is largely interconnected and is a key driver of LUC. An average LUC emission factor associated with soybean was estimated by calculating the total LUC emissions attributable to globally-traded soybean and soybean cake and then dividing this by total global soybean cake exports. Because the emission intensity was applied to all traded soybean and soybean cake, the approach equally distributes the LUC emissions across all importing countries irrespective of where the soybean is produced.

Reduced time-frame approach. Annual deforestation rates are highly variable, so the period over which the rates of LUC are estimated can therefore have a significant influence on results. Since data from forestry inventories are only available from 1990, this assessment was based on the average rates of LUC over the period 1990-2006. This not only coincides with a period of high rates of deforestation but also high soybean area expansion. In the reduced time frame approach, the LUC emissions are calculated based on the average rates of LUC over the period from 2002-07, while maintaining the underlying assumptions in the study.

3.3.2 Results

Effect of LUC approach on soybean LUC emission factor. Table C9 reports the LUC factors for soybean cake (kg CO_2-eq per kg soybean cake) calculated using each of the approaches. The choice of method for estimating LUC EFs can strongly influence the emission intensity of livestock products and illustrates the complexity of analysing LUC processes.

Table C9. Summary of soybean LUC emission intensity for the four approaches

Scenario	Argentina	Brazil
	(kg CO_2-eq per kg soybean cake)	
GLEAM approach (current study)	0.93	7.69
PAS 2050-1:2012	4.23	3.21
One-Soy	2.98	2.98
Reduced time-frame	0.34	3.70

Source: Authors' calculations.

The *PAS 2050-1: 2012* approach produces markedly different LUC emission factors due to the assumptions made regarding the land use category against which additional land for soybean production was gained and the relative share of this gain (Table C10). Unlike Brazil, Argentina has a higher EF using the default assumption (that expanded crop areas are derived from forest, grassland and perennial crops in equal proportion) than using the relative rates of change. The higher proportion of soybean cultivated on expanded areas in Argentina (76 percent) compared to Brazil (55 percent), combines with the default LUC assumptions, to give Argentina a higher soybean EF than Brazil under PAS 2050-1:2012.

The strength of the *One-Soy* approach is that it recognizes that global demand is a key driver of LUC. However, it penalizes those countries whose production is not directly associated with LUC and may not provide the right signals to producers and consumers of soybean.

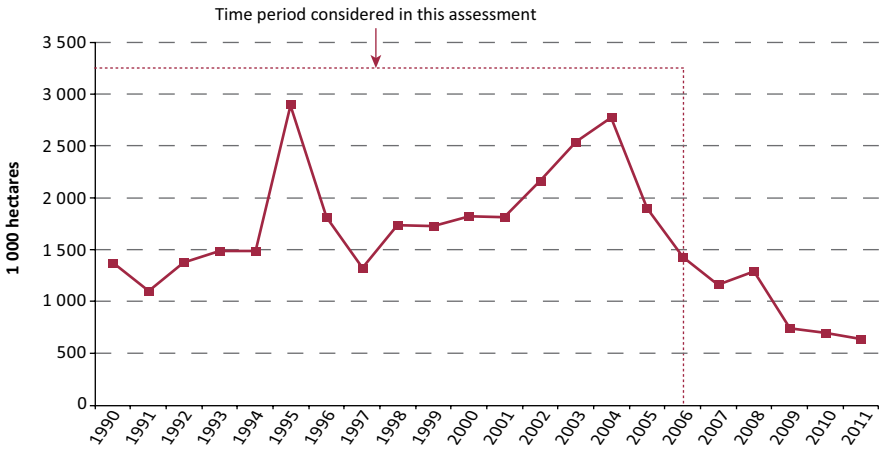
In the *reduced time-frame approach*, the emission intensity of soybean cake from Argentina and Brazil reduces by more than half. Average annual deforestation rates appear to be close over the two periods 1990-2006 and 2002-2007 (1.76 and 1.98 million ha respectively, Figure C4), but the average annual rates of soybean expansion differ and they are higher for 2002-2007: between 1990 and 2006, the soybean area in Brazil increased by 534 000 ha/year whereas the increase for the period 2002-2007 was 840 000 ha/year. The lower emission intensity for 2002-2007 therefore results from the rate of deforestation relative to the rate of soybean expansion, not from the absolute change in deforestation rate.

Table C10. Proportion of expanded soybean area derived from each land-use category

Land-use category	GLEAM approach		PAS 2050-1:2012 approach	
	Brazil	Argentina	Brazil	Argentina
	percentage			
Forest	100	22	51 (33)	23 (33)
Grassland	0	0	0 (33)	0 (33)
Shrubland	0	31	0 (0)	0 (0)
Annual cropland	0	44	46 (0)	61 (0)
Perennial cropland	0	0	3 (33)	16 (33)

Note: Figures in brackets are the PAS 2050-1 default land use transformations.
Sources: Based on FAOSTAT (2012).

Figure C4.
Annual forest loss in Brazil



Source: INPE, 2012.

Table C11. Estimated changes in pasture area and annual carbon losses for the reduced time-frame approach

Country	Change in pasture area *(1 000 ha)*	Carbon losses *(tonnes CO_2/ha/year)*
Brazil	3 563.6	- 51.0
Chile	1 079.3	- 51.1
Paraguay	1 464.6	- 48.8
Nicaragua	311.6	- 48.5
Honduras	170.0	- 50.8
Ecuador	No gain in pasture	-
Panama	60.3	- 50.8
El Salvador	45.3	- 50.8
Belize	0.3	- 51.1
Total/average	**6 695.3**	**- 50.4**

Source: Authors' calculations.

For pasture expansion, emissions are highly sensitive to the time period chosen; using a ten-year time-frame scenario, annual carbon losses are 50.4 tonnes CO_2 ha^{-1} yr^{-1} (Table C11) while in the current study annual carbon losses were estimated at 32 tonnes CO_2 ha^{-1} yr^{-1}. Shorter periods, however, place emphasis on deforestation resulting in higher annual carbon losses per hectare placing higher relative weighting of near-term emissions.

4. COMPARISON WITH OTHER STUDIES

The emissions intensity for LUC per kg of soybean and soybean cake calculated in this study are compared with other studies in Table C12. The emissions intensity used in this study is higher than some other studies, but within the overall range.

The emissions intensity of soybean is highly dependent on the calculation method and assumptions (Flysjo *et al.*, 2012). Variation arises from differences in:

- Calculation of C losses in soil and vegetation (above- and below-ground).
- Quantification of land-use transitions – i.e. how much of the LUC can be attributed to cropping.
- Allocation of LUC arising from cropping to specific crops, e.g. emissions are usually allocated to one of the following: (a) soybean grown in country/region; (b) all expanding crops grown in country region; (c) all crops grown globally. This leads to huge variations in the emissions per kg of crop.
- The time period over which emission are allocated.

Table C12. Soybean LUC emissions per unit of output and hectare

Study	Area covered by study	Emissions	*Converted/all soybean /all crops
FAO (2010)	Argentina	1.04 kg CO_2-eq/kg soybean	All soybean
FAO (2010)	Brazil	7.69 kg CO_2-eq/kg soybean cake	All soybean
FAO (2010)	Brazil	8.54 kg CO_2-eq/kg soybean cake	All soybean
FAO (2010)	Brazil	12.81 kg CO_2-eq/kg soybean cake	Converted
FAO (2010)	Brazil	14.23 kg CO_2-eq/kg soybean	Converted
Leip *et al.* (2010) grass>soybean	South America	1.50 kg CO_2-eq/kg soybean cake	All soybean Cited in Flysjo *et al.* (2012)
Leip *et al.* (2010) mix>soybean	South America	3.10 kg CO_2-eq/kg soybean cake	All soybean Cited in Flysjo *et al.* (2012)
Leip *et al.* (2010) forest>soybean	South America	10.00 kg CO_2-eq/kg soybean cake	All soybean Cited in Flysjo *et al.* (2012)
Sonesson *et al.* (2009, p13)	Brazil	1.50 kg CO_2-eq/kg soybean	All soybean ~0.6 of this is due to LUC
Audsley *et al.* (2010, p.59)	Brazil	5.30 kg CO_2-eq/kg soybean	All soybean
Audsley *et al.* (2010, p.59)	Argentina	1.60 kg CO_2-eq/kg soybean	All soybean
Castanheira & Freire (2011)	Low (Argentina)	~0.5 kg CO_2-eq/kg soybean	Converted
Castanheira & Freire (2011)	High (Brazil)	~15 kg CO_2-eq/kg soybean	Converted
Nemecek *et al.* (2012)	Brazil	1.47 kg CO_2-eq/kg soybean	All soybean Brazil, LUC, Ecoinvent v2.2
Nemecek *et al.* (2012)	Brazil	5.21 kg CO_2-eq/kg soybean	All soybean Brazil, LUC, Ecoinvent v3.0
Reijnders & Huijbregts (2008)	Brazil – cerrado	1 to 2.7 kg CO_2-eq/kg soybean	Converted
Reijnders & Huijbregts (2008)	Brazil – forest	5 to 13.9 kg CO_2-eq/kg soybean	Converted
FAO (2010)	Brazil – deforestation	37.00 kg CO_2-eq/ha	Converted
FAO (2010)	Brazil – deforestation	22.20 kg CO_2-eq/ha	All soybean
Audsley *et al.* (2009)	All LUC	1.43 kg CO_2-eq/ha	Allocates LUC to all crops globally
Audsley *et al.* (2010, p.59)	Brazil – deforestation	37.00 kg CO_2-eq/ha	Converted
Audsley *et al.* (2010, p.59)	Brazil – grassland	11.00 kg CO_2-eq/ha	Converted
Reijnders & Huijbregts (2008)	Brazil – forest	14 to 39 kg CO_2-eq/ha	Converted
Schmidt *et al.* (2011)	All LUC	8.42 kg CO_2-eq/ha	Allocates LUC to all crops globally

**EF* for (a) converted land; (b) average over all soybean grown in country/region; or (c) all crops grown globally.

Table C13. Comparison of studies on LUC associated with pasture expansion in Brazil

Study and area	Approach	Scope	Carbon losses *(tonnes CO_2-eq /ha)*
Current study (Brazil)	IPCC stock-based approach (stock difference method) Period: 1990-2006	Biomass Soil carbon Dead organic matter	506.7
Cederberg *et al.*, 2011 (Brazil -Legal Amazon Area)	Net committed emissions approach Period: 1986-2006	Biomass Soil carbon CH_4 and N_2O	572
Leip *et al.*, 2010 (Beef imported into EU from Brazil)	Net committed emissions approach Period: 1986-2006	Biomass Soil carbon CH_4 and N_2O	568.7

For pasture expansion, with the exception of Brazil where impacts of deforestation have been analysed to a greater degree, there are relatively few estimates of the impact of carbon losses the due to deforestation. We therefore compared the results obtained for Brazil with estimates from other studies (Table C13).

Despite the difference in calculation approach, our estimates are very similar to those found in the literature. This may be partly coincidental because the approaches differed in many respects; for example, the period assessed, the calculation method and assumptions and well as emission factors. Cederberg *et al.* (2011) apply different carbon stock losses for the different pools and take into account the impacts on fire used in forest clearing on CO_2 emissions.

The estimates of LUC emissions presented in this report are still very preliminary and need to be interpreted with caution. This is an important area for improvement of GLEAM and it is planned that future developments of the model will include a more detailed and complete assessment of LUC emissions.

5. LAND USE

For the reasons explained above, this analysis could not incorporate C stock changes under constant land use. This section attempts to evaluate the effect of this simplification on results. Given the importance of grasslands as a potential as a C sink (Soussana *et al.*, 2010), we focus our case study on this land use rather than on feed-crops.

Furthermore, we selected the European Union for this evaluation in view of data availability in this region. National inventories in the European Union are indeed increasingly accurate because Member States are requested to maintain and monitor the area of permanent grassland by the Common Agricultural Policy. Member States are required to report annual estimates of their total area of permanent grassland.

Soussana *et al.* (2010) estimate an average grassland C sequestration rate of 5 ± 30 g C/m^2/year for temperate grasslands under baseline, constant land use. This estimate is derived from an exhaustive literature review, and inventories of SOC stocks at regional or local level, mainly from Western Europe.

Using this estimate, we computed that permanent grasslands in the European Union (estimated at 62.7 million ha) represent a sink of 3.1 ± 18.8 million tonnes C per year, equivalent to 11.5 ± 69.0 million tonnes CO_2-eq per year. This estimate

Table C14. Total GHG emissions from the ruminant sector in the European Union and changes in C stocks in permanent pasture

Systems	Total emissions based on a LCA approach and excluding land use[1]	C sequestration in permanent grassland under baseline constant management[2]
	(million tonnes CO_2-eq/year)	
Total ruminant sector	**390.5**	**11.5 ± 69.0**
Cattle, grazing	25.6	
Cattle, mixed	322.8	
Small ruminants, grazing	4.6	
Small ruminants, mixed	37.4	

[1] Based on GLEAM.

[2] Based on Soussana *et al.* (2010).

is compared with the 390.5 million tonnes CO_2-eq emitted yearly by the ruminant sector in the European Union (Table C14).

Taking into account C stock changes in permanent pastures, net emissions from the EU ruminant sector are therefore estimated between 310 and 448 million tonnes CO_2-eq/year.

Net sequestration/emission of C in permanent pasture under stable management practices may thus be significant in the European Union, and should be included in the assessment of GHG emissions of the sector. The estimate computed here is however one order of magnitude smaller than the sum of all other emissions along the supply chain. Furthermore, even in a region where data availability is comparatively high, the uncertainty about C fluxes is such that it cannot be ascertained if permanent grasslands are net sequesters or emitters of carbon.

The European Union only accounts for a limited share of total grassland area (about 2 percent according to FAOSTAT, 2013), so including land use sequestration/emissions could have even greater effects on net emissions of the sector in other regions. For example, Cerri *et al.* (2004) measured that brasilian pastures established in the early 90's could store up to 330 $g.m^{-2}$ of carbon in the 20 first centimeters of soil. This would however require a better understanding SOC dynamics in grasslands and the development of models and databases to monitoring and predicting changes in C stocks.

REFERENCES

Armentano, T.V. & Menges, E.S. 1986. Patterns of change in the carbon balance of organic soil-wetlands of the temperate zone. *Journal of Ecology*, 74: 755–774.

Audsley, E., Brander, M., Chatterton, J., Murphy-Bokern, D., Webster, C. & Williams, A. 2009. *How low can we go? An assessment of greenhouse gas emissions from the UK food system and the scope to reduce them by 2050.* Food Climate Research Network and WWF. UK.

Audsley, E., Angus, A., Chatterton, J., Graves, A., Morris, J., Murphy-Bokern, D., Pearn, K., Sandars, D. & Williams, A. 2010. *Food, land and greenhouse gases. The effect of changes in UK food consumption on land requirements and greenhouse gas emissions.* London: The Committee on Climate Change.

Bickel, U. & Dros, J. M. 2003. *The impacts of soybean cultivation on Brazilian ecosystems.* Bonn, AIDEnvironment-WWF): p 33. (available at http://assets.panda.org/downloads/impactsofsoybean.pdf).

BSI. 2008. PAS 2050:2008. Specification for the assessment of the life cycle greenhouse gas emissions of goods and services. UK: British Standards Institution (BSI).

BSI. 2012. PAS 2050-1:2012. Assessment of life cycle greenhouse gas emissions from horticultural products Supplementary requirements for the cradle to gate stages of GHG assessments of horticultural products undertaken in accordance with PAS 2050. British Standards Institution. London.

Brandao, A.S.P., Castro de Rezende, G. & Da Costa Marques, R.W. 2005. Agricultural growth in the period 1999–2004, outburst in soybeans area and environmental impacts in Brazil. IPEA Discussion Paper No. 1062. Instituto de Pesquisa Econômica Aplicada. Brasilia.

Brown, J.C., Koeppe, M., Coles, B. & Price, K.P. 2005. Soybean production and conversion of tropical forest in the Brazilian Amazon: the case of Vilhena, Rondônia. *Ambio,* 34: 462–9.

Carvalho, G.O., Nepstad, D., McGrath, D., Vera Diaz. M. del C. & Barros, A.C. 2002. Frontier expansion in the Amazon. Balancing development and sustainability. *Environment Sci. Policy Sustainable Dev.*, 44: 32–42.

Castanheira, E. & Freire, F. 2011. *Life-cycle greenhouse gas assessment of soybeans.* Paper presented at Life-Cycle Management Conference, 2011. Berlin.

Cederberg, C., Persson, M.U., Neovius, K., Molander, S. & Clift, R. 2011. Including Carbon Emissions from Deforestation in the Carbon Footprint of Brazilian Beef. *Environmental Science & Technology*, 45 (5): 1773–1779.

Cerri, C.C., Melillo, J.M., Feigl, B.J., Piccolo, M.C., Neill, C., Steudler, P.A., Carvalho, M.S., Godinho, V.P., Cerri, C.E.P. & Bernoux, M. 2005. Recent history of the agriculture of the Brazilian Amazon Basin. *Outlook on Agriculture*, 34(4): 215–223.

Cerri, C.E.P., Paustian, K, Bernoux, M., Victoria, R.L., Melillo, J.M. & Cerri, C.C. 2004. Modelling changes in soil organic matter in Amazon forest to pasture conversion with the Century model. *Global Change Biology*, 10(5):815-832.

Coleman, K., Jenkinson, D.S., Crocker, G.J., Grace, P.R., Klir, J., Korschens, M., Poulton, P.R. & Richter, D.D. 1997. Simulating trends in soil organic carbon in long-term experiments using RothC-26.3. *Geoderma* 81: 29–44.

Conant, R.T. & Paustian, K. 2002. Potential soil carbon sequestration in overgrazed grassland ecosystems. *Global Biogeochemical Cycles*, 16(4): 1143. doi:10.1029/2001GB001661.

Costa de Campos, B., Carneiro Amado, T. J., Bayer, C., Nicoloso, Rodrigo da Silveira, & Fiorin, J.E. 2011. Carbon stock and its compartments in a subtropical oxisol under long-term tillage and crop rotation systems. *Rev. Bras. Ciênc. Solo* 35(3): 805-817.

Del Grosso, S.J., Parton, W.J., Mosier, A.R., Hartman, M.D., Brenner, L., Ojima, D.S. & Schimel, D.S. 2001. Simulated interaction of carbon dynamics and nitrogen trace gas fluxes using the DAYCENT model. In Shaffer, J., Liwang Ma & S. Hansen, eds. *Modelling carbon and nitrogen dynamics for soil management*, pp. 303-332. Boca Raton, Florida, USA, CRC Press.

Dieckow, J., Zendonadi dos Santos, N., Bayer, C., Molin, R., Favaretto, N. & Pauletti, V. 2010. No-tillage crop rotations, C sequestration and aspects of C saturation in a subtropical Ferralsol. 19th World Congress of Soil Science, Soil Solutions for a Changing World. Brisbane, Australia.

FAO. 2009. *State of the World's Forests 2009*. FAO publication, ISBN 978-92-5-106057-5. Rome, Italy.

FAO-FRA. 2010. *Global Forestry Resource Assessment 2010*. United Nations Food and Agriculture Organization: Rome, 2010.

FAO. 2010. *Greenhouse gas emissions from the dairy sector – A life cycle assessment*, by Gerber, P., Opio, C., Vellinga, T., Herderson, B. & Steinfeld, H. FAO. Rome.

FAOSTAT. 2011. *FAO Statistical Database*. Accessed 2011.

Falloon, P. & Smith, P. 2002. Simulating SOC changes in long-term experiments with RothC and CENTURY: Model evaluation for a regional scale experiment. *Soil Use and Management*, 18: 101–111.

Fearnside, P.M. 2005. Deforestation in Brazilian Amazonia: history, rates and consequences. *Conservation Biology*, 19(3): 680–688.

Flysjö, A., Cederberg, C., Henriksson, M. & Ledgard, S. 2012. The interaction between milk and beef production and emissions from LUC - critical considerations in life cycle assessment and carbon footprint studies of milk. *Journal of Cleaner Production*, 28: 134–142.

Hart, P.B.S. 1984. *Effects of soil type and past cropping on the nitrogen supplying ability of arable soils*. University of Reading, UK.

Hernandez, M., Argel, P.J., Ibrahim, M.A. & Mannetje, L. 1995. Pasture production, diet selection and liveweight gains of cattle grazing *Brachiaria brizantha* with or without *Arachis pintoi* at two stocking rates in the Atlantic zone of Costa Rica. *Trop. Grassl*., 29 (3): 134-141

Houghton, R.A. & Goodale, C.L. 2004. Effects of LUC on the carbon balance of terrestrial ecosystems. In DeFries, R.S., Asner, G.P. & R.A. Houghton, eds. *Ecosystems and Land-use Change*. Washington, D.C., American Geophysical Union.

IPCC. 2000. *Land Use, Land-Use Change, and Forestry*. Cambridge, UK, Cambridge University Press.

IPCC. 2006. *2006 IPCC Guidelines for National Greenhouse Gas Inventories prepared by the National Greenhause Gas Inventories Programme,* Eggleston, H.S., Buenida, L., Miwa, K., Nagara, T. & Tanabe, K. (eds). Published: IGES, Japan.

Jenkinson, D.S., Hart, P.B.S., Rayner, J.H. & Parry, L.C. 1987. Modelling the turnover of organic matter in long-term experiments at Rothamsted. *INTECOL Bulletin* 15: 1-8.

Jones, M.B. & Donnelly, A. 2004. Carbon sequestration in temperate grassland ecosystems and the influence of management, climate and elevated CO_2. *New Phytologist*, 164: 423–439.

Kirschbaum, M.U.F. & Paul, K.I. 2002. Modelling C and N dynamics in forest soils with a modified version of the CENTURY model. *Soil Biology and Biochemistry*, 34: 341–354.

Lal, R. 1999. Soil management and restoration for C sequestration to mitigate the accelerated greenhouse effect. *Progress in Environmental Science*, 1: 307–326.

Lal, R. 2004. Soil carbon sequestration impacts on global climate change and food security. *Science*, 304: 1623–1627.

Leip, A., Weiss, F., Wassenaar, T., Perez, I., Fellmann, T., Loudjani, P., Tubiello, F., Grandgirard, D., Monni, S. & Biala, K. 2010. *Evaluation of the livestock sector's contribution to the EU greenhouse gas emissions (GGELS) - Final Report*, European Commission, Joint Research Centre.

Li, C., Frolking, S. & Frolking, T.A. 1992. A model of nitrous oxide evolution from soil driven by rainfall events: 1. Model structure and sensitivity. *Journal of Geophysical Research*, 97(D9): 9759–9776.

Li, C., Frolking, S. & Harriss, R. 1994. Modeling carbon biogeochemistry in agricultural soils. *Global Biogeochem Cycles*, 8: 237–254.

Li, C. 1996. The DNDC model. In D.S. Powlson, P. Smith & J.U. Smith, eds. *Evaluation of Soil Organic Matter Models Using Existing, Long-Term Datasets*, pp. 263–267. NATO ASI Series I, Vol. 38. Heidelberg,Springer-Verlag.

Morton, D.C., DeFries, R.S., Shimabukuro, Y.E., Anderson, L.O., Arai, E., Espiritu-Santo, F. del B., Freitas, R. & Morisette, J. 2006. Cropland expansion changes deforestation dynamics in the southern Brazilian Amazon. *PNAS USA*, 103(39): 14637–41.

Mueller, C.C. 2003. Expansion and Modernization of Agriculture in the Cerrado – The Case of Soybeans in Brazil's Center-West, p. 28.

Murty, D, Kirschbaum, M.U.F, McMurtrie, R.E & McGilvray, H. 2002. Does forest conversion to agricultural land change soil organic carbon and nitrogen? A review of the literature. *Global Change Biology*, 8: 105–123.

Nemecek, T., Weiler, K., Plassmann, K., Schnetzer, J., Gaillard, G., Jefferies, D., Garcia-Suarez, T., King, H. & Milà I Canals L. 2012. Estimation of the variability in global warming potential of worldwide crop production using a modular extrapolation approach. *Journal of Clean Production*, 31: 106–17.

Nepstad, D., Schwartzman, S., Bamberger, B., Santilli, M., Ray, D., Sschlesinger, P., Lefebvre, P., Alencar, A., Prinz, E., Fiske, G. & Rolla, A. 2006. Inhibition of Amazon deforestation and fire by parks and indigenous lands. *Conservation Biology*, 20: 65–73.

Pacheco, P. 2012. Soybean and oil palm expansion in South America: A review of main trends and implications. CIFOR Working Paper 90. Center for International Forestry Research. Bogor, Indonesia.

Parton, W.J., Schimel, D.S., Cole, C.V. & Ojima D.S. 1987. Analysis of factors controlling soil organic matter levels in Great Plains grasslands. *Soil Science Society of America Journal*, 51: 1173–1179.

Parton,W.J., Hartman, M.D., Ojima, D.S. & Schimel, D.S. 1998. DAYCENT: its land surface submodel: description and testing. *Global Planet Change*, 19: 35–48.

Paustian, K., Cole, C.V., Sauerbeck, D. & Sampson, N. 1998. CO_2 mitigation by agriculture: An overview. *Climatic Change*, 40: 135–162.

Post, W.M. & Kwon, K.C. 2000. Soil carbon sequestration and land-use change: processes and potential. *Global Change Biology*, 6(3): 317–327.

Reijnders, L. & Huijbregts, M.A.J. 2008. Biogenic greenhouse gases linked to the life cycles of biodiesel derived from European rapeseed and Brazilian soybeans. *Journal of Cleaner Production,* 16: 1943-1948.

Schmidt, G.A., Jungclaus, J.H., Ammann, C.M., Bard, E., Braconnot, P., Crowley, T.J., Delaygue, G., Joos, F., Krivova, N.A., Muscheler, R., Otto-Bliesner, B.L., Pongratz, J., Shindell, D.T., Solanki, S.K., Steinhilber, F. & Vieira, L.E.A. 2011. Climate forcing reconstructions for use in PMIP simulations of the last millennium (v1.0). *Geoscientific Model Development*, 4: 33-45.

Sisti, C.P.J. , dos Santos, H.P., Kohhann, R., Alves, B.J.R., Urquiaga, S. & Boddey R.M. 2004. Change in carbon and nitrogen stocks in soil under 13 years of conventional or zero tillage in southern Brazil. *Soil & Tillage Research*, 76: 39–58.

Soussana, J.F., Tallec, T. & Blanfort, V. 2010. Mitigating the greenhouse gas balance of ruminant production systems through carbon sequestration in grasslands. *Animal*, 4(3): 334–350.

Smith, P., Smith, J., Wattenbach, M., Meyer, J., Lindner, M., Zaehle, S., Hiederer, R., Jones, R.J.A., Montanarella, L., Rounsevell, M., Reginster, I. & Kankaanpää, S. 2006. Projected changes in mineral soil carbon of European forests, 1990–2100. *Canadian Journal of Soil Science*, 86: 159–169.

Smith, P., Martino, D., Cai, Z., Gwary, D., Janzen, H., Kumar, P., McCarl, B., Ogle, S., O'Mara, F., Rice, C., Scholes, B. & Sirotenko, O. 2007. Agriculture. In B. Metz, O.R. Davidson, P.R. Bosch, R. Dave & L.A. Meyer, eds. *Climate Change 2007: Mitigation. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC*). New York, Cambridge University Press.

Sonesson, U., Cederberg, C. & Berglund, M. 2009. *Greenhouse gas emissions in animal feed production decision support for climate certification*. Uppsala, Sweden. Available online: http://www.klimatmarkningen.se/wp-content/uploads/2009/12/2009-2-feed.pdf

Vieira, F. C. B., Bayer, C., Zanatta, J.A., Mielniczuk, J. & Six, J. 2009. Building Up Organic Matter in a Subtropical Paleudult under Legume Cover-Crop-Based Rotations. *Soil Science Society of America Journal*, 73(5): 1699-1706.

Wassenaar, T., Gerber, P., Verburg, M., Rosales, M., Ibrahim, M. & Steinfeld, H. 2007. Projecting land-use changes in the Neotropics: The Geography of Pasture Expansion into Forest. *Global Environmental Change*, 17: 86–104.

APPENDIX D

Postfarm emissions

GHG emissions accounted for in the post farmgate part of the supply chain include emissions related to fuel combustion and energy use in the transport, processing and refrigeration of products. The system boundary is from the farmgate up to the retail point. During this phase of the life cycle, three distinct emission streams were studied: emissions from the transport and distribution of live animals, milk and meat (domestic and international); GHG emissions from processing and refrigeration; and emissions related to the production of packaging material.

The system boundary for this part of the food chain included emissions from the farmgate to the retail distribution centre. Excluded from the analysis were estimates of GHG emissions from on-site waste-water treatment facilities, emissions from animal waste[18] at the slaughter site, the retail and consumption part of the food chain (household transport and preparation) and disposal of packaging and waste, which fall outside the scope of the system boundary studied but may warrant further research. Due to the lack of data, emissions related to by-products (rendering material, offal, etc.) are therefore currently excluded. However, we investigated the impact of allocating emissions to slaughter by-products (Appendix F).

1. APPROACH AND ASSUMPTIONS

1.1 Milk from ruminant species

The quantification of post farmgate emissions for milk produced by cattle, small ruminants and buffalo was based on a similar approach. The approach (and level of complexity) was largely influenced by two factors: the importance of the subsectors contribution to global milk production and the availability of data. Consequently, a more comprehensive approach was applied to the milk from the global cattle dairy sector, as outlined in FAO's report on GHG emissions in the dairy sector published in 2010.[19]

In the estimation of post farmgate emissions for small ruminant and buffalo milk, a similar but simplified approach was adopted; for small ruminants, it was assumed that all milk that left the farm was processed into cheese. FAOSTAT production statistics on goat and sheep cheese production were used to identify countries where cheese production is important. In producing countries with no cheese production, the sheep and goat milk was assumed to be consumed on farm and hence no post farmgate emissions were estimated for these countries. In addition, since not all milk is processed and traded, the proportion of small ruminant milk leaving the farm was estimated from the cheese production and total milk production within the country.

[18] In some countries, manure/slurry from the slaughterhouse is anaerobically digested and the biogas is used for heating and electricity. The challenge is that there insufficient information available on on-site energy generation from animal waste; thus, the resulting substituted energy and avoided GHG emissions are not considered in the calculations.

[19] FAO. 2010. http://www.fao.org/docrep/012/k7930e/k7930e00.pdf

The difference in calculation approach between cow's milk and buffalo milk is that for dairy cattle milk six products were considered (processed milk, cheese, whey, yoghurt, skimmed milk powder and whole milk powder), while post farmgate emissions for buffalo milk comprised emissions related to transport and processing of raw milk into processed milk. Emissions related to international trade of dairy products was only considered for the cattle dairy sector.

1.2 Meat from ruminant species

GHG emissions reported for this part of the food chain are based on the finished product leaving the facility and do not account for meat co-products and rendering products; however, in a life cycle assessment, when a system produces multiple products each of which have economic value, it is standard practice to assign some of the emissions from that process to each of the co-products.

In this analysis, all emissions were allocated to the carcass and therefore meat carries the whole burden. Post farmgate emissions for meat include: emissions associated with the transport of live animals to slaughterhouses, emissions related to slaughter and primary processing of carcasses, refrigeration of carcasses at processing plant and transport and refrigeration of product. Emissions related to international trade of meat products (carcasses and boneless meat) are taken into account. Due to the complexity of tracking trade flows of live animals the related emissions are excluded from this analysis.

2. ENERGY CONSUMPTION

Energy consumption is the most important source of GHG emissions from the post farmgate supply food chain. Table D1 presents average regional and country CO_2 emission coefficients applied in this analysis. The CO_2 intensities are determined by the composition of the energy sources employed and average GHG emissions from electricity consumption was modelled as a mix of existing electricity sources (e.g. coal, hydro, nuclear, oil, etc.) in different countries and regions taken from the International Energy Agency (IEA, 2009).

Table D1. Average regional specific CO_2 emissions per MJ from electricity and heat generation

Region/country	CO_2 emissions *(g CO_2/MJ)*
Europe 27	99
North America	142
Australia	254
New Zealand	84
Japan	120
Other Pacific	139
Russian Federation	90
Latin America	54
Asia (excluding China)	202
China	216
Africa	175

Source: IEA (2009).

The variation in CO_2 intensity is explained by the different energy sources and energy mixes utilized in different regions and countries. For example, regions such as Asia and Africa, and countries like Australia that rely on coal as their dominant source of energy for electricity production, have on average higher CO_2 emissions compared with Latin America and New Zealand with lower CO_2 emissions per MJ produced owing to the higher proportion of electricity that is based on renewable resources like hydroelectric power which are recognized to be carbon neutral.

3. EMISSIONS RELATED TO TRANSPORT

The food sector is transport-intensive – large quantities of food are transported in large volumes and over long distances. This can sometimes be of significance but, in terms of the overall contribution to the life cycle carbon footprint of a product, most LCA studies have found that the contribution of transport is relatively small. The carbon implications of food transport is not only a question of distance; a number of other variables, such as transport mode, efficiency of transport loads and the condition of infrastructure (road quality), fuel type, etc., are important determinants of the carbon intensity of products.

The efficiency of different transport modes varies considerably. Transport modes differ significantly in energy intensity and hence GHG emissions. Air transport has a very high climate change impact per tonne transported, whereas sea transport is relatively efficient. Long-distance transport by ship is very energy efficient, with estimates between 10 and 70 g CO_2 per tonnes-km, compared with estimates of 20-120 and 80-250 g CO_2 per tonnes-km for rail and road, respectively (Marintek, 2008). Poor road infrastructure has an impact on the emission per unit product transported because it increases fuel consumption. Cederberg *et al.* (2009) found that, in Brazil, due to generally poor road conditions, the consumption of diesel was estimated to be 25 percent higher than under normal road conditions. Different loads also affect the efficiency of utilization of transport per unit of product. Larger loads transported for longer distances are more efficient than lighter loads transported over shorter distances.

During transportation, food also often requires refrigeration which increases the use of energy and also introduces leakage of refrigerants into the GHG emissions equation (refrigerants are often high in climate impact).

Emissions related to transport were estimated for the different phases, that is, transportation of live animals from the farm to the slaughter plant and transportation of the processed product from plant to retail centre for distribution. In the case of international trade, emissions were calculated for transport from slaughter plant to the port of export to the retail point for distribution. In an effort to estimate the contribution of international freight transport to GHG emissions, we combined data on trade flows, transportation mode, transport EFs and distances.

The following sections provide a detailed description of the methodology and the assumptions used in the estimation of emissions associated with the transport of live animals and meat. For the approach on milk, a detailed description is provided in FAO's report on GHG emissions in the dairy sector published in 2010.[20]

[20] FAO. 2010. http://www.fao.org/docrep/012/k7930e/k7930e00.pdf

3.1 Transport of live animals from the farm to slaughter plant

Due to the complexity of live animal movements and data limitations, several simplifications and assumptions were made:

- *Share of animals transported to slaughter plants*: Not all animals produced are slaughtered in slaughter plants/abattoirs; slaughtering may also take place on-farm or may be carried out by local butchers within the vicinity of production and thus may not involve the transportation of live animals. For industrialized countries, it was assumed that about 98 percent of the animals are slaughtered in slaughterhouses. In developing countries, the share of animals transported to slaughter plants varied between 15 and 75 percent. A lower share was assumed for developing countries based on the assumption that slaughtering infrastructure is generally lacking and that animals are often slaughtered in closer proximity to where they are raised, with slaughter being carried out by local butchers or the household itself. Other factors taken into consideration include the importance of exports within the economy, where we assumed that key exporting developing countries such as Brazil, Argentina, Paraguay, Botswana and Namibia (due to phytosanitary requirements of importing countries) would have a higher share of animals slaughtered in slaughter plants.
- *Average distance between farm and slaughter plant*: Data on distances between the farm and slaughter plants was taken from literature for industrialized regions: an average distance of 80 km for Europe and 200 km for North America. In developing countries, due to poor infrastructure, slaughter is assumed to take place near the point of sale: an average distance of 50 km was assumed.
- *Mode of transport:* We assumed that a greater proportion of live animals was transported by road.
- *Emission intensity per kg of carcass transported*: Based on secondary data, two average coefficients were utilized in this study for two groupings of countries: 0.21 and 0.38 kg CO_2-eq per tonnes CW-km for industrialized and developing countries, respectively.

Transport emissions of livestock between the farm and the slaughter plant were calculated using the equation below:

$$GHG_{transport}^{farm\text{-}slaughterplant} = D_{farm\text{-}plant} \cdot ef_{transport} \cdot sh_{live\ animal}^{farm\text{-}plant}$$

where:

$GHG_{transport}^{farm\text{-}slaughterplant}$ = GHG emission intensity, kg CO_2-eq/kg CW-km

$D_{farm\text{-}plant}$ = average distance between farm and slaughter plant, km

$ef_{transport}$ = average EF for transport, kg CO_2-eq/kg CW-km

$sh_{live\ animal}^{farm\text{-}plant}$ = share of animals transported from farm to slaughter plant, percentage

Table D2. Emission intensity for road transport

	Winther *et al*. 2009, *(100 percent)**	Winther *et al*. 2009, *(100 percent)**	Ecoinvent, *(100 percent)**	Ecoinvent, *(70 percent)**	Ecoinvent, *(90 percent)**	AEA 2008	Cederberg *et al*. 2009
	(kg CO_2-eq/tonnes CW-km)						
Articulated lorry, max load 32 tonne							0.11
Lorry, chilled, max load 20 tonne	0.085	0.102	0.18	0.16	0.14	0.08-0.25	
Lorry, frozen, max load 20 tonne	0.073	0.099	0.19	0.17	0.15	0.08-0.25	0.145

Note: Emission intensities also include emissions related to leakage of cooling agents.

* The EFs represent the percentage of the vehicle utilized and accounts for the fact that vehicles will not be fully utilized at all times.

Source: SIK (2010).

3.2 Transport and distribution of meat from processing plant to retail point

The calculation of GHG emissions associated with meat transport included the transport of meat from slaughter plant to a retail distribution point. Transport and distribution emissions sources comprise emissions from fuel combustion during transport, as well as emissions from energy consumption for refrigeration and refrigerant leakage from chilled vehicles or container ships. Two modes of transport were considered in this phase: refrigerated road transport and marine transport.

Road transport. Refrigerated road transport covered here refers to transport between the processing plant and the domestic market and, in the case of international trade, transport from plant to port and entry port to retail distribution centre in importing country. Table D2 presents emission intensities for different modes of road transport taken from peer-reviewed studies and databases such as Ecoinvent. Average emission intensities were found to vary depending on the transport load (tonnage), transport utilization and type of product transported (chilled or frozen).

In this study, the following average emission intensity values presented in Table D3 below were used. Regarding the transport of meat from processing plant directly to the domestic retail, we assumed that the product is transported as chilled carcass by a small vehicle with a maximum load of 20 tonnes within a minimum retail distance of 50 km.

Ocean transport. In 2005, about 6.5 and 0.97 million tonnes of beef and lamb were traded globally (FAOSTAT, 2012). Emissions from the international trade of meat were calculated on the basis of the amount and type of product traded, distances

Table D3. Average emissions intensities associated with road transport from plant to retail

	Chilled	Frozen
	(kg CO_2-eq/tonnes CW-km)	
Carcass	0.18	0.20
Boneless	0.117	0.130

Source: SIK (2010).

between the slaughterhouse and retail centre, and the average GHG emission per kg of product transported.

- *Trade:* A trade matrix was developed based on FAOSTAT trade flow data in order to determine key exporters (Table D4 as an example), destinations and quantities traded. This analysis covers almost 85 percent of the total amount of beef and lamb traded globally. A distinction is made between the type of meat traded (whether carcass or boneless) because it has implications for the amount of energy used for refrigeration during transportation and consequently CO_2 emissions.
- *Distance:* Distances were estimated between the major exporting and importing ports and it was assumed that the traded product was destined to major cities which are key population and consumption hubs. Emissions were calculated for the average distance for transport between the exporting country and importing country (port to port) and the transit distance inside the importing country to main retail centre. Distance matrices were estimated from http://sea-distances.com/index.htm and http://www.distances.com/.
- *Vessel size:* It was assumed that smaller ships are utilized for shorter distances (e.g. transport of products within regions) and larger ships for longer distances such as inter-continental trade. Table D5 presents emission intensities for ocean transport taken from secondary sources and demonstrates the variation in emission intensity for different vessel sizes.

Table D4. International trade in beef, 2005

Key exporters	tonnes
Brazil	1 285 805
Australia	991 945
USA	439 862
Ireland	363 372
Netherlands	351 757
New Zealand	344 289
Germany	335 044
Canada	323 729
Argentina	297 091
Uruguay	249 609
Total	**6 316 672**

Source: FAOSTAT (2011).

Table D5. Emission intensity for ocean transport

Container ship	Winther *et al.* (2009)	AEA (2008)	Cederberg *et al.* (2009)	Ecoinvent
	(kg CO_2-eq/tonnes CW-km)			
Large, chilled/frozen	0.037	0.018	0.014	0.011
Small, chilled/frozen	0.056		0.061	0.043

Note: Emission intensities also include emissions include related to leakage of cooling agents.
Source: SIK (2010).

Based on secondary data, the average emission intensities applied were 0.025 and 0.05 kg CO_2-eq per tonne product (CW) transported per km for large and small container ships transporting carcasses, respectively and 0.014 and 0.029 kg CO_2-eq per tonne CW per km for large and small container ships transporting bone-free meat.

To manage the versatile nature and complexity of trade flows, we only accounted for trade from and to the most significant trading partners.

4. EMISSIONS RELATED TO SLAUGHTER AND PRIMARY PROCESSING OF MEAT

GHG emissions assessed here include emissions from the direct inputs of energy in the slaughter and primary processing of meat and milk, as well as the GHG emissions related to use and leakage of refrigerants. The meat sector also produces a range of co-products including by-products such as bones, blood, fat, offal, feather, etc. Due to the lack of data on the total amount of raw material rendered, this analysis does not take into account emissions associated with the co-products.

Average energy use per kg of carcass weight during slaughter was based on studies from Sweden (Anon, 2002), Denmark, Finland and Spain (Lafargue, 2007) and the European Union (Ramirez *et al*., 2006). Due to the limited data on energy use during this phase, in this study we assumed an average value of 1.4 MJ/kg CW and 4.5 MJ/kg CW for beef and lamb, respectively. Slaughterhouse emissions were calculated by combining this average value with the average regional specific CO_2 emissions per MJ of energy (taking into account regional/country electricity generating mixes) given in Table D1 to obtain the average GHG emissions per kg of carcass processed. Table D6 presents regional average emission factors for processed beef and lamb and mutton and illustrates the importance of energy source as well as the energy intensity associated with the processing of different meat. Compared with beef, processing of lamb and mutton on average has higher emission intensity per kg product processed because of the high energy intensity of the process (4.5 MJ/kg CW) and, when combined with high emitting energy sources such as coal, the emission intensity is high as is the case in Australia (Table D6).

Table D6. Regional emission factors for processing of beef and lamb

Region	Beef	Lamb and mutton
	(kg CO_2-eq/tonnes CW-km)	
EU27	0.14	0.45
North America	0.20	0.64
Australia	0.40	1.14
New Zealand	0.12	0.38
Japan	0.17	0.54
Other Pacific	0.20	0.63
Russian Federation	0.13	0.41
Latin America	0.07	0.24
Asia (excluding China)	0.30	0.91
China	0.30	0.97
Africa	0.25	0.78

Source: Authors' calculations.

5. EMISSIONS RELATED TO PRODUCTION OF PACKAGING MATERIALS

Packaging is a fundamental element of almost every food product and a vital source of environmental burden and waste. The type of packaging used also influences transport efficiency because it has its own weight but also because it affects the weight/volume ratio of the product. Two types of packaging can be distinguished: primary packaging and secondary packaging. Primary packaging is packaging closest to the product and often follows the product all the way to the consumer. Secondary packaging is used to assemble together primary packaging to shelter the product during transport and make it possible to transport more of the product at a time. The climate impact of packaging is one of the least studied aspects within the food chain. Due to the lack of data on the global variations in packaging of meat, this study applied 0.05 kg CO_2-eq per kg CW for both primary and secondary packaging from slaughter-plant to retail.

REFERENCES

AEA. 2008. *Comparative Life Cycle Assessment of Food Commodities Produced for UK Consumption through a Diversity of Supply Chains.* Appendix 3 – Post Farm Gate Activity Data. Cranfield University. Report to Defra 2008.

Anon. 2002. *Maten och miljön Livscykelanalys av sju livsmedel,* (Food and the environment Life Cycle Assessment of seven food items). LRF, Sweden.

Cederberg, C., Meyer, D. & Flysjö, A. 2009. *Life cycle inventory of greenhouse gas emissions and use of land and energy in Brazilian beef production.* SIK Report No 792.

Ecoinvent. 2009. Swiss Centre for Life Cycle Inventories database. Available at http://www.ecoinvent.ch/.

FAO. 2010. *Greenhouse gas emissions from the dairy sector – A life cycle assessment*, by Gerber, P., Opio, C., Vellinga, T., Herderson, B. & Steinfeld, H. FAO. Rome.

FAOSTAT. 2011. FAO Statistical Database. Accessed 2011.

FAOSTAT. 2012. FAO Statistical Database. Accessed 2012.

IEA. 2009. CO_2 emissions from fuel combustion. IEA Statistics. International Energy Agency. Paris.

Lafargue, P.L. 2007. *LCA of Spanish meals with different protein sources.* Master's thesis, Dept. of Energy and Environment, Chalmers University of Technology, Gothenburg, Sweden.

MARINTEK. 2008. Updated Study on Greenhouse Gas Emissions from Ships Phase 1 – Preliminary results Presented to First Inter-sessional Meeting of the Working Group on GHG Emissions from Ships, June 24, 2008.

Ramírez, C.A., Patel, M. & Blok, K. 2006. How much energy to process one pound of meat? A comparison of energy use and specific energy consumption in the meat industry of four European countries. *Energy,* 31(12): 2047–2063.

Winther, U., Ziegler, F., Hognes, E.S., Emanuelsson, A., Sund, V. & Ellingsen, H. 2009. *Carbon footprint and energy use of Norwegian seafood products.* Sintef Report SFH80 AH096068.

APPENDIX E

Emissions related to energy use

This appendix presents the approach and coefficients applied in this study for estimating GHG emissions from direct on-farm energy use (non-feed related) and embedded energy in farm buildings and equipment. Direct and indirect emissions were estimated for all ruminant species; a general approach is used for all species with a few modifications taking into account differences between production typologies and species, but also between herd (dairy and beef).

1. INDIRECT (EMBEDDED ENERGY): EMISSIONS RELATED TO CAPITAL GOODS

Capital goods including machinery, tools and equipment, buildings such animal housing, forage and manure storage are a means of production. Though not often considered in LCAs, capital goods carry with them embodied emissions associated with manufacture and maintenance. These emissions are primarily caused by the energy used to extract and process typical materials that make up capital goods such as steel, concrete or wood. This assessment focuses on the quantification of embedded energy in capital goods including farm buildings (animal housing, feed and manure storage facilities) and farm equipment such as milking and cooling equipment, tractors and irrigation systems.

To determine the effective annual energy requirement, the total embodied energy of the capital energy inputs was discounted and we assumed a straight-line depreciation of 20 years for buildings, 10 years for machinery and equipment and 30 years for irrigation systems. A simplified approach was adopted in the calculations; emission coefficients were defined for the dairy cattle sector and these were then extrapolated to the beef cattle, buffalo and small ruminant sector.

1.1 Farm infrastructure

Emissions of a representative set of farm buildings were calculated from typical material of building components, including steel, concrete and wood used in the construction of animal housing, manure storage and feed storage facilities. Data related to the density of the building material was taken from various sources and literature.

- *Animal housing*: Five different levels of housing were defined with varying degrees of quality and emissions related to these were calculated (Table E1). These five housing types were then distributed across the different production systems (grassland and mixed), AEZs (arid, humid and temperate), and country grouping [OECD, least developed countries (LDCs) and other developing countries] based on the level of economic development. The percentage allocated for the different values of housing was based on two criteria: (i) livestock density in the two production systems and three AEZs based on number of adult females; and (ii) the average milk yield per cow per year. Tables E2 and E3 illustrate the allocation of embedded energy in small ruminant housing in arid zones in OECD countries and the average emission factor (accounting for depreciation).

Table E1. Typology of animal housing considered in this assessment

Level of investment and definition	Characteristics			Production system
	Floor, foundation, walls	**Roof, roof-frame**	**Supports**	
High: *high technology and use of high quality materials*	Material: concrete	Material: steel	- Stanchions - Columns - Rafters	- Industrial units - Peri-urban - Fattening units
Average: *intermediate level of technology and use of good quality materials*	Without walls; or ½ walls (concrete)		- Stanchions - Columns - Rafters	- Peri-urban - Fattening units - Mixed systems
Low	No walls, floor not paved	Material: steel	Material: Steel	Mixed systems
Very low	Cement floor or unpaved floor (dirt) No walls	Material: steel for roof	Local/hand-made material e.g. wood for columns/ rafters	- Mixed systems - Peri-urban
Nil: *situation with no housing or existing shelter such as kraals made from local materials (wood, manure) and no embedded energy involved.*				

Source: Authors.

Table E2. An example of a life cycle inventory for a high investment structure for small ruminants

Material	Structure	GWP_{100} *(kg CO_2-eq[1])*	Quantity of material per unit *(kg of material/25 kg LW - AFSR[2])*	Emission intensity *(kg CO_2-eq/25 kg LW AFSR[2])*
		A	B	C= A/B
Concrete	Floor	262.61	0.10	26.3
Concrete	Support – foundation	262.61	0.03	6.8
Steel – structural	Support – stanchions	1.79	0.52	21.0
Steel – structural	Roof frame – rafters	1.79	0.89	9.6
Steel – structural	Roof frame – purlins	1.79	1.04	3.1
Bricks – concrete	Walls	262.61	0.03	4.7
Galvanized metal – shed	Roof	1.79	1.07	4.1
Total				**83.7**

[1] Data taken from Ecoinvent database.
[2] AFSR: Adult Female Small Ruminant.
Source: Authors' calculations.

Table E3. Allocation of embedded energy in housing – an example for small ruminants in arid zones in OECD countries

Country grouping	Level of investment	Emission intensity *(kg CO_2-eq/25 kg LW AFSR[1])*	Allocation *(percentage)*	Emission factor *(kg CO_2-eq/25 kg LW AFSR[1])*
OECD	High	83.7	20	16.7
	Average	76.7	20	15.3
	Low	47.0	50	23.5
	Very low	10.5	-	0.0
	Nil	0.00	10	0.0
Total			100	**55.6**
Depreciation (20 years)				**2.8**

[1] AFSR: Adult Female Small Ruminant.

- *Manure storage:* The calculation for energy embodied in manure storage facilities was based on a similar methodology and allocation technique outlined above. As capital investment, only a platform of concrete was considered and calculated as a percentage of the floor-surface of the standard shelter (25 percent on 90 days and 50 percent on 180 days of manure storage). The period of manure storage considered includes 90 days in arid and humid areas and 180 days in temperate days in both grassland and mixed systems. Although liquid manure storage plays an important role in industrialized regions particularly for dairy, only solid manure storage was considered for this assessment.
- *Feed storage:* The calculation for energy embodied in feed storage facilities was based on a similar methodology and allocation technique outlined for housing and manure storage. The period of feed storage considered includes 90 days in arid and humid areas and 180 days in temperate days in both grassland and mixed systems. Due to their importance in a majority of countries, only hay and straw were used as the basis for feed density. The required volume of storage capacity was calculated on the basis of roughage requirements (based on 2 percent intake of DM) and the Bulk Specific Weight and Density[21] for hay and straw. The quality of the feed storage was assumed to be similar to the animal housing infrastructure.

1.2 Farm equipment

Emissions embodied in farm equipment were calculated on the basis of the five levels of farm infrastructure (ranging from nil to high), with allocation criteria similar to those outlined for farm infrastructure. For these calculations, farm equipment was divided into three categories: tractors, tractor implements and hand tools; milking and milk storage equipment; and irrigation facilities. Emissions related to steel were derived from the Ecoinvent database.

- *Tractors, implements and hand tools*: The calculation for energy used in the manufacture of tractors and tractor implements and tools is related to the number of tractors used per hectare; an average weight of steel per hectare based on Dyer and Desjardins (2005); and the stocking rate of adult females per hectare. It is assumed that in areas with over 1 000 ha per tractor, the use of hand tools is prevalent and for these situations we estimated 5kg of hand tools.
- *Milking and storage/cooling equipment*: Equipment taken into account includes bulk tanks and cans, post bars, vacuum pump, pipelines, plate cooler units. Table E4 presents the milking and storage/cooling equipment considered in this study.
- *Irrigation systems*: Two basic types of irrigation systems were considered: border strip and spray irrigation and were applicable only to the high and average level of investment farm. Due to the lack of more recent data, the calculation for energy embodied in irrigation systems is based on the approach used by Wells (1998).

[21] This is a measurement of a feed's mass (weight) per unit volume of space the feed occupies; the standard unit is kg/m^3.

Table E4. Milking, cooling and storage equipment considered in this assessment

Equipment	Description
Coolers	Medium-scale herd composed of 40 cows producing 20 l/day (milked twice a day); using a tank of 1600 litres Small-scale herd composed of 14 cows producing 20 l/day (milked twice a day); using 10 cans of 60 litres each
Post bars	Medium-scale herd – 4+4 posts steel made Medium-scale herd – 2 posts wood made
Pipeline	Medium-scale herd – double pipeline set suspended over the central corridor
Milking vacuum pump	Medium-scale herd – consider an average typology: 2 mobile and 1 fixed floor
Cooling system	Medium-scale herd – consider an average value among low, medium, high

Source: Authors.

Table E5 presents average emission factors for embedded energy for on-farm capital goods in dairy cattle production. For beef cattle and buffalo, we took a simplified approach by applying 50 percent of the EF coefficient calculated for dairy cattle. Emission factors used for small ruminant dairy are presented in Table E6 and a similar approach of applying 50 percent of the EFs to small ruminant meat herds was adopted.

2. DIRECT ENERGY: EMISSIONS RELATED TO ON-FARM ENERGY USE

On-farm energy in ruminant production relates to the use of energy for milking, milk pumping, on-farm cooling of milk, ventilation, heating and lighting, water heating, watering and feeding of animals.

Various studies have estimated the amount of direct energy used on farm (Barrington *et al*., 1999; Dalgaard *et al*., 2000; Cederberg and Mattsson, 2000; ADAS, 2000; Haas *et al*., 2001; Wells, 2001; Ludington and Johnston, 2003; Barber and Pellow, 2005; Casey and Holden, 2005; Dyer and Desjardins, 2006; Saunders and Barber, 2007; DEFRA, 2007a, 2007b; Schils *et al.*, 2007; FEC, 2008; Horndahl, 2008; DairyCo, 2009; Thomassen *et al*., 2008; CAFRE, 2009; Bestfootforward (personal communication, 2010); ATTRA, 2010; Williams *et al*., 2010; Rotz *et al.*, 2010). Based on these studies, it is estimated that the average energy use is 0.219 kWh/kg raw milk.

It is however difficult to make an accurate estimate of the average energy use for these individual farm processes as well as the type of energy used because of the lack of disaggregated data. However, four studies (Bestfootforward (personal communication, 2010); Ludington and Johnston, 2003; DEFRA, 2007b); and Thomassen *et al*., 2009) provide a breakdown by source, which indicates that 38 percent of total direct energy consumed on-farm is electricity and 62 percent non-electricity. Using the results above (i.e. total direct energy use is 0.219 kWh/kg raw milk, which is split 38:62 electricity: non-electricity) and assuming that the main non-electricity use is diesel, the emissions can be calculated, see Table E7. The two coefficients (0.083 and 0.135 kWh/kg milk) are used in the calculation of the EFs for on-farm direct energy use.

Countries were ranked by milk yield, then categorized into five groups (representing the five categories of dairy farm mechanisation: High, Average, Low, Very low, Nil). Energy use will vary between these five levels. It was assumed that the

Table E5. Average emission factors for embedded energy for dairy cattle

Grouping	System	Capital goods	Arid (kg CO_2-eq/ 100 kg LW)	Humid (kg CO_2-eq/ 100 kg LW)	Temperate (kg CO_2-eq/ 100 kg LW)
OECD	Grassland based	Buildings	4.42	4.72	9.03
		Machinery & Implements	13.78	16.22	28.16
	Mixed based[1]	Buildings	4.89	5.08	9.55
		Machinery & Implements	16.22	19.03	30.23
LDC countries	Grassland based	Buildings	0.68	0.68	0.83
		Machinery & Implements	1.35	1.35	1.35
	Mixed based[1]	Buildings	1.33	1.33	1.89
		Machinery & Implements	1.98	1.98	1.98
Non-OECD	Grassland based	Buildings	1.71	2.31	3.32
		Machinery & Implements	2.94	5.85	4.04
	Mixed based[1]	Buildings	2.38	3.04	6.64
		Machinery & Implements	3.56	6.62	18.55

[1] Includes landless systems
Source: Authors' calculations.

Table E6. Average emission factors for embedded energy for dairy sheep and goats

Grouping	Production system	kg CO_2-eq/25 kg LW	kg CO_2-eq/100 kg LW
LDC	Arid	1.00	0.04
	Humid	0.82	0.03
	Temperate	0.73	0.03
OECD	Arid	5.65	0.23
	Humid	5.05	0.20
	Temperate	6.76	0.27
Other developing	Arid	2.01	0.08
	Humid	2.62	0.11
	Temperate	6.01	0.24

Source: Authors' calculations.

Table E7. Total on-farm direct energy use and associated emissions for high level dairy farms

Category	Rate of energy use (kWh/kg milk)	Emissions (kg CO_2-eq/kWh)	Emissions (kg CO_2-eq/kg milk)
Electricity	0.08	0.54	0.05
Non-electricity	0.14	0.27	0.04
Total			**0.08**

Source: Authors' calculations.

Table E8. Emissions from direct energy for different levels of mechanization

Category	Rate of electricity use	Rate of non-electricity	Emissions from electricity	Emissions from non-electricity	Total emissions from direct energy
	(kWh/kg milk)		*(kg CO_2-eq/kg milk)*		
High	0.08	0.14	0.05	0.04	**0.08**
Average	0.08	0.07	0.05	0.02	**0.06**
Low	0.08	0.03	0.05	0.01	**0.05**
Very low	0.00	0.01	0.00	0.00	**0.00**
Nil	0.00	0.00	0.00	0.00	**0.00**

Source: Authors' calculations.

Table E9. Emission factors for direct on-farm energy use for dairy cow milk production in OECD and non-OECD countries

Region	Electricity EF[1]	Default global EF	Grassland			Mixed		
	($kgCO_2/kWh$)							
Unadjusted EF			**Arid**	**Humid**	**Temperate**	**Arid**	**Humid**	**Temperate**
Europe (Unadjusted EF)			0.071	0.072	0.074	0.072	0.074	0.074
Developing countries			0.020	0.020	0.020	0.027	0.027	0.027
Non-OECD			0.038	0.044	0.05	0.045	0.054	0.062
Adjusted emission factors								
EU-27	0.36	0.54	0.059	0.060	0.061	0.060	0.061	0.061
OECD-Europe	0.34	0.54	0.058	0.059	0.060	0.059	0.060	0.060
USA	0.54	0.54	0.071	0.072	0.074	0.072	0.074	0.074
Canada	0.19	0.54	0.048	0.049	0.050	0.049	0.050	0.050
OECD North America	0.50	0.54	0.068	0.069	0.071	0.069	0.071	0.071
Australia	0.90	0.54	0.094	0.095	0.098	0.095	0.098	0.098
Japan	0.44	0.54	0.064	0.065	0.067	0.065	0.067	0.067
South Korea	0.46	0.54	0.066	0.067	0.068	0.067	0.068	0.068
New Zealand	0.21	0.54	0.049	0.050	0.051	0.050	0.051	0.051

[1] IEA (2010).

Source: Authors' calculations.

rate of electricity use would be the same for high, average and low systems, where milking activities are largely mechanized. It was further assumed that no electricity is used in very low and nil level systems. For the allocation across the five categories, the median adult female (ADF) weight and milk yield were used and the milk yield per kg of ADF calculated for each category. Table E8 presents the emission intensity of milk from direct on-farm energy use for the different levels of mechanization.

On-farm energy use was then adjusted to reflect the variations across farming systems in terms of level of mechanisation and energy use efficiency. It was assumed that 50 percent of OECD emissions are from electricity. The EFs for OECD countries were adjusted to take into account variations in the amount of CO_2 emitted per kWh electricity. It was assumed that non-OECD countries do not use mains electricity, and standard emission factors are used for diesel/petrol (which means

Table E10. Regional emission factors for direct on-farm energy use

Region	Beef: grassland based	Beef: mixed	Sheep and goats: meat
	kg CO_2-eq/kg LW		
Europe			
EU27	0.18	0.21	0.33
OECD-Europe	0.17	0.21	0.33
Non-OECD Europe	0.07	0.09	0.19
North America			
USA	0.24	0.29	0.34
Canada	0.12	0.15	0.31
Other	0.22	0.27	0.34
Pacific			
Australia	0.36	0.42	0.38
Japan	0.20	0.24	0.33
South Korea	0.21	0.25	0.34
New Zealand	0.12	0.16	0.31
OECD Pacific	0.22	0.27	0.34
Pacific average	0.00	0.00	0.34
Non-OECD Pacific	0.00	0.00	0.17
Former Soviet Union	0.07	0.09	0.16
Latin America			
Brazil	0.07	0.09	0.15
Other	0.07	0.09	0.16
Asia			
India	0.07	0.09	0.19
China	0.07	0.09	0.18
Thailand	0.07	0.09	0.17
Other	0.07	0.09	0.18
Africa	0.07	0.09	0.18
Middle East	0.07	0.09	0.18

Source: Authors' calculations.

that emissions in some countries, e.g. Brazil, will be overestimated). Table E9 presents the adjusted EFs for direct on-farm energy use for milk production in OECD countries and EFs for non-OECD countries.

Direct on-farm energy for non-dairy herd (beef cattle, buffalo, small ruminant meat herd/flock): Direct energy use is associated primarily with the handling of manure, bedding and feed, which are dependent on the system (i.e. grass or mixed) and the level of mechanization, rather than the climate. Therefore it was assumed that the energy use for a given mechanization level and system is independent of climate. We assumed that minimal direct energy use is associated with meat production was assumed –in developing regions - low levels housing and mechanized feed, bedding manure handling. Table E10 presents regional EFs for direct on-farm energy use for ruminant meat production used in this assessment.

REFERENCES

ADAS. 2000. Energy use in organic farming systems OF0182. ADAS Consulting Ltd. Terrington, UK. Available at http://orgprints.org/8169/

ATTRA. 2010. Dairy Farm Energy Efficiency. Available at www.attra.ncat.org/attra-pub/PDF/dairyenergy.pdf

Barber, A. & Pellow, G. 2005. Energy Use and Efficiency Measures For the New Zealand Dairy Farming Industry. AgriLINK New Zealand Ltd.

Barrington, S., Choiniere, D. & Clarke, S. 1999. COWPOWER, a computer system to optimize standby power units for dairy operations. ASAE/CSAE Meeting Presentation—Paper No. 99–3014.

CAFRE. 2009. Report of Pilot Energy Benchmarking Project 2007/2008.

Casey, J.W. & Holden, N.M. 2005 Analysis of greenhouse gas emissions from the average Irish milk production system, *Agricultural Systems*, 86(1): 97-114.

Cederberg, C. & Mattsson, B. 2000. Life cycle assessment of milk production — a comparison of conventional and organic farming. *Journal of Cleaner Production*, 8(1): 49–60.

DairyCo. 2009. Energy efficiency on farm – a practical guide. Agriculture and Horticulture Development Board. Kenilworth, UK.

Dalgaard, T., Niels Halberg, N. & Porter John, R. 2001. A model for fossil energy use in Danish agriculture used to compare organic and conventional farming. *Agriculture, Ecosystems & Environment*, 87(1): 51–65.

DEFRA. 2007a. The Environmental, Social and Economic Impacts Associated with Liquid Milk Consumption in the UK and its Production. A Review of Literature and Evidence. DEFRA Project Code EVO 2067. Department for Environment, Food and Rural Affairs. London.

DEFRA. 2007b. Direct energy use in agriculture: opportunities for reducing fossil fuel inputs.DEFRA Project Code AC0401. Department for Environment, Food and Rural Affairs. London.

Dyer, J.A. & Desjardins, R.L. 2006. An integrated index of electrical energy use in Canadian agriculture with implications for greenhouse gas emissions. *Biosystems Engineering*, 95(3): 449–460.

Ecoinvent. 2009. Swiss Centre for Life Cycle Inventories database. Available at http://www.ecoinvent.ch/

FEC Service. 2008. Dairy Technology Powerpoint Presentation. FEC Services Ltd. Available http://www.dardni.gov.uk/ruralni/energy_efficiency_dairy.pdf

Haas, G., Wetterich, F. & Köpke, U. 2001 Comparing intensive, extensified and organic grassland farming in southern Germany by process life cycle assessment. *Agriculture, Ecosystems & Environment,* 83(1-2): 43–53.

Horndahl, T. 2008. Energy Use in Farm Buildings Swedish University of Agricultural Sciences Report 2008:8.

IEA. 2009. CO_2 emissions from fuel combustion. IEA Statistics. International Energy Agency. Paris.

IEA. 2010. CO_2 emissions from fuel combustion Highlights, p. 107. International Energy Agency. Paris.

Ludington, D. & Johnson, E.L. 2003 Dairy farm energy audit summary report. Nyserda, Albany.

Rotz, C.A., Montes, F. & Chianese, D.S. 2010. The carbon footprint of dairy production systems through partial life cycle assessment. *J. Dairy Sci.*, 93: 1266–1282.

Saunders, C. & Barber, A. 2007. Comparative energy and greenhouse gas emissions of New Zealand's and the UK's dairy industry. Research Report No. 297 Lincoln University. Christchurch, New Zeeland.

Schils, R.L.M., de Haan, M.H.A., Hemmer, J.G.A., van den Pol-van Dasselaar, A., de Boer, J.A., Evers, A.G., Holshof, G., van Middelkoop, J.C. & Zom, R.L.G. 2007. DairyWise, a whole-farm dairy model. *J. Dairy Sci*., 90: 5334–5346.

Thomassen, M.A., Dalgaard, R., Heijungs, R. & de Boer, I. 2008. Attributional and consequential LCA of milk production, *Int. J. Life Cycle Assess.*, 13: 339–349.

Wells, C. 2001. Total energy indicators of agricultural sustainability: dairy farming case study. Technical Paper 2001/3. Ministry of Agriculture and Forestry. Wellington, New Zealand.

Williams, A., Pearn, K., Sandars, D.L., Audsley, E., Parsons, D. & Chatterton, J. 2010. Analysis of the 2007/8 DEFRA Farm Business Survey Energy Module DEFRA Project Code RMP 5465 Natural Resources Management Centre, Cranfield University. 106 pp.

APPENDIX F

Relative value of slaughter by-products and effect on allocation of emissions

The main edible product from slaughtered animals is meat, but slaughterhouses also produce a whole range of by-products (organs, hide, blood, etc.). Between 30 and 60 percent of animal weight, depending on the species, does not end up as meat for human consumption.

Little documented information is usually available on the marketing of by-products from abattoirs but it is generally considered that they constitute a crucial part of profitability, with a more than significant share of the margin. They are subdivided into edible and non-edible materials.

1. EDIBLE BY-PRODUCTS

The main edible by-products of a slaughtered animal are offal, also known as variety meat or organ meat. Offal is divided into red (heart, livers, kidneys, lungs, tongue, cheek meat and deboned head trimmings) and white (intestine, stomachs, sweetbread [thymus and pancreas] and brain). Edible by-products can also be blood and fats that are fit for human consumption, and used in further processed products such as sausages.

According to a survey in the French meat industry, all edible materials from the carcass, including meat and offal, account for 45 percent of the live weight of an adult cattle (see Table F1). By-products are therefore 55 percent of the animal live weight. This is consistent with the results of a study on yields of by-products in various breeds of cattle slaughtered in Texas in 1989 (Terry *et al.*, 1990). It is also

Table F1. Beef cattle products and by-products, by type of use

Use of animal products and by-products (ABP)	Beef *(percentage of LW)*
EDIBLE	
Meat, offal, blood and fats for human consumption	45
INEDIBLE	
ABP withdrawn for sanitary reasons, SRM*, wastes	10
Protein, blood and fats (pet food, animal feed, drug industry)	20
Bones (feed industry, glue, gelatine)	8
Skins & hides (leather)	6
Digestive tract content (compost/fertilizers)	10
Lost due to carcass chilling and drying	1

* Specified risk material with regard to BSE (brain, eye, medulla, etc.).

Source: FranceAgriMer. 2012. *Observatoire des coproduits* (based on a survey of 40 meat plants in France).

consistent with the results of a more recent USDA study (Marti *et al.*, 2011), that estimated total by-products at 44 percent of total live weight, but did not include the digestive tract content (approximately 10 percent).

Edible by-products, mainly offal, account for around 12 percent of adult cattle live weight (Ockerman and Hansen, 2000). Human consumption of offal varies by culture and region, but can be found almost everywhere, in developed as well as in developing countries. Following animal health crises, such as the outbreak of *bovine spongiform encephalopathy* (BSE) in 1996, and the ban on the use of these products by a number of countries, the global offal market accounts for 15 to 20 percent of production.

World trade of bovine offal is estimated at one million tonnes per year. Asia (in particular China and Japan) is the main outlet for bovine offal, and is far from being self-sufficient, with 40 percent of global imports. Russian Federation doubled its imports in the past ten years, importing more than 100 000 tonnes of beef offal today, despite the ban on U.S. beef in 2004 due to BSE. Other significant importers include Egypt and Central Africa.

Offal exporters are the main beef exporters: United States (27 percent), Australia (14 percent), Argentina (12 percent) and Brazil (9 percent). In other countries, offal is often sold locally.

2. NON-EDIBLE BY-PRODUCTS

For adult cattle, non-edible by-products represent on average 55 percent of the total live weight. Material to be eliminated, such as by-products withdrawn for sanitary reasons (e.g. liver with flukes), specified risks materials and wastes from the first water treatment, account for 10 percent of the animal weight and are a cost for the meat plant.

Hides and skin constitute the most profitable non-edible by-products of the meat industry, with about 6 percent of the animal weight and sometimes up to 75 percent of the by-products value (Marti *et al.*, 2011). They are also the most internationally traded by-products, with Italy and Turkey as major outlets for many exporters.

In terms of weight, the most important group of non-edible by-products (accounting for 20 percent of total live weight) is constituted by floor trimmings, blood and fats used mostly for pet food but also for animal feed (processed animal protein, like meat and bone meal), or in the drug or cosmetic industry. Bones (8 percent of the weight) often go through rendering with this category to produce processed animal protein. They can also be used to produce glue or gelatine that go back into the human consumption chain.

Digestive tract content is usually about 10 percent of the animal weight and is used as fertilizer or as biogas material on the meat plant to produce energy.

3. VALUE OF BY-PRODUCTS

Edible and non-edible by-products accounted for 11 percent of the total value of the carcass sold by slaughterhouses in 2011, according to a survey of 10 cattle slaughterhouses in France (Observatoire des prix et des marges, 2012). The share of by-products in the total value tends to increase over time (it was only 6 percent in 2005).

This result is consistent with a study by Terry *et al.* (1990) that estimates the value of edible and inedible by-products from cattle at 9 to 12 percent of the total live

Table F2. Total revenue from one adult cattle sold by the slaughterhouse and share of by-products

Year	Total revenue *(€/kg)*	All by-products value *(€/kg)*	All by-products *(percentage)*	Edible by-products value *(€/kg)*	Edible by-products *(percentage)*	Non-edible by-products *(percentage)*
2005	4.19	0.28	6	0.14	3	3
2006	4.39	0.29	6	0.15	3	3
2007	4.39	0.38	9	0.15	4	5
2008	4.5	0.26	6	0.16	4	2
2009	NA	NA	NA	0.17	NA	NA
2010	4.69	0.4	9	0.16	4	5
2011	4.96	0.53	11	0.16	3	8

NA: Not Applicable.

Source: Observatoire des prix et des marges, 2012; Service de Nouvelles des Marchés.

Table F3. Emissions intensity of beef with and without allocation to slaughter by-products in Western Europe

	kg CO_2-eq/kg LW
No allocation to by-products	18.8
With allocation to by-products	17.7

Source: Authors' calculations.

value. It is also consistent with Marti *et al.* (2011), who estimated that by-products added value to one steer at 10 percent in average over the period 2000 to 2011.

Nevertheless, because of consumption habits, value for edible by-products can be very different from one country to another. For example, offal like hearts or stomach has greater value on the Chinese market than on any other market.

According to data from the Rungis Wholesale Market in France, total value of offal for one adult cattle was € 52.2 in 2011, that is to say 0.16 cents per kg of total products for one animal. Offal market prices were lower in 2005, and the market is very sensitive to sanitary crises, but the contribution of edible by-products in the total revenue from slaughtered adult cattle is generally stable at about 3 to 4 percent. We estimate that the value of other edible by-products is not significant compared with edible offal.

Non-edible by-products therefore account for the rest of the revenue from by-products; about 8 percent of the total revenue in 2011, a share that has increased by 5 percent since 2005.

The global value of non-edible by-products is quite volatile and this is mainly driven by the value of hides and skins. The world skin markets drop of 2008 and 2009 is reflected in Table F2 with a decrease of non-edible by-products in 2008.

This case study in France is one of the few examples available. Results appear to be consistent with a similar study by USDA but they cannot be seen as representative on a global scale since the categories and actual uses of slaughter by-products varies greatly from region to region and in time. Furthermore, alternative types of allocation (e.g. dry mass) could be used however these require further developments.

Nevertheless, because of the similarities among Western European breeds and among European markets of animal products, we can extrapolate the results of the French case study to Western Europe. Table F3 presents the effect of allocation

emissions to by-products using 6 percent as the allocation value of emissions to slaughter by-products in Western Europe.

Due to the lack of a comprehensive global data on by-products in the meat sector, the allocation of emissions to slaughter by-products could not be performed in this assessment. This may be improved in a future assessment depending on information shared by the industry and the development of harmonized methods to allocate by-products at slaughterhouses.

REFERENCES

Lapasin, C., Gac, A., Scislowski, V., Chevillon, P., & Guardia, S. 2012. Recherche de méthode d'évaluation de l'expression de l'empreinte carbone des produits viande. France Agrimer, Paris. http://idele.fr/domaines-techniques/elevage-environnement-et-territoires/evaluation-environnementale/publication/idelesolr/recommends/recherche-de-methodes-devaluation-de-lexpression-de-lempreinte-carbone-des-produits-viande.html

Marti, D.L., Johnson, R.J. & Mathews, K.H. 2011. Where's the (Not) Meat? By-products From Beef and Pork Production. A Report from the Economic Research Service, USDA. http://www.ers.usda.gov/media/147867/ldpm20901.pdf

Observatoire des prix et des marges. 2012. http://agriculture.gouv.fr/IMG/pdf/Rapport_parlement_2012_v8_cle01dc4d.pdf.

Ockerman, H.W. & Hansen, C.L. 2000. *Animal By-product Processing and Utilization,* First edition, Lancaster, PA. Technomic.

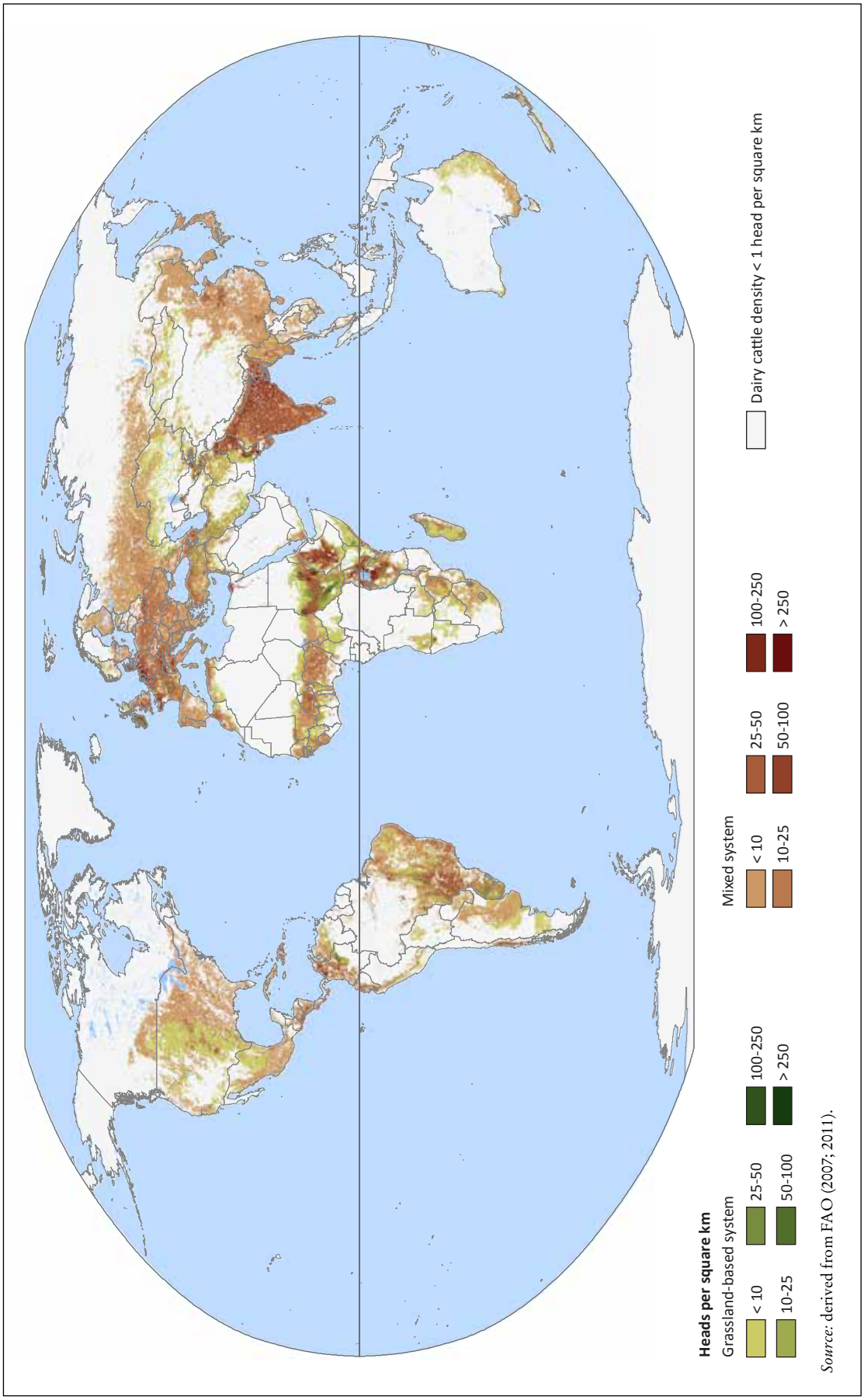
Terry, C.A., Knapp, R.H., Edwards, J.W., Mies, W.L., Savell, J.W. & Cross, H.R. 1990. Yields of by-products from different cattle types. *Journal of Animal Sciences*, 68: 4200–4205.

APPENDIX G

Maps

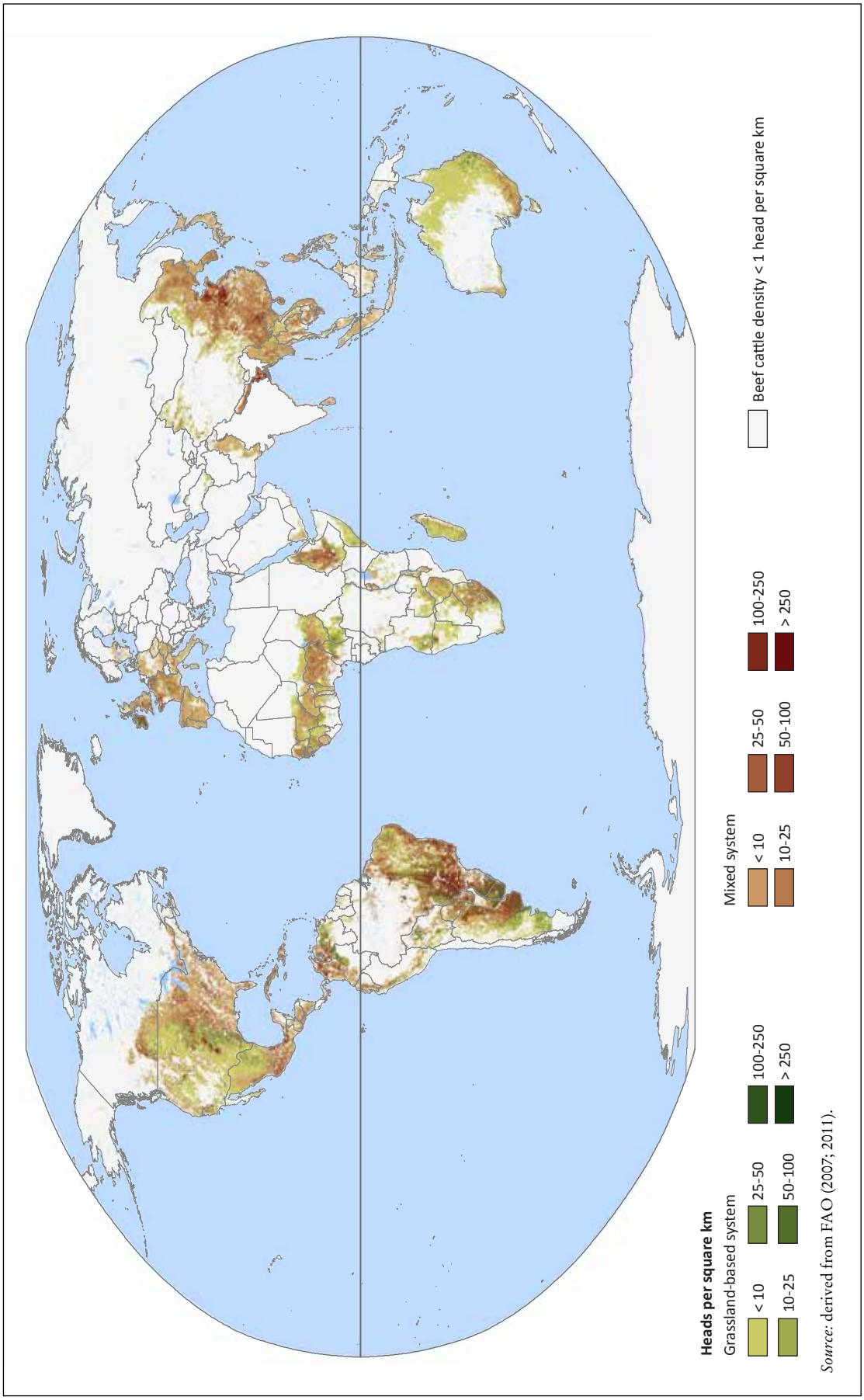
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Map 1
Distribution of dairy cattle populations



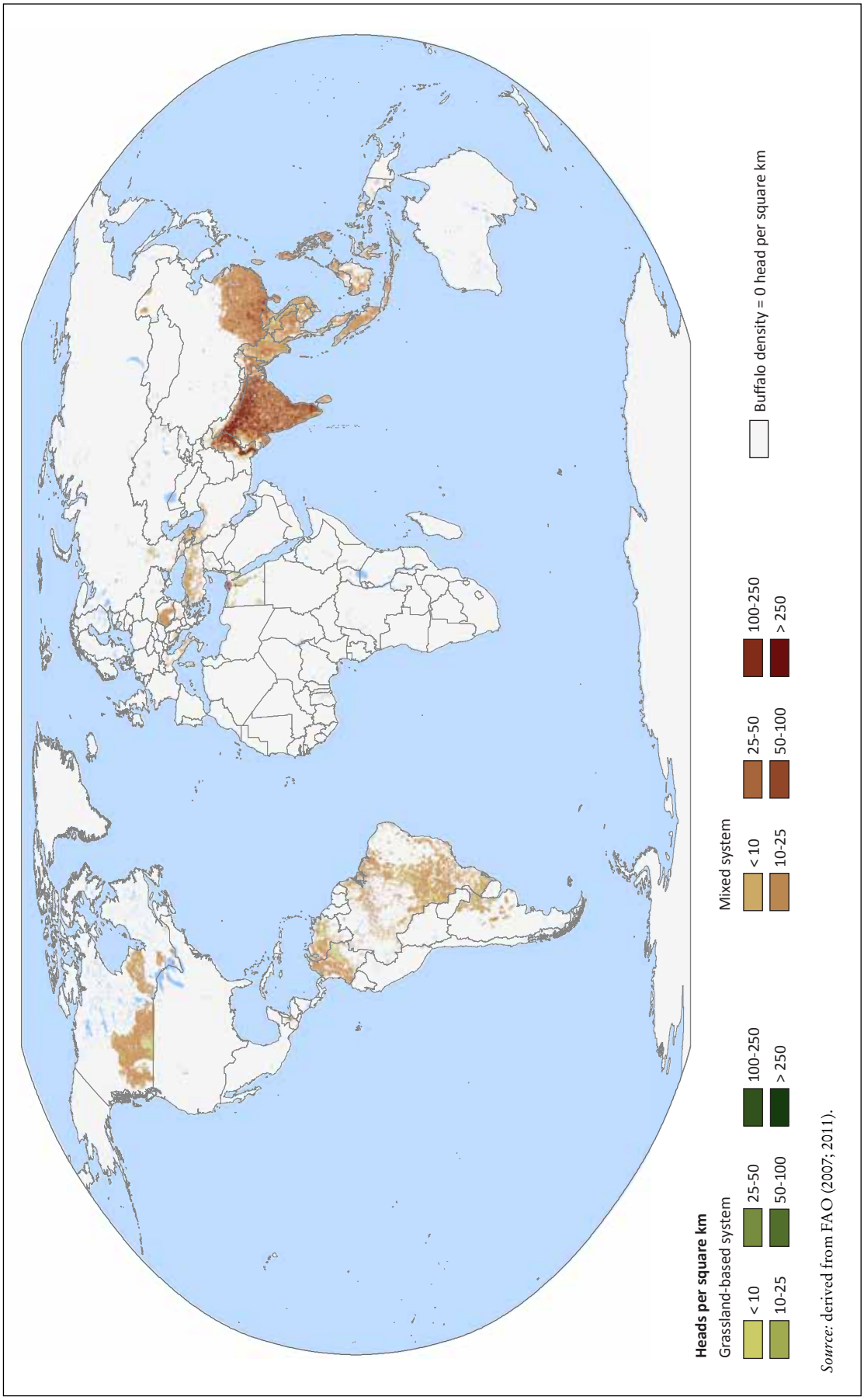
Source: derived from FAO (2007; 2011).

Map 2
Distribution of beef cattle populations



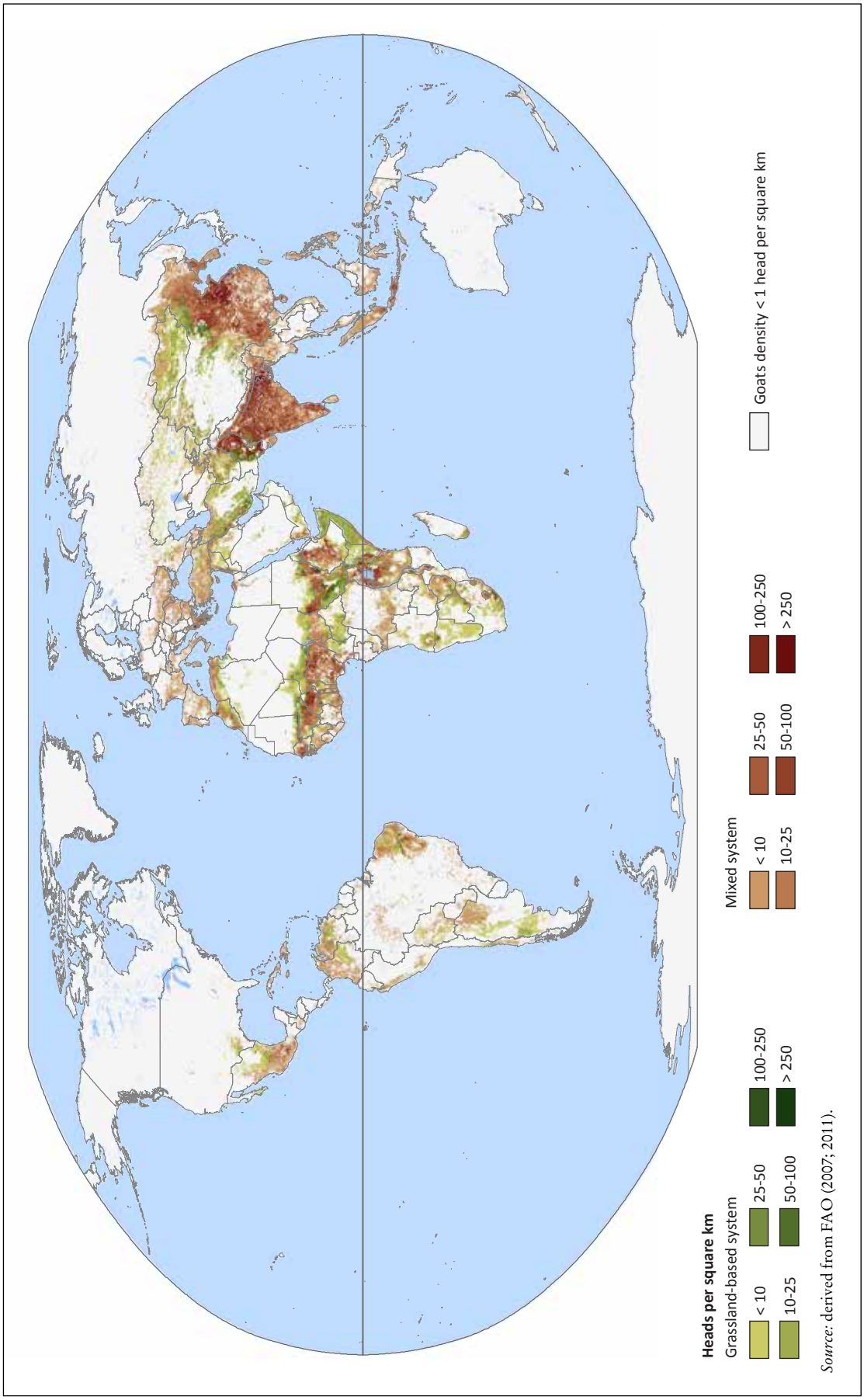
Source: derived from FAO (2007; 2011).

Map 3
Distribution of buffalo populations



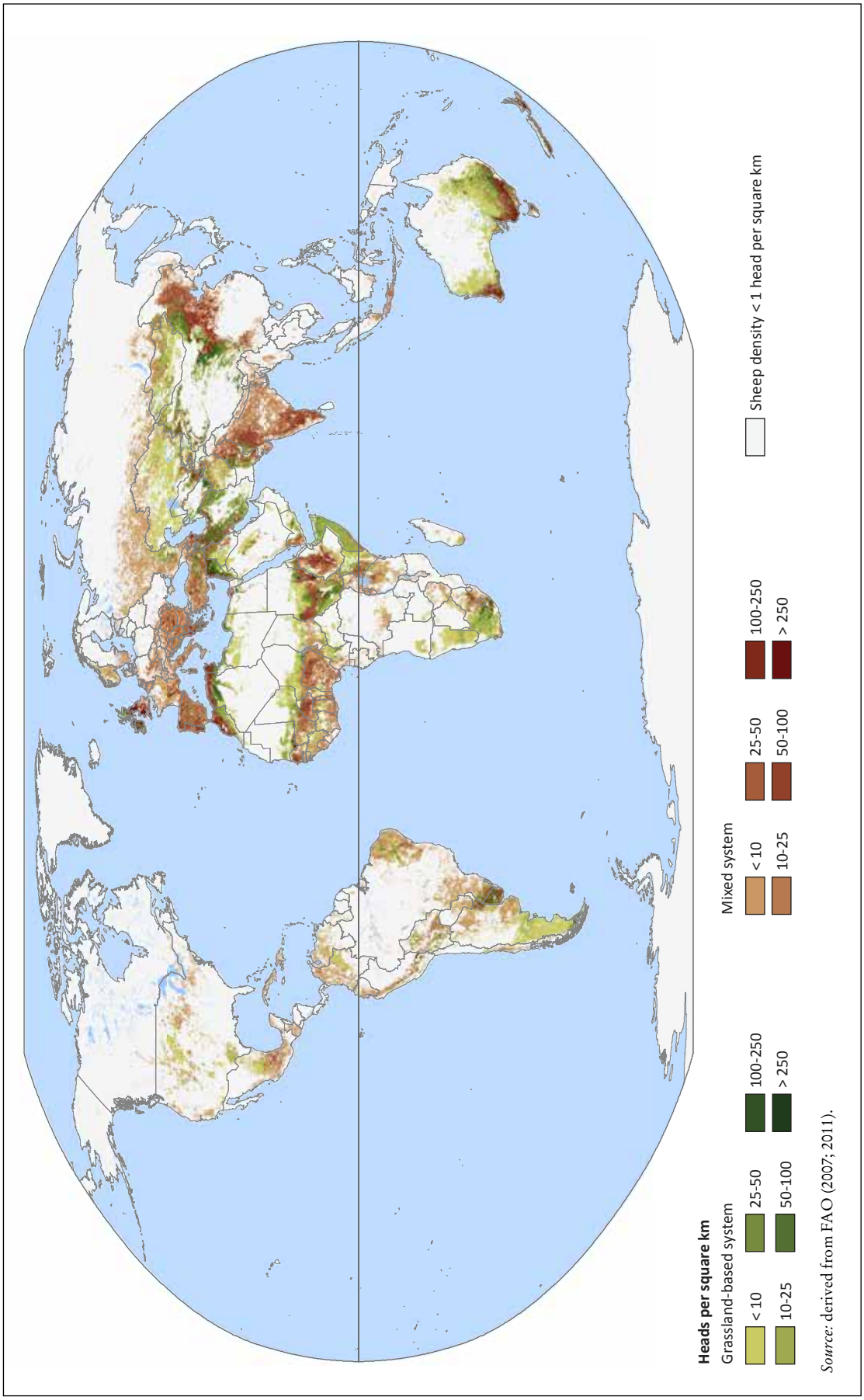
Source: derived from FAO (2007; 2011).

Map 4
Distribution of goat populations



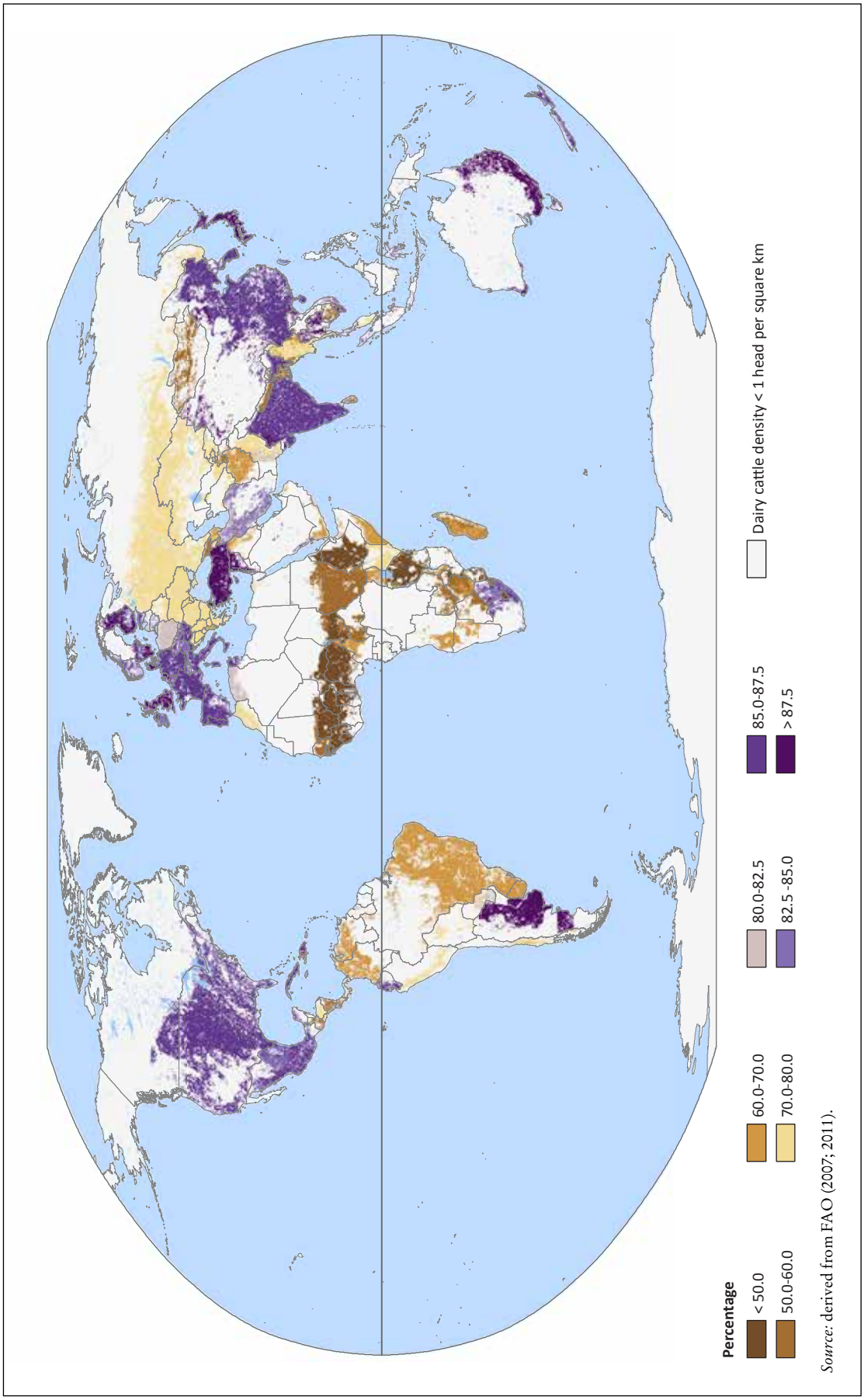
Source: derived from FAO (2007; 2011).

Map 5
Distribution of sheep populations



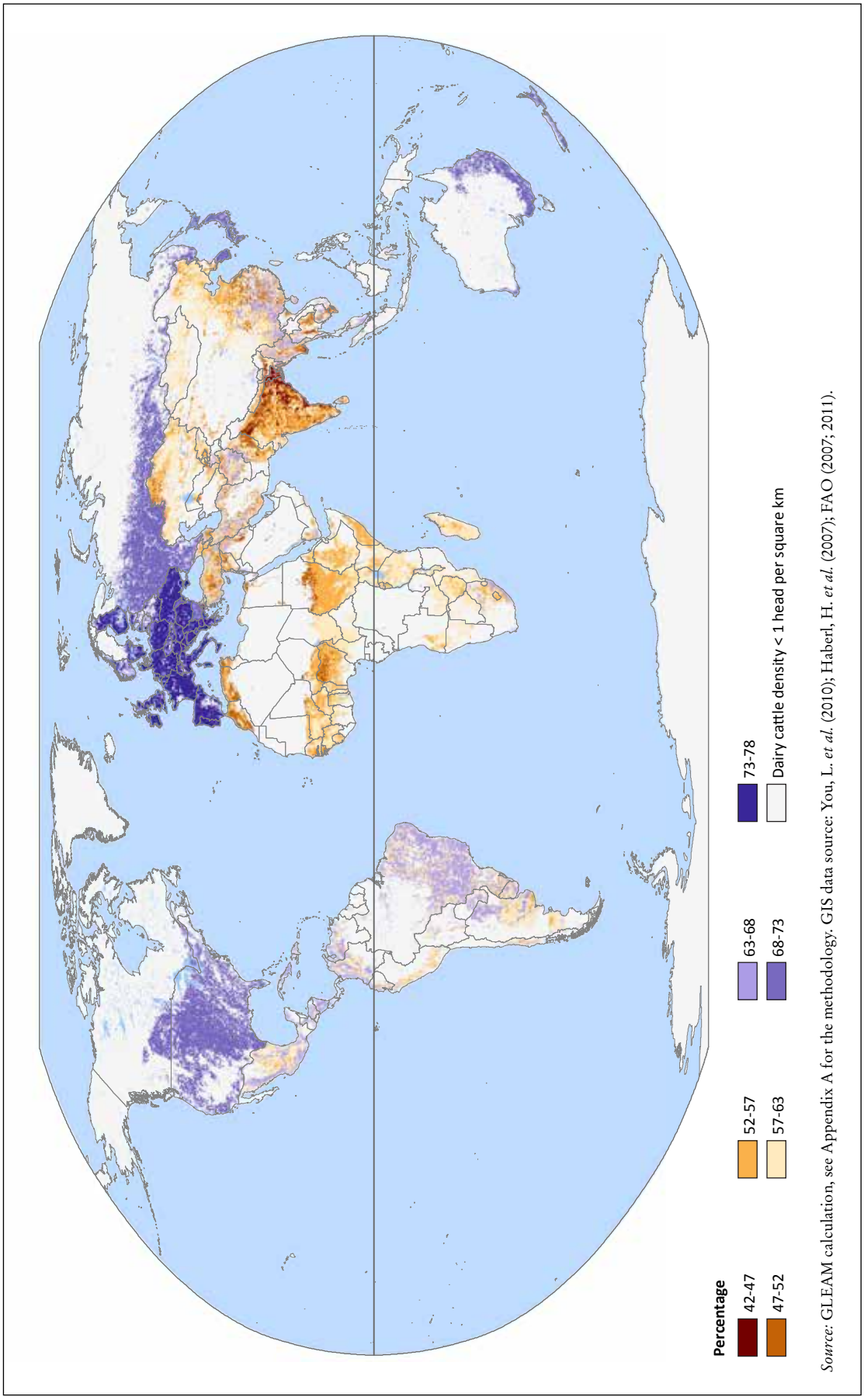
Source: derived from FAO (2007; 2011).

Map 6
Proportion of milk protein in total protein from cattle dairy herds



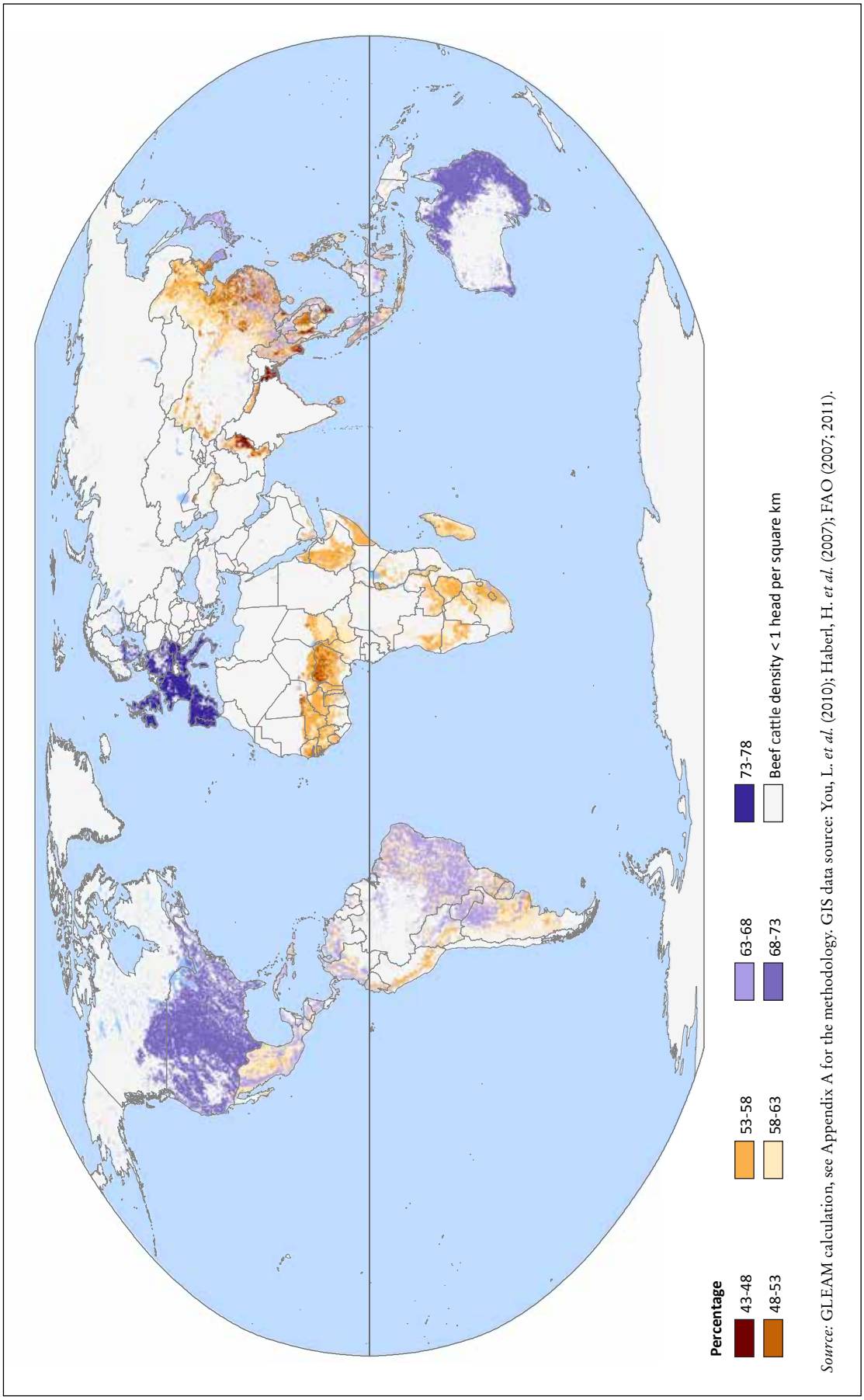
Source: derived from FAO (2007; 2011).

Map 7
Average feed digestibility for dairy cattle



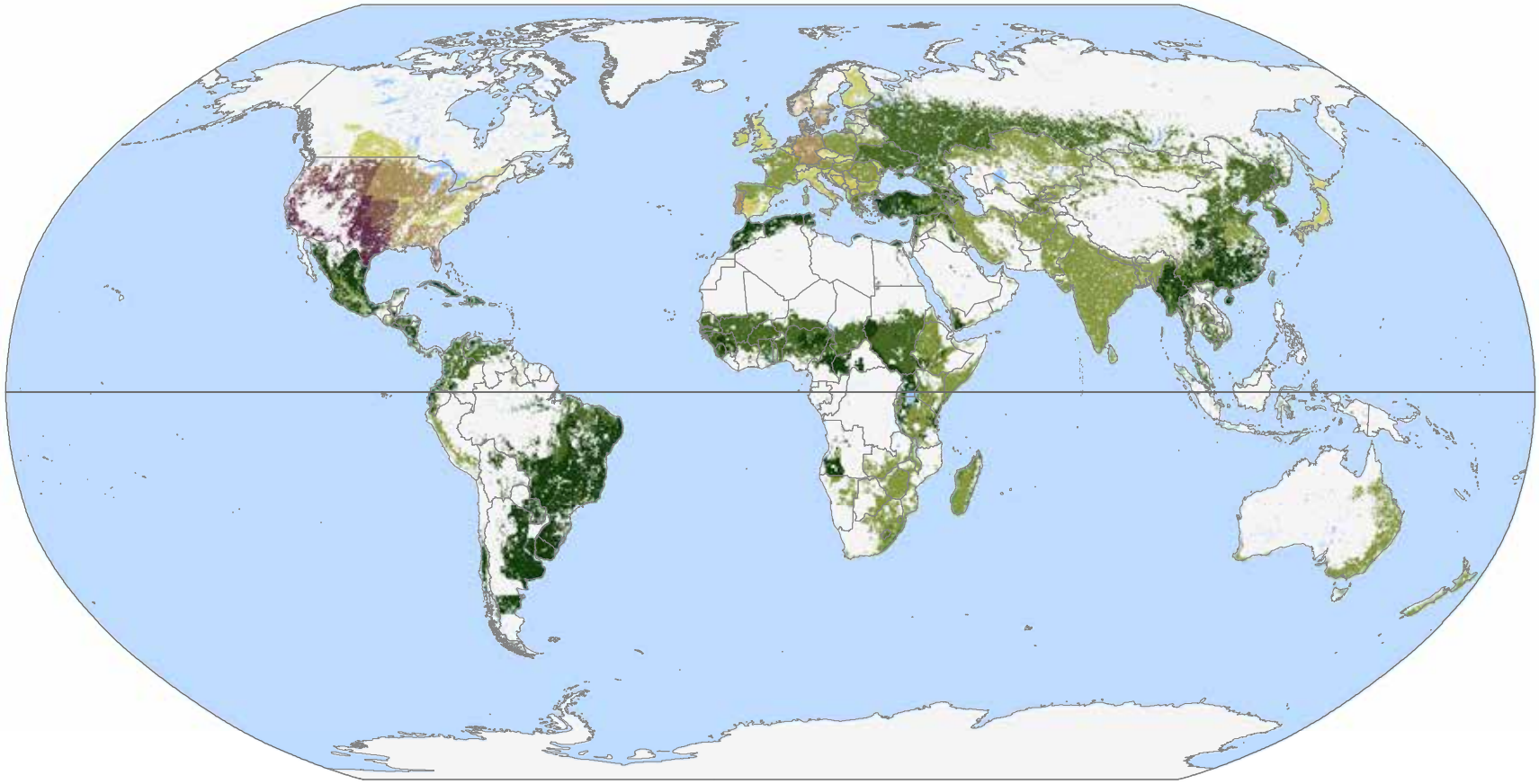
Source: GLEAM calculation, see Appendix A for the methodology. GIS data source: You, L. *et al.* (2010); Haberl, H. *et al.* (2007); FAO (2007; 2011).

Map 8
Average feed digestibility for beef cattle



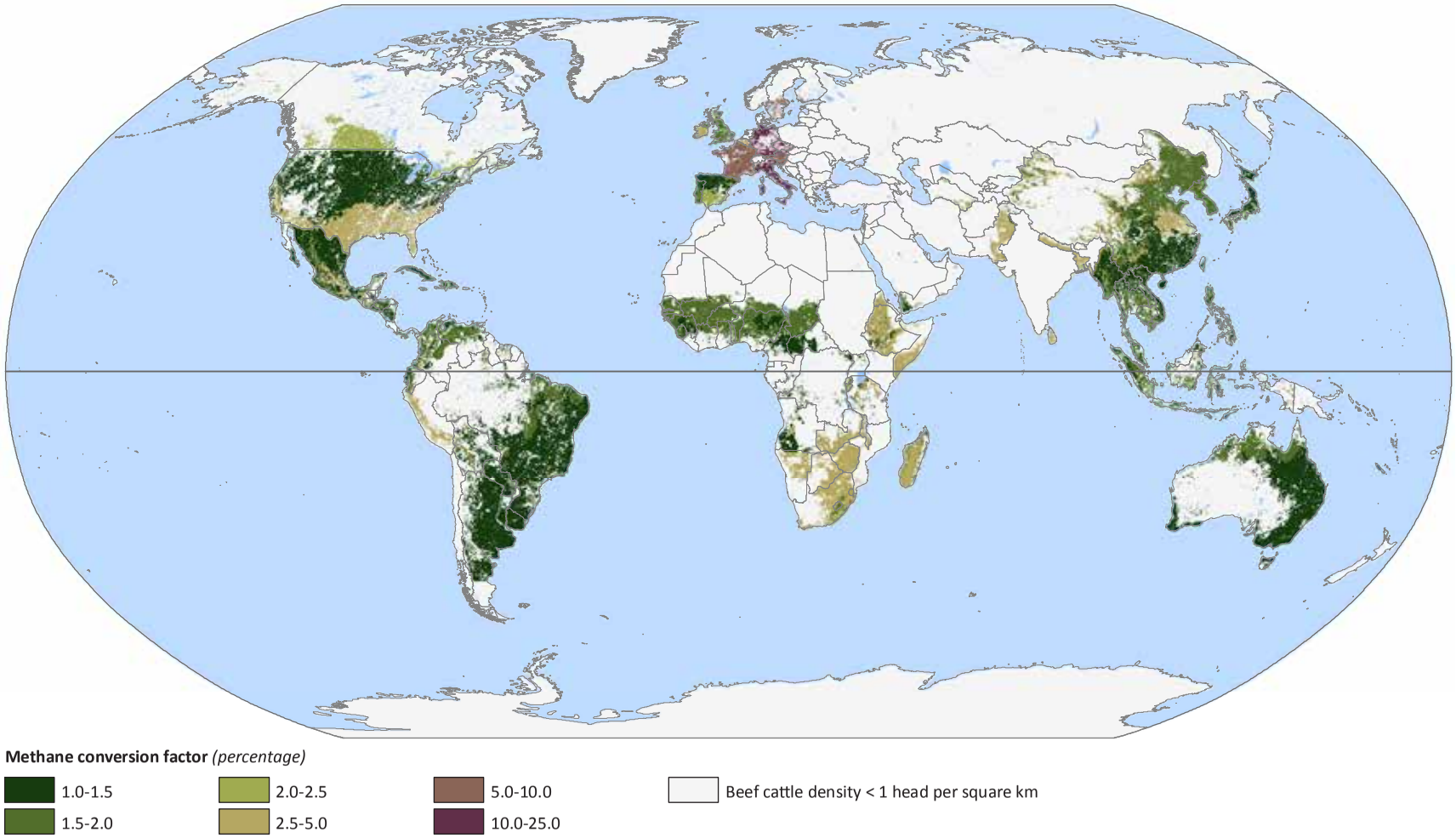
Source: GLEAM calculation, see Appendix A for the methodology. GIS data source: You, L. *et al.* (2010); Haberl, H. *et al.* (2007); FAO (2007; 2011).

Map 9
Manure methane conversion factor for dairy cattle



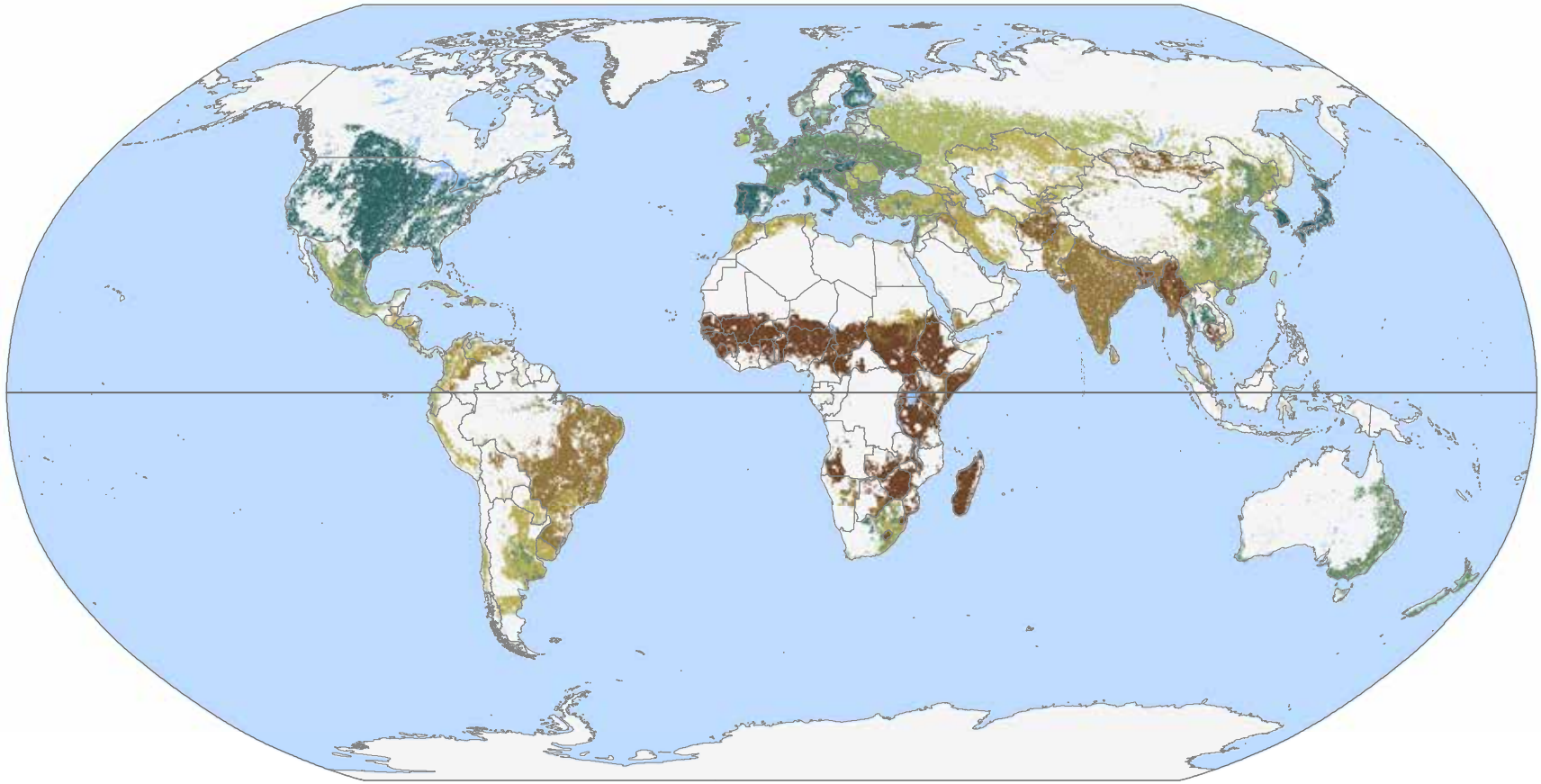
Source: GLEAM calculation, see Appendix A for the methodology. Main input data: IPCC (2006); Hijmans, R.J. *et al.* (2005); FAO (2011).

Map 10
Manure methane conversion factor for beef cattle



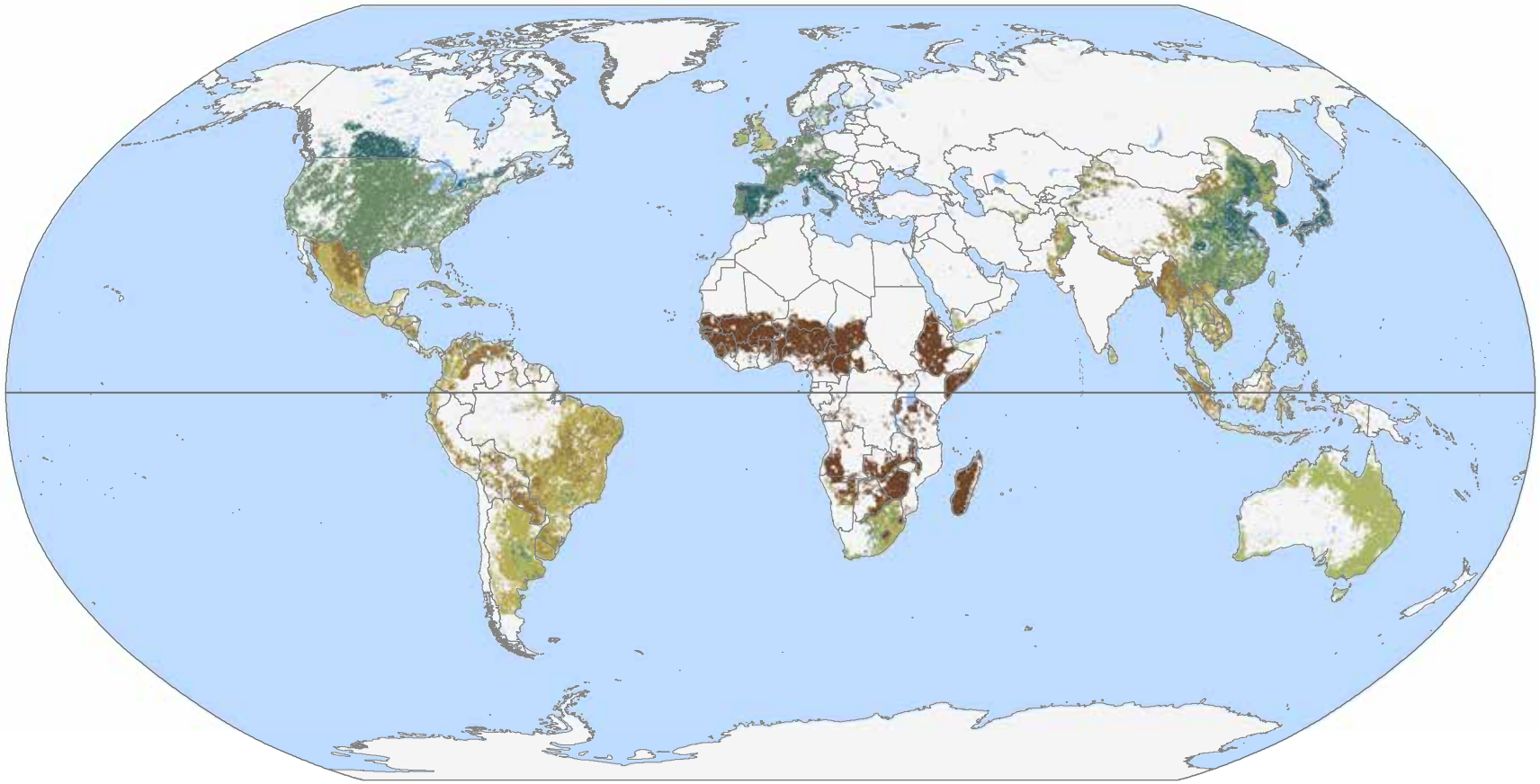
Source: GLEAM calculation, see Appendix A for the methodology. Main input data: IPCC (2006); Hijmans, R.J. *et al.* (2005); FAO (2011).

Map 11
Proportion of feed N retained in product – dairy cattle herds



Source: GLEAM calculation, see Appendix A for the methodology.

Map 12
Proportion of feed N retained in product – beef cattle herds



Source: GLEAM calculation, see Appendix A for the methodology.

REFERENCES

FAO. 2007. *Gridded livestock of the world 2007* by Wint, W. & Robinson, T.P. FAO. Rome.

FAO. 2011. *Global livestock production systems*, by Robinson, T.P., Thornton, P.K., Franceschini, G., Kruska, R.L., Chiozza, F., Notenbaert, A., Cecchi, G., Herrero, M., Epprecht, M., Fritz, S., You, L., Conchedda,G., & See, L. FAO. Rome.

Haberl, H., Erb, K.-H., Krausmann, F., Gaube, V., Bondeau, A., Plutzar, C., Gingrich, S., Lucht W. & Fischer-Kowalski M. 2007. Quantifying and mapping the global human appropriation of net primary production in Earth's terrestrial ecosystem. *Proceedings of the National Academy of Sciences of the USA.* 104: 12942-12947.

Hijmans, R.J., Cameron, S.E., Parra, J.L., Jones P.G. & Jarvis A. 2005. Very high resolution interpolated climate surfaces for global land areas. *International Journal of Climatology,* 25: 1965-1978.

IPCC. 2006. IPCC guidelines for national greenhouse gas inventories. Prepared by the National Greenhouse Gas Inventories Programme, H. S. Eggleston, L. Buendia, K. Miwa, T. Ngara & K. Tanabe K. eds. IPCC. Kanagawa.

You, L., Crespo, S., Guo, Z. Koo, J., Ojo, W., Sebastian, K., Tenorio, T.N., Wood, S. & Wood-Sichra, U. 2010. Spatial Production Allocation Model (SPAM) 2000, Version 3. Release 2. Available at http://MapSPAM.info.

APPENDIX H

Country list

The country grouping used in this assessment is based on the FAO Global Administrative Unit Layers (GAUL). The GAUL aims at compiling and disseminating the most reliable spatial information on administrative units for all the countries in the world providing a contribution to the standardization of the spatial dataset representing administrative units. Country classification is done on a purely geographic basis. For further information: http://www.fews.net/docs/special/GAUL_Disclaimer.pdf

LATIN AMERICA AND THE CARIBBEAN (LAC)

Anguilla
Antigua and Barbuda
Argentina
Aruba
Bahamas
Barbados
Belize
Bolivia
Brazil
British Virgin Islands
Cayman Islands
Chile
Colombia
Costa Rica
Cuba
Dominica
Dominican Republic
Ecuador
El Salvador
Falkland Islands (Malvinas)
French Guiana
Grenada
Guadeloupe
Guatemala
Guyana
Haiti
Honduras
Jamaica
Martinique
Mexico
Montserrat
Netherlands Antilles
Nicaragua
Panama
Paraguay
Peru
Puerto Rico
Saint Kitts and Nevis
Saint Lucia
Saint Vincent and the Grenadines
Suriname
Trinidad and Tobago
Turks and Caicos Islands
United States Virgin Islands
Uruguay
Venezuela

SUB-SAHARAN AFRICA (SSA)

Angola
Benin
Botswana
Burkina Faso
Burundi
Cote d'Ivoire
Cameroon
Cape Verde
Central African Republic
Chad
Comoros
Congo
Democratic Republic of the Congo
Djibouti
Equatorial Guinea
Eritrea
Ethiopia
Gabon
Gambia
Ghana
Guinea
Guinea-Bissau
Kenya
Lesotho
Liberia
Madagascar
Malawi
Mali
Mauritania

Mauritius
Mayotte
Mozambique
Namibia
Niger
Nigeria
Rwanda
Reunion
Saint Helena
Sao Tome and Principe
Senegal
Seychelles
Sierra Leone
Somalia
South Africa
Swaziland
Togo
Uganda
United Republic of Tanzania
Zambia
Zimbabwe

NEAR EAST AND NORTH AFRICA (NENA)
Algeria
Armenia
Azerbaijan
Bahrain
Cyprus
Egypt
Gaza Strip
Georgia
Iraq
Israel
Jordan
Kazakhstan
Kuwait
Kyrgyzstan
Lebanon
Morocco
Oman
Qatar
Republic of Sudan
Saudi Arabia
South Sudan
State of Libya
Syrian Arab Republic
Tajikistan
Tunisia
Turkey
Turkmenistan
United Arab Emirates
Uzbekistan
West Bank
Western Sahara
Yemen

SOUTH ASIA
Afghanistan
Bangladesh
Bhutan
British Indian Ocean Territory
India
Iran (Islamic Republic of)
Maldives
Nepal
Pakistan
Sri Lanka

EASTERN EUROPE
Belarus
Bulgaria
Czech Republic
Hungary
Moldova, Republic of
Poland
Romania
Slovakia
Ukraine

RUSSIAN FEDERATION
Russian Federation

EAST ASIA AND SOUTHEAST ASIA
Brunei Darussalam
Cambodia
China
Christmas Island
Democratic People's Republic of Korea
Hong Kong
Indonesia
Japan
Lao People's Democratic Republic
Macau
Malaysia
Mongolia
Myanmar
Philippines
Republic of Korea
Singapore
Thailand
Timor-Leste
Viet Nam

OCEANIA
American Samoa
Australia
Cook Islands
Fiji
French Polynesia
Guam
Kiribati

Marshall Islands
Micronesia (Federated States of)
Nauru
New Caledonia
New Zealand
Niue
Norfolk Island
Northern Mariana Islands
Palau
Papua New Guinea
Pitcairn
Saint Pierre et Miquelon
Samoa
Solomon Islands
Tokelau
Tonga
Tuvalu
Vanuatu
Wake Island
Wallis and Futuna

WESTERN EUROPE

Albania
Andorra
Austria
Belgium
Bosnia and Herzegovina
Croatia
Denmark
Estonia
Faroe Islands
Finland
France
Germany
Greece
Guernsey
Iceland
Ireland
Isle of Man
Italy
Jersey
Latvia
Liechtenstein
Lithuania
Luxembourg
Madeira Islands
Malta
Monaco
Montenegro
Netherlands
Norway
Portugal
Republic of Serbia
San Marino
Slovenia
Spain
Svalbard and Jan Mayen Islands
Sweden
Switzerland
The former Yugoslav Republic of Macedonia
United Kingdom of Great Britain and Northern Ireland

NORTH AMERICA

Bermuda
Canada
Greenland
United States of America









MITIGATING EMISSIONS FROM CALIFORNIA'S DAIRIES

Considering the Role of Anaerobic Digesters in Mitigating Emissions from California's Dairies

By Ruthie Lazenby

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Emmett Institute on Climate Change & the Environment
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Considering the Role of Anaerobic Digesters in Mitigating Emissions from California's Dairies

By Ruthie Lazenby[1]

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1 Ruthie Lazenby is the Shapiro Fellow in Environmental Law and Policy at UCLA School of Law for 2023-2025. She was previously a Staff Attorney at the Environmental Justice Clinic at Vermont Law School and a Legal Fellow in the Environmental Justice program at New York Lawyers for the Public Interest. All views expressed in this paper are solely those of the author. The author thanks Sabrina Ashjian, Gabriel Grief, and Julia Stein for their review and input on this paper.

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I. Introduction

This white paper addresses several contested and commonly-raised issues related to the promotion of dairy digesters as the primary policy mechanism to reduce greenhouse gas (GHG) emissions from dairy operations in California. The purpose of this paper is to provide context for ongoing conversations regarding the role of dairy digesters in California's Low Carbon Fuel Standard (LCFS), as well as potential dairy methane regulations pursuant to SB 1383 (2016). The report analyzes and offers key takeaways for each of the following issues:

- The variety of manure management systems used on dairies and their respective prevalence and emissions;
- The appropriateness and applicability of the life cycle analysis used by the Air Resources Board (CARB) to evaluate the carbon intensity of fuels derived from dairy biogas in the LCFS program;
- The relationship between LCFS incentives for dairy biogas and dairy consolidation;
- The risk of emissions leakage were CARB to regulate dairy methane;
- The role of LCFS credits for fuels derived from dairy biogas in meeting California's climate targets.

II. Manure Management Systems and GHG Emissions

California's Low Carbon Fuel Standard (LCFS) assumes that liquid manure management systems are the standard practice for dairies and, as a result, that they are the appropriate baseline against which to compare a given climate intervention. By setting liquid manure management systems as the reference scenario, emissions reductions from digesters appear to be relatively higher because this method of manure management generates more emissions that can then be captured. While liquid manure management systems are the predominant approach in California, they are one of the more polluting manure management systems available. They are also less common in other dairying states. Dairies in all states, however, are eligible for LCFS credits and shaped by that program's incentives. This section describes how common liquid manure management systems are and what alternatives are available.

The major sources of GHG emissions in the dairying process are feed production, enteric fermentation, and manure management. These are present in all dairy operations to varying degrees. The relative contributions of feed, enteric fermentation, and manure management vary based on the practices employed. Emissions from feed production, for example, can be especially high in "high-yielding milk production systems."[2] Manure management emissions can vary significantly based on the scale of the operations and the specific practices employed, while enteric emissions tend to scale proportionally to herd size. While estimates of relative contributions vary, methane from enteric fermentation and feed production are generally thought to be the largest sources, followed by manure management.

A. Common Manure Management Systems

Livestock produce waste. Historically, when dairy farms were pasture-based and much smaller than the contemporary American dairy, cows deposited their waste in the pasture where it would degrade and incorporate into the soil over time. As dairy industrialized over the course of the 20th century, and particularly as the industry consolidated over the past 30 years, the amount of waste produced at the largest operations has become too great for the available land to absorb safely. When manure is

2 M. Henriksson, C. Cederberg, and C. Swensson, *Carbon Footprint and Land Requirement for Dairy Herds Rations: Impacts of Feed Production Practices and Regional Climate Variations*, 8 Animal 8, 1329 (2014), https://doi.org/10.1017/S1751731114000627.

land-applied above agronomic rates, or above the rate at which the crops and soil can absorb nutrients, it results in contamination to local waterways. As a result, larger-scale dairy (and other livestock) operations have had to develop new methods that allow them to collect the waste and store it until land is available and weather conditions allow for it to be safely disposed of.[3]

Manure management systems can be divided into three components: "1) manure handling, the method of manure removal or management in animal housing or grazing areas; 2) manure storage, the infrastructure and method for holding manure until its application; and 3) manure application and manner in which manure is land applied, typically for crop fertilization."[4] Different practices are available to dairies at each step in this process.

Different approaches are more suitable to different operations based on scale and location. The scale of the operation impacts the choice of manure management system for several reasons. On large-scale operations, there is generally inadequate pastureland available for grazing and inadequate cropland for manure application. As a result, feed must be purchased[5] and manure must be stored until the conditions are right and the land is available for spreading. The manure lagoon is the dominant form of manure storage for these large-scale operations. Anaerobic lagoons are designed minimize the amount of land required for spreading.[6] Concentrating manure production creates risks to air and water[7] so manure transport, storage, and spreading must all be carefully managed.

At the smaller-scale, dairies typically graze their cows and supplement with little to no purchased feed. Manure is produced at quantities and concentrations less likely to cause nutrient pollution and is typically land-applied on a regular basis (though some small and mid-sized farms may also use short-term storage for manure).

A key point of differentiation between dairy manure management systems is manure consistency: Some farms maintain their manure in solid form and others liquify the manure. Larger farms with manure lagoons tend to transport manure in liquid form, often using flush systems. Smaller farms more often maintain solid manure that can be land-applied daily.[8]

The specific practices adopted throughout the different parts of the manure management system affect one another as well, with the initial choice of manure consistency imposing decisive constraints.[9] One study found "clear patterns of related strategies, largely determined by the handling of manure as a liquid, slurry, or solid."[10] The diagram below was developed out of a survey of Wisconsin dairies to study how certain practices tend to lead to others. For example, larger operations tend to use freestall barns. The survey found that 68% of operations using freestall barns select a skid steer over various alternatives to collect

3 H.A. Aguirre-Villegas and R.A. Larson, *Evaluating Greenhouse Gas Emissions from Dairy Manure Management Practices Using Survey Data and Lifecycle Tools*, J. of Cleaner Production 143 (2017) 169e179, http://dx.doi.org/10.1016/j.jclepro.2016.12.133. This Wisconsin survey found that farms had more land per "animal unit" than larger farms, likely because "neither large farms nor permitted facilities have the sufficient land to agronomically recycle excreted P (Table C.4), suggesting that land is not increasing proportionally to the number of cows as farms grow."

4 Meredith T. Niles et al., *Manure Management Strategies Are Interconnected with Complexity Across U.S. Dairy Farms*, 17 PLoS One 6 (2022), https://www.ncbi.nlm.nih.gov/pmc/articles/PMC9165779/.

5 Food and Water Watch, *The Economic Cost of Food Monopolies: The Dirty Dairy Racket* (January 2023), https://www.foodandwaterwatch.org/wp-content/uploads/2023/01/RPT2_2301_EconomicCostofDairy-WEB.pdf ("Larger farms are less likely to graze their cattle on pasture and instead rely on purchased feed, which is the single largest source of livestock industry greenhouse gas emissions"); *see also* U.N. Food and Agriculture Organization, *Tackling Climate Change Through Livestock: A Global Assessment of Emissions and Mitigation Opportunities* (2013), https://www.fao.org/3/i3437e/i3437e.pdf ("Feed production and processing, and enteric fermentation from ruminants are the two main sources of emissions, representing 45 and 39 percent of sector emissions, respectively. Manure storage and processing represent 10 percent. The remainder is attributable to the processing and transportation of animal products.")

6 Missouri State University Extension, Lagoons for Storage/Treatment of Dairy Waste, https://extension.missouri.edu/publications/wq304.

7 *See* A. Naranjo et al., *Greenhouse Gas, Water, and Land Footprint Per Unit of Production of the California Dairy Industry Over 50 Years*, 103 J. Dairy Sci. 4 (Feb. 6, 2020), https://www.journalofdairyscience.org/article/S0022-0302(20)30074-6/fulltext

8 H.A. Aguirre-Villegas and R.A. Larson, *Evaluating Greenhouse Gas Emissions from Dairy Manure Management Practices Using Survey Data and Lifecycle Tools*, *supra* note 3.

9 *See generally* Meredith T. Niles et al., *Manure Management Strategies Are Interconnected with Complexity Across U.S. Dairy Farms*, *supra* note 4.

10 *Id.*

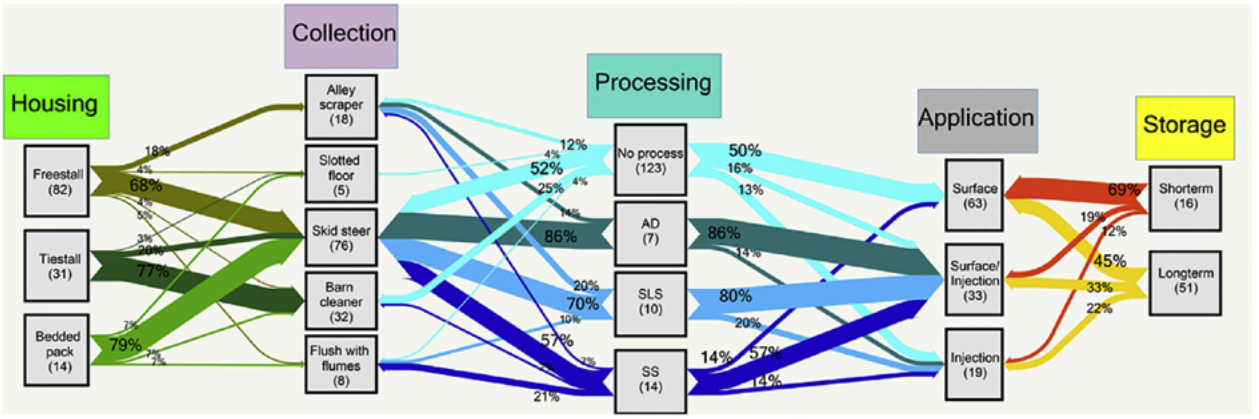


Fig. 3. Probabilities (%) of adopting a manure management practice (rectangular boxes) given the adoption of another practice. Values in parenthesis represent number of farms. Totals <100% indicate missing values.

FIGURE 1 Via H.A. Aguirre-Villegas and R.A. Larson, Evaluating Greenhouse Gas Emissions from Dairy Manure Management Practices Using SurveyData and Lifecycle Tools, Journal of Cleaner Production 143 (2017) 169e179, http://dx.doi.org/10.1016/j.jclepro.2016.12.133.

manure. Smaller operations tend to use tiestall barns and the survey found that 77% of tiestall barns select a barn cleaner over various alternatives to collect manure. The kinds of collection processes in turn impact the ways that manure can be efficiently stored, processed, and so on.

The fact that manure management processes are interrelated matters because it determines how flexible and open to change these systems are. The Wisconsin study came to the crucial conclusion that: "the inter-related nature of these systems demonstrates how MMS [Manure Management Systems] are often locked in across farm systems through structural and equipment investments... This suggests that changing MMS is complex and requires not only a shift in the potential handling method, but also potential shifts in storage and application equipment as well. Flush handling can't easily shift to scraper handling, without potentially shifting from liquid to a slurry and then investing in a surface application tank or truck system."[11]

The study also found that dairies using solid manure management systems were "highly heterogenous, where farmers may have a suite of alternative manure management strategies available to them, and substitution is viable."[12] The study found that dairies using liquid manure management systems, on the other hand, had "very few substitutes in their MMS, suggesting greater investment in certain infrastructures, which are not easily changed."[13]

This of particular concern in California, where liquid manure management systems dominate. It is not good news for advocates interested in relying on technological changes to reduce emissions from the dairy industry. It means that mitigation interventions can be constrained by decisions about manure consistency and ultimately by the scale of operation. This means that taking dairy decarbonization seriously requires reconsidering the federal and state policies that have consistently favored industrial-scale facilities.

1. Prevalence of Different Manure Management Systems

Confinement dairies with liquid manure management systems are more common in California than nationally. Manure lagoons are used on 58%

11 *Id.*
12 *Id.*
13 *Id.*

Manure Share (MS) and Methane Conversion Factor (MCF) of Manure Management Systems

Waste Management System	Pasture	Daily Spread	Solid Storage	Liquid/ Slurry	Anaerobic Lagoon	Deep Pit
MS by system and location						
■ U.S. Average	7%	15%	23%	21%	32%	2%
■ California	1%	11%	9%	21%	58%	0%
■ Wisconsin	7%	12%	42%	24%	12%	4%
MCF by system and location						
■ U.S. Average	1.2%	0.2%	2.6%	28.6%	69.9%	28.6%
■ California	1.5%	0.5%	4.0%	35%	75%	35%
■ Wisconsin	1.0%	0.1%	2.0%	22%	66%	22%

FIGURE 2 Via Jeongwoo Han, Marianne Mintz, and Michael Wang, Waste-to-Wheel Analysis of Anaerobic-Digestion-Based Renewable Natural Gas Pathways with the GREET Model ANL/ESD/11-6, note 13.

percent of dairies in California and 32% percent of dairies nationally.[14] In Tulare and Glenn Counties specifically, one survey found that 96% of dairies use storage or treatment ponds.[15] A 2011 survey of California dairies found that most had freestalls for housing and collect manure thorough flushing and/or daily scraping.[16]

Wisconsin is the number two state for dairy nationally after California, but the practices of Wisconsin dairies look different than those in California. Manure lagoons and liquid manure management systems are less common than in California. A survey of Wisconsin dairies found that they are prevalent on larger operations[17] but uncommon on smaller farms. Because Wisconsin had more smaller farms at the time of the survey, liquid systems were less common overall. 70% of permitted (larger) facilities used liquid manure management systems while 80% of smaller farms used solid manure management systems. Smaller Wisconsin operations tend to land-apply manure immediately, while the largest permitted operations rely heavily on long-term storage (lagoons). The major processing techniques used in the Wisconsin survey were: sand separation (50%), anaerobic digestion and solid-liquid separation (20%), solid-liquid separation and sand separation (10%).

Note that a key difference between dairies in California and colder climates like Wisconsin is that land application is rarely possible during the winter, because the ground is frozen. Instead, permitted facilities typically land apply in batches in the spring and the fall. Additionally, concerns around runoff due to rains when manure is land applied several times a week may be reduced due to California's drier climate.

California's model of dairying generally and manure management specifically has proliferated

14 Jeongwoo Han, Marianne Mintz, and Michael Wang, *Waste-to-Wheel Analysis of Anaerobic-Digestion-Based Renewable Natural Gas Pathways with the GREET Model ANL/ESD/11-6*, Argonne National Laboratory (September 2011), https://publications.anl.gov/anlpubs/2011/12/71742.pdf.

15 D. Meyer et al., *Survey of Dairy Housing and Manure Management Practices in California*, 94 J. Dairy Sci. 9, 4744 (Sept. 2011), https://www.journalofdairyscience.org/article/S0022-0302(11)00489-9/fulltext.

16 H.A. Aguirre-Villegas and R.A. Larson, citing Meyer et al. 2011.

17 *Id.* ("large and permitted facilities handle slurry and liquid manure and have freestalls.")

in other states in recent years.[18] Some analyses distinguish between "traditional" dairying states like New York and Wisconsin, which still tend to have smaller farms on average, and "modern" dairying states, which tend to be in the West where the California-model has become more common.

2. *GHG Impacts of Different Manure Management Systems*

The variability in the climate, geography, scale, and practices of American dairies makes it challenging to make general comparisons regarding their emissions. Due in part to the many possible permutations of these practices and scales, there are limited comparative studies of emissions from small, pasture-based operations and large-scale dairy CAFOs. However, one of the few such studies "indicated that for the metric of milk production per farmland area, the environmental impact (in relation to potential resource utilization and pollutants) was lower for the pasture-based system than the confinement system. Furthermore, the pasture-based system had a lower total environmental impact compared with the confinement system."[19]

The same study acknowledged, however, that "some studies suggested that economies of scale and efficient management could put large farms in a better environmental position (Saam et al., 2005)."[20] The California dairy industry regularly makes this claim, touting its increasing efficiency as decreasing emissions intensity per cow. However, this perspective "misses the holistic economic and environmental impact of concentrating production on larger farms."[21]

Scale, of course, affects emissions and other environmental impacts on dairies. The volume of manure produced has direct implications for GHG emissions. Not only does more manure mean more emissions, but it typically means longer storage periods during which manure can emit GHGs.[22]

The manure form/consistency also has direct implications for GHG emissions. For example, "solid manures have less available water and are usually stored in stock piles that promote aeration, which reduces CH4 emissions. Liquid manures are stored on pits that promote anaerobic conditions, increasing CH4 emissions. Larger dilutions of manure imply larger manure volumes to be handled, which affects GHG emissions due to increased energy consumption"[23] Liquifying manure using flush systems can reduce ammonia emissions in the barn, but increases methane emissions.[24]

18 Rick Barrett and Lee Bergquist, *Industrial Dairy Farming is Taking Over in Wisconsin, Crowding Out Family Operations and Raising Environmental Concerns*, Milwaukee Journal Sentinel (Dec. 6, 2019), https://www.jsonline.com/in-depth/news/special-reports/dairy-crisis/2019/12/06/industrial-dairy-impacts-wisconsin-environment-family-farms/43186671002/ ("...massive milking operations, popularized in California, shatter the traditional model of Wisconsin farms. With so many cattle, they run the risk of contaminating groundwater and overwhelming lakes, rivers and streams with runoff pollution while making it harder for smaller farms to compete."); Lilli LeGardeur, *Milk It*, Louisiana Life (Jan. 4, 2008), https://www.louisianalife.com/milk-it/ ("90 percent of Louisiana dairy farms are "pasture-based," ... In confinement dairying – a relatively new style popular out West – cows are fenced inside dirt-floor lots and have all their food delivered ... Confinement dairying, by the way, is also called California-style dairying, after the state where it originated. So, to a Louisiana dairy farmer, those TV commercials depicting California cows gallivanting in fields of clover are doubly irritating. They know that most of those California critters never set foot in a grassy pasture. As one local farmer so adroitly observed, "Happy Cows – my ass.""); David Barboza, *America's Cheese State Fights to Stay that Way, Wisconsin Struggles to Keep Pace with West*, New York Times (June 28, 2001), https://www.nytimes.com/2001/06/28/business/america-s-cheese-state-fights-stay-that-way-wisconsin-struggles-keep-pace-with.html ("With the California-style operations, as they are called, about 2,000 megafarms, with an average herd size of 650 cows, produce more milk than 18,000 mostly smaller farms in Wisconsin, where the average herd is 80.")

19 Alice Moscovici Joubran et al., *Invited Review: A 2020 Perspective on Pasture-Based Dairy Systems and Products*, 104 J. Dairy Sci. 7, 7364 (July 2021), citing O'Brien et al., 2012; O'Brien and Hennessy, 2017, https://www.sciencedirect.com/science/article/pii/S0022030221005166.

20 H.A. Aguirre-Villegas and R.A. Larson, *Evaluating Greenhouse Gas Emissions from Dairy Manure Management Practices Using Survey Data and Lifecycle Tools*, *supra* note 3.

21 Claire Kelloway, *Fewer Global Dairy Corporations Drive Overproduction and Pollution, Harming Small Farmers, Report Finds*, Food & Power (July 18, 2020), https://www.foodandpower.net/latest/2020/06/18/fewer-global-dairy-corporations-drive-overproduction-and-pollution-harming-small-farmers-report-finds?rq=dairy.

22 H.A. Aguirre-Villegas and R.A. Larson, *Evaluating Greenhouse Gas Emissions from Dairy Manure Management Practices Using Survey Data and Lifecycle Tools*.

23 *Id*. at 172.

24 Cal. Air Res. Board, Short-Live Climate Pollutant Reduction Strategy (March 2017), https://ww2.arb.ca.gov/sites/default/files/2020-07/final_SLCP_strategy.pdf; Alice Rocha, *How Handling Manure Waste from Dairy Cattle Impacts Greenhouse Gas Emissions and Climate Impacts*, UC Davis CLEAR Center (May 14, 2021), https://clear.ucdavis.edu/explainers/how-handling-manure-waste-dairy-cattle-impacts-greenhouse-gas-emissions-and-climate ("Scraping and vacuuming, on the other hand, may leave thin layers of manure on the ground which can come in contact with cattle urine causing the emission of ammonia. The latter is generated by a reaction between urea in urine and the urease enzyme in manure.")

The Wisconsin survey modeled emissions from the dairy industry there, and found that:

- Long-term storage is common on larger farms handling liquid manure, which generally increases GHG emissions.
- A natural crust formation during storage creates aerobic conditions on the surface and reduces wind velocity, decreasing methane and ammonia emissions respectively, but increasing nitrous oxide emissions. Total GHG emissions are higher without this crust.
- Frequent manure application reduces both GHG and ammonia emissions from storage due to the shorter retention times and the reduced surface area. These emissions can increase, however, during application as more ammoniacal nitrogen and volatile solids are available to promote nitrous oxide, methane, and ammonia release. Daily or weekly application can also lead to runoff and leaching during precipitation events or snowmelt, resulting in potential eutrophication and loss of valuable nutrients.[25]

Regarding anaerobic digestion in particular, the Wisconsin survey found that:

- Out of the reported processing technologies, anaerobic digestion is the most effective to reduce GHG emissions from both energy and manure.
- Emission reductions from energy come from the displaced emissions that biogas-based electricity has when replacing grid electricity.
- Reductions from manure are mostly from the capture of methane during digestion which is then converted to carbon dioxide during combustion, as well as the reduction of carbon available to produce methane in storage.
- Solid-liquid separation further reduces GHG emissions as fewer volatile solids enter long term storage within the liquid fraction.
- After digestion, ammonia emissions are increased during digestate storage because: 1) mineralization in the digester increases ammoniacal nitrogen, and 2) the inexistence of a natural crust on the storage surface reduces the physical barrier that prevents aeration.[26]

B. Enteric and Other Non-Manure Management Emissions

Reducing emissions from manure management is critical. However, manure management contributes fewer emissions than enteric fermentation.[27] The reduction of enteric emissions has generally been sidelined as a more challenging technical problem because it is based on the natural feature of the ruminant digestive system. Considering the impact of various interventions on both enteric and manure management emissions, however, should be a component of any effort to meet climate targets for dairy.

While enteric fermentation and manure management primarily generate methane, the substantial emissions from feed production include nitrous oxide which is "emitted from cultivated soils and significantly influenced by cultivation practices, especially nitrogen (N) fertilization."[28] Emissions from feed vary based on the amount of feed imported and the composition of rations which themselves can vary based on geography and climate. Dairy feed can be homegrown—either on pasture or harvested corn or grass fermented as silage—or imported (including concentrates, silage, byproducts, and other grains).

Most dairy cows in California eat what's called

25 H.A. Aguirre-Villegas and R.A. Larson, *Evaluating Greenhouse Gas Emissions from Dairy Manure Management Practices Using Survey Data and Lifecycle Tools*, *supra* note 3.
26 *Id.*
27 *Id.*
28 M. Henriksson, C. Cederberg, and C. Swensson, *Carbon Footprint and Land Requirement for Dairy Herds Rations: Impacts of Feed Production Practices and Regional Climate Variations*, citing Bouwman et al., 2002, *supra* note 2.
29 Conor McCabe, *Dairy Cows – the Original Upcyclers: How Ruminant Digestion Turns Byproducts into High-Quality Nutrition*, UC Davis CLEAR Center (Jan. 07, 2022), https://clear.ucdavis.edu/explainers/dairy-cows-original-upcyclers.

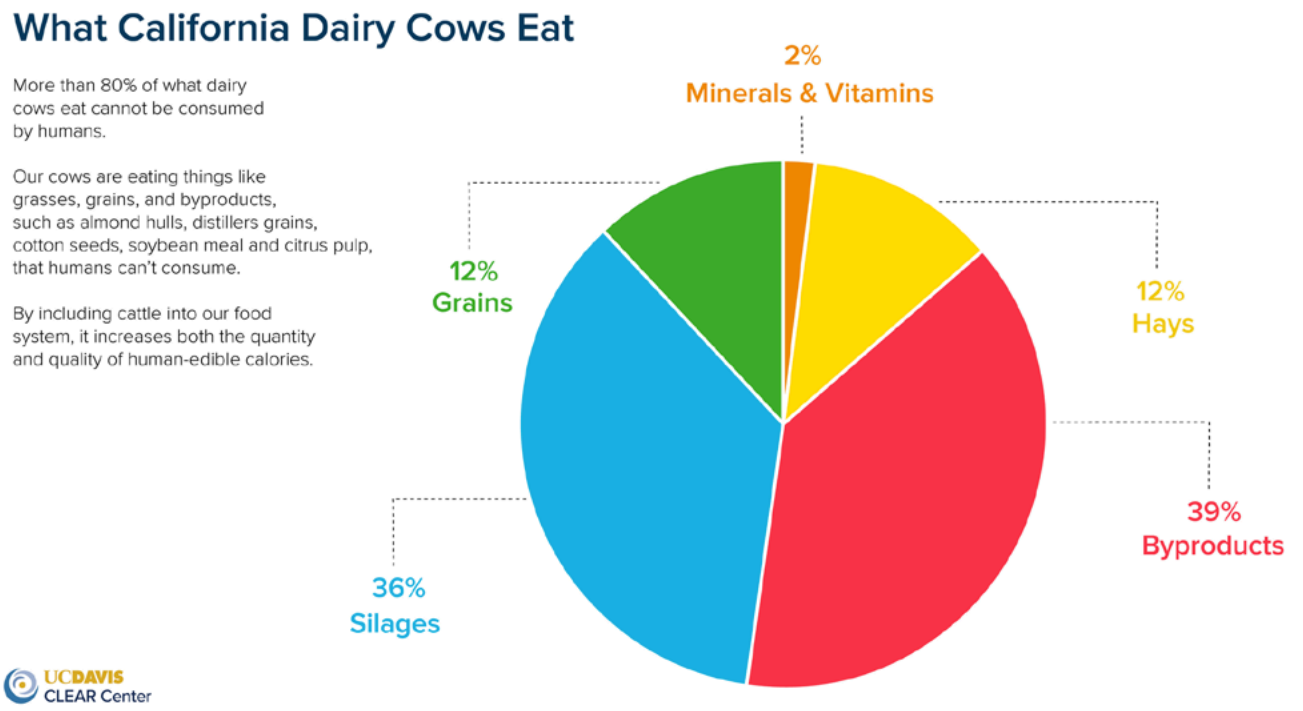


Figure 3: Composition of dairy cattle diets across 40 California dairies. Byproducts include cotton seeds, canola meal, dried distillers grains, almond hulls, soy hulls, whey, fat supplements, soybean meal, corn gluten, wheat byproducts, and rice bran.
Credit: CLEAR Center

FIGURE 3 Via Conor McCabe, Dairy Cows – the Original Upcyclers: How Ruminant Digestion Turns Byproducts into High-Quality Nutrition, supra note 29.

a "total mixed ration."[29] Total mixed ration "is essentially a nutritionally formulated feed mix, combining feeds formulated to a specific nutrient content. Such feeds may contain forage (grass silage, hay, or straw), grains (corn, oats, wheat, and barley), protein feeds (soybean, cottonseed, linseed, and groundnut), minerals, vitamins, feed additives, and by-products."[30]

The nutrition profile of grasses consumed through grazing, in contrast, is different, "with potential nutritional benefits, compared with conventional milk derived from total mixed ration."[31] The emissions intensity of each method is also different, depending on the particular composition of grazing forage and of a total mixed ration diet. For example, "Some studies have demonstrated benefits of inclusion of white clover in pasture, due to its ability to reduce nitrous oxide emissions, fix atmospheric nitrogen, and reduce carbon footprint (Ledgard et al., 2009; Yan et al., 2013)."[32] The UC Davis article also cites a Cornell study claiming that the emissions from using byproducts as dairy feed are 60% less than the alternative, which they define as sending the byproducts to a landfill for incineration.

30 Alice Moscovici Joubran et al., *Invited Review: A 2020 Perspective on Pasture-Based Dairy Systems and Products, supra* note 19.
31 *Id.*
32 *Id.*

C. California's Dairy Methane Reduction Strategy

According to California's Short-Lived Climate Pollutant Strategy, "California's dairy and livestock industries account for more than half of the State's total methane emissions and for about five percent of the State's GHG inventory."[33] On dairies, the strategy attributes 20% of emissions to enteric fermentation and 25% to manure management. California has more dairy cows and more dairy methane emissions than any other state.[34] Crucially, the strategy explains that California "also has higher per-milking cow methane emissions than most of the rest of the United States, due to the widespread use of flush water lagoon systems for collecting and storing manure."

The SLCP Strategy noted several potential mitigation measures, including switching away from flush water lagoon systems and switching to pasture-based dairy management.[35] CARB also convened a sub-working group in 2018, which put forth many recommendations on non-digester interventions. In practice, however, CARB has overwhelmingly focused mitigation efforts on the construction and operation of anaerobic digesters ("biogas control systems") on dairy operations and applies a high baseline emissions standard to California operations. Digesters capture the methane emitted from anaerobic lagoons, resulting in the perpetuation of flush water lagoon systems.

California's Alternative Manure Management Program (AMMP) has sought to support measures to mitigate manure emissions other than digesters. All measures other than digesters have been deemed "alternative manure management strategies," despite the fact that they remain commonplace practices is other parts of the country. From 2015-2021, the California Department of Food and Agriculture awarded $195 million to dairy digester projects through the DDRP program and $68.3 million to AMMP projects.

D. Key Takeaways: Manure Management Systems and GHG Emissions

Generalizing about GHG emissions from manure management can be challenging because emissions vary based on factors including soil type, climate, and the specific GHG, but the following are generally true:

- **The more cows an operation has, the more manure is produced, and the more methane is generated**, all else being equal. Decreasing per-cow emissions will not necessarily lead to overall methane reductions if the industry grows.

- **Anaerobic lagoons generate more methane emissions than shorter-term manure storage or more frequent land application.** This is because the manure is stored for a longer period of time and generates more emissions in liquid form.

- **Liquifying manure using flush systems can decrease ammonia emissions but will increase methane emissions**. Flushing also requires large quantities of water. See CARB's Short-Lived Climate Strategy for a discussion of emissions from California dairy practices.

- **Manure lagoons and liquid manure management systems are standard on industrialized dairies because they operate at a scale that makes regular land application of manure unsafe, requiring long-term manure storage.** The industrialized model of dairying generates too much manure to spread regularly on the land without causing nutrient pollution. As a result, industrial-scale dairies must store

33 Cal. Air Res. Board, Short-Live Climate Pollutant Reduction Strategy (March 2017), https://ww2.arb.ca.gov/sites/default/files/2020-07/final_SLCP_strategy.pdf.
34 *Id*. at 63.
35 *Id*. at 65.

manure for long periods of time, land applying only when cropland is available and the climactic conditions are appropriate. This requires operations to transport manure from barns to manure lagoons where it can be stored.

- **Manure lagoons and liquid manure management systems are far less common on small and mid-sized dairies, which can apply manure to land more frequently.** Smaller operations often have adequate land to spread manure safely at more regular intervals. As a result, they don't have to store manure for long periods of time—one of the major sources of methane emissions. This also gives smaller operations more flexibility and a greater range of options for how they manage manure. Not only do smaller operations generate fewer emissions, but their systems are less rigid than those of industrial operations. They can adapt to new mitigation measures more easily.

- **The industrialized model of dairying was pioneered in California and exported nationally. Industrialized dairies are more common in California than anywhere else in the country.[36] California's incentives for digesters are again promoting an industrialized model of dairying nationwide.** Dairy digesters, and the lucrative LCFS credits that manure biogas can generate, are only feasible on the largest dairies operations. While industrial-scale facilities are the norm in California, this isn't the case in many other dairying states where smaller operations are still more common. Smaller scale dairies aren't suited to digesters precisely because they do not have highly emitting lagoons; however, lucrative LCFS incentives for digesters are available nationwide. At the same time, additional revenue from LCFS credits further bolsters the competitive edge of the largest operations. Creating incentives for dairies to adopt liquid manure management practices with anaerobic lagoons could increase emissions in other states where these polluting systems are less common.

- **California is also promoting alternative manure management practices, but these have been funded at a fraction of the rate of digesters.** What CARB calls "alternative manure management strategies" are not radical departures from dairying practice. The Alternative Manure Management Program (AMMP) defines these practices as essentially anything that's not a digester (those practices "that don't include use of an anaerobic digester, and support management of manure in a dry form.")[37] The broad range of practices that fit within this definition—like solid separation, conversion from flush to scrape in conjunction with some form of drying or composting of collected manure, and pasture-based management—are common nationwide.[38]

- **Even with CARB's aggressive digester push, California is significantly behind on its methane targets** and, according to CARB's analysis, relying on digesters alone to reach the target would cost an additional $3.9 billion. See CARB's 2022 Dairy and Livestock Methane Progress Report here.

36 See, e.g., Dr. John W. Siebert, *A Word from the Bad Guys*, UC Davis (Oct. 1984), http://s3-us-west-2.amazonaws.com/ucldc-nuxeo-ref-media/c709e8dc-9761-4850-bd9d-735f0d1092d9; (UC Davis professor speaks directly to dairy farms outside of California to address the perception that California dairies are "heartless corporate farms"); Rick Barrett and Lee Bergquist, *Industrial Dairy Farming Is Taking Over in Wisconsin, Crowing out Family Operations and Raising Environmental Concerns*, Milwaukee Journal Sentinel (Feb. 11, 2020), https://www.jsonline.com/in-depth/news/special-reports/dairy-crisis/2019/12/06/industrial-dairy-impacts-wisconsin-environment-family-farms/4318671002/ ("...massive milking operations, popularized in California, shatter the traditional model of Wisconsin farms..."); Lili LeGardeur, *Milk It*, Louisiana Life (Jan. 4, 2008), https://www.louisianalife.com/milk-it/ ("90 percent of Louisiana dairy farms are "pasture-based," ... In confinement dairying – a relatively new style popular out West – cows are fenced inside dirt-floor lots and have all their food delivered ... Confinement dairying, by the way, is also called California-style dairying, after the state where it originated.").

37 Cal. Dep't of Food and Ag., Alternative Manure Management Program, https://www.cdfa.ca.gov/oefi/AMMP/.

38 *Id.*

Around the country, in California, and in the Central Valley itself, farmers and community members are reimagining our food systems. California policymakers have a crucial role to play leading the nation in this conversation. California policymakers should be thinking creatively and holistically about what a just transition would look like for California dairies and the policy mechanisms that would be required to support a more sustainable industry.

III. Life Cycle Analysis Assumptions and Applications

The Low Carbon Fuel Standard (LCFS) allows dairies to generate credits for the production of manure biogas-derived transportation fuels. These credits are intended to incentivize the construction and operation of anaerobic digesters on dairy operations.

The LCFS calculates the carbon intensity (CI) of different transportation fuels by analyzing the life-cycle greenhouse gas emissions associated with a given fuel. To conduct these life cycle analyses, the LCFS uses "fuel pathways," which delineate which processes are included in a given fuel's life cycle. The program employs a version of the "GREET" model, which stands for the "The Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation" model.[39] The GREET model was developed by Argonne National Laboratory.

There are several different kinds of pathways in the LCFS program. Lookup table pathways are applied to conventional fuels where the basic values are well-established. Fuel producers can simply look up the CI values for these fuels because they are set by CARB. Tier 1 pathways allow producers of alternative fuels to input operational data into a simplified version of the CA-GREET model to calculate the CI of their fuel. Tier 2 pathways allow alternative fuel producers to use the full CA-GREET model to conduct a custom CI analysis.

Evaluating the completeness and accuracy of LCFS manure biogas life cycle analyses is challenging because almost all participating swine and dairy operations have opted to use the customizable Tier 2 pathway. This means there is not one single life cycle analysis for biogas; instead, most of the several hundred producers that generate credits for the capture of manure methane have conducted their own customized analysis using the CA-GREET model. However, there are several issues apparent in CARB's Tier 1 pathway and considerations regarding the GREET model overall.

Life cycle analyses generally could be critiqued on a number of bases, including the emissions they opt to include, the reference scenario they assume, how emissions are quantified, and whether the model's assumptions are borne out in on-the-ground monitoring. Based on forthcoming research, it is our understanding is that, *when all is working as intended*, CARB's life cycle analysis for manure-derived biofuels generally reflects the actual emissions and reductions from biogas control systems. That is, if we accept the assumptions built into the model, the emissions and reductions counted by the model are generally accurate in practice when biogas systems are functioning as intended. The primary issues with the life cycle analyses for manure-derived biofuels, therefore, are high-level disagreements about the appropriate reference scenario and the life cycle analysis' focus on transportation emissions at the expense of agricultural emissions, as well as more specific monitoring to groundtruth those assumptions and to monitor for fugitive emis-

39 Argonne National Laboratory, *GREET: The Greenhouse Gases, Regulated Emissions, and Energy Use in Technologies Model: The Gold Standard for Life Cycle Analysis of Technologies and Energy Systems* (May 2020), https://www.anl.gov/sites/www/files/2020-10/GREET_Impact_Sheet.pdf.

40 Our research on this topic was informed by a background interview with an environmental scientist who shared their evaluation of monitoring concerns as well information about forthcoming research.

sions, which are a "substantial" concern.[40]

A. Groundtruthing Life Cycle Analysis Estimates and Reported Reductions with Data

One article describes the downside to "bottom-up" emissions analyses like CARB's:

> *Bottom-up inventories, including those used by the US Environmental Protection Agency (US EPA, 2017) and the California Air Resources Board (Charrier, 2016), estimate dairy emission rates at the state level based on the total number of cows and herd demographics and on the average statewide manure management approach, CH_4 emissions factor, and climate. However, livestock emissions, especially from dairies, remain one of the largest uncertainties in these inventories (Maasakkers et al., 2016), as there is no comprehensive information source for the number of cows or manure management strategies*.[41]

California has a lot riding on the reported (on-paper) emissions reductions from dairy digesters. These estimates should be groundtruthed with actual monitoring. On its own terms—that is, if concerns about the assumptions made in CARB's life cycle analysis models are temporarily set aside—forthcoming research based on a single facility suggests that CARB's manure biogas life cycle analyses are accurate when biogas control systems are working as intended. However, biogas control systems may not always work as intended. One environmental scientist our team spoke with cited "substantial" concern about fugitive emissions from digester systems. Fugitive emissions are essentially leaks where the captured methane can escape and be vented to the atmosphere.

CARB itself came to this conclusion in the wake of a methane survey, acknowledging:

> "As expected with any new technology, during the initial operational deployment of [anaerobic digesters (AD)] situations may arise including leaks or higher-than-predicted venting that can impact the desired methane control efficiency. Characterizing potential AD fugitive emissions through the use of tools like the NASA JPL flyovers can help achieve and maintain the expected methane reductions by helping digester operators optimize their systems and reduce revenue loss."[42]

CARB requires an engineering review for biogas pathway applications, but no ongoing monitoring at the facility level, and does not conduct ongoing monitoring at the regional level itself. Monitoring for methane from dairies overall is challenging because the emissions are so dispersed, intermittent, and can depend on variables like soil type and weather. Unfortunately, unlike other air pollutants like ammonia, methane monitoring is not well-suited to community monitoring efforts. Fortunately, California is home to environmental scientists with this expertise. One environmental scientist suggested that a cost-effective approach to monitoring that prioritized measurable and preventable emissions would be third-party monitoring of fugitive emissions from biogas control systems. At a bare minimum, CARB should be collaborating with these scientists to ensure the methane emissions it reports as captured are not leaking out through biogas control system.

41 Alison R. Marklein et al., *Facility-Scale Inventory of Dairy Methane Emissions in California: Implications for Mitigation*, 13 Earth System Sci. Data 3 (March 22, 2021), https://essd.copernicus.org/articles/13/1151/2021/essd-13-1151-2021.html.

42 Cal. Air Res. Board, *Introduction to the Phase I Report of the California Methane Survey from the Staff of the California Air Resources Board* (October 2, 2017), https://ww2.arb.ca.gov/sites/default/files/2020-07/ca_ch4_survey_phase1_report_2017.pdf.

B. High-Level Life Cycle Analysis Concerns: Reference Scenario Assumptions

The purpose of the CA-GREET model is to estimate the CI of transportation fuels. In evaluating the emissions impact of the displacement of conventional fuels by new, alternative fuels, the structure of the analysis is to assume a static baseline or reference scenario. The analysis can then evaluate a specific alternative fuel intervention against that reference scenario, where the new fuel is the only change. In the manure biogas life cycle analyses, therefore, the model assumes a dairying reference scenario upon which the transportation fuel intervention operates. CARB's reference scenario is based on the dominant approach to dairying in California. That is, CARB's life cycle analysis assumes the ongoing presence of industrial-scale confinement dairies with liquid manure management systems. There are two important critiques of this assumption:

- Rather than seek to change the dairying model to one that generates fewer GHG emissions, CARB takes this system as a given and builds on top of it.
- Because LCFS credits are available nationally, but the reference scenario is based on the (more-polluting) California model of dairying, the program could incentivize a harmful shift in practices from out-of-state dairies at the same time it entrenches those practices at home.

The reference scenario is illustrated concretely by the life cycle analysis' assumption that, if not for the addition of an anaerobic digester, manure would be stored in anaerobic lagoons and, if not for the digester, manure methane would be vented directly to the atmosphere. This is not the case on many of the thousands of farms otherwise eligible for LCFS credits nationwide.[43] Rather than devise a mitigation intervention applicable to these farms, CARB simply excludes them from the program if their practices do not match those in the reference scenario. This is unfortunate, because it limits eligibility for the lucrative LCFS credits to operations with the most polluting practices (those that match the reference scenario).[44]

Manure lagoons are used on 58% percent of dairies in California but only 32% percent of dairies nationally.[45] One early GREET study acknowledged that not all dairies use anaerobic lagoons, explaining: "EPA also estimates MCFs of wet (e.g. anaerobic lagoon, liquid slurry and deep pit) and dry (e.g. daily spread and pasture) manure management systems for cool, temperate and warm climate zones... Note that in Wisconsin, solid storage is used for a larger share and anaerobic lagoons for a smaller share of manure than in the United States as a whole, while in California more than 50% of manure is treated by anaerobic lagoon."[46] But given the concentration of this model of dairying in California's Central Valley, CARB has settled on this reference scenario.

In addition to ensuring that LCFS credits are only available to the largest polluters, this reference scenario allows these operations to claim massive emissions reductions since reductions are equivalent to their "captured" or "avoided" emissions.[47]

43 LCFS credits are not limited to California dairies. Operators need only to inject the resulting natural gas into a common carrier pipeline in North America and link the energetic attributes of that biogas with a pipeline withdrawal for natural gas sold in California. The same principle is applied for electricity generated in the combustion of biogas on-site. (Note, however, that the 2023 SRIA for the new LCFS regulation did propose altering the book-and-claim accounting system.)

44 Traditional pasture-based dairies leave manure in pasture where it is deposited by cows. This is possible because manure is produced in quantities below agronomic rates—the available land can adequately and safely absorb the nutrients from the manure. Industrial scale operations collect and store manure for two reasons. First, they generally hold livestock in confinement, so the manure isn't deposited in pasture as a matter of course and needs to be cleaned out of barns. Second, too much manure is produced on industrial-scale facilities for the available land to absorb nutrients without creating serious environmental harms. As a result, manure is collected and stored in "lagoons." To transport manure into lagoons, manure is typically flushed out of barns, liquifying it and creating new emissions in the process. Manure from the lagoons can periodically be spread on land ("land-applied") at or below agronomic rates.

45 Jeongwoo Han, Marianne Mintz, and Michael Wang, *Waste-to-Wheel Analysis of Anaerobic-Digestion-Based Renewable Natural Gas Pathways with the GREET Model ANL/ESD/11-6*.

46 *Id.*

This means that the more emissions they generate, the more they can capture, the more reductions they can claim publicly, and the more revenue they obtain through LCFS credits. Finally, by calculating credits that are issued nationally based on a California-specific reference scenario, the program risks shifting practices in other states towards California's more polluting model of dairying.

C. High-Level Life Cycle Analysis Concerns: Focus on Transportation, Not Agriculture

The goal of the GREET model used by CARB is to estimate life cycle emissions of transportation fuels, not to estimate emissions from agriculture. Transportation fuel life cycle analyses differ markedly from agriculture life cycle analyses.[48] Biofuels like manure biogas straddle agriculture and transportation fuel life cycle analyses, requiring value judgements about where to set system boundaries. Life cycle analyses for biofuels are well-characterized by the paper cited above as follows:

> *Particularly with biofuels, policy-related requirements, modeling assumptions, analysis limitations, and software can have a significant effect on results (Agostini, Giuntoli, Marelli, & Amaducci, 2020; Hoekman & Broch, 2018; Obnamia, Dias, MacLean, & Saville, 2019). As a result, users need to carefully consider the context, usefulness, and applicability of these complex analyses. Many biofuel life cycle accounting policies and studies try to evaluate the changes that biofuel production has on food production systems. To evaluate impacts to production systems, most analyses use some metric to first assess the status quo such as a reference system (Hoekman & Broch, 2018), business-as-usual (BAU) scenario, or baseline, and then quantify changes that biofuel production creates. As a result, most biofuel-related system boundaries (Figure 8) also include quantifications which involve product substitution or displacement (Vadenbo, Hellweg, & Astrup, 2017).*[49]

A paper by Argonne National Laboratory scientists reiterates that, in the case of biofuels, "GHG emissions for RNG pathways are highly dependent on the specifics of the reference case, as well as on the process energy emissions and methane conversion factors assumed for the RNG pathways."[50] The goal of the LCFS biogas life cycle analysis is to compare the status quo with an alternative where anaerobic digesters are used to capture methane and the resulting transportation fuel displaces conventional fuel use.

Concretely:[51] the GREET model's life cycle anal-

47 Cal. Air Res. Board, *Tier 1 Simplified CI Calculator Instruction Manual: Biomethane from Anaerobic Digestion of Dairy and Swine Manure*, https://ww2.arb.ca.gov/sites/default/files/classic/fuels/lcfs/ca-greet/tier1-dsm-im.pdf?_ga=2.140068787.1623257348.1702923028-1380165209.1657241991.

48 Writing on fuel life cycle analyses, scientists from Argonne National Library explained: "A fuel cycle typically includes feedstock recovery and transportation, fuel production, transportation and distribution, and combustion as an end use." Jeongwoo Han, Marianne Mintz, and Michael Wang, *Waste-to-Wheel Analysis of Anaerobic-Digestion-Based Renewable Natural Gas Pathways with the GREET Model ANL/ESD/11-6*. A different paper by Argonne National Laboratory scientists characterized the system boundaries for animal agriculture systems, on the other hand, as follows: "The process considered for animal systems in cradle-to-farm-gate system boundaries normally include feed production, animal husbandry, manure storage and farm management. Farm-gate-to-grave systems include processes such as transportation of product from farm to processing plants, manufacturing of packing materials such as bottles for milk and cartons for eggs, and distribution to retailers and consumers." Heidi Sieverding et al., *A Life Cycle Analysis (LCA) Primer for the Agricultural Community*, 112 Agronomy J. 5, 3788 (May 6, 2020), https://acsess.onlinelibrary.wiley.com/doi/pdfdirect/10.1002/agj2.20279.

49 *Id.*

50 *Id.*

51 The LCFS calculator for Tier 1 pathway for biogas from swine and dairy manure requires applicants to "add facility information and verifiable monthly feedstock, operational energy use, fuel production and co-product data, and transport distances used in calculating the CI of biomethane from dairy and swine manure digesters." Cal. Air Res. Board, *Tier 1 Simplified CI Calculator Instruction Manual Biomethane from Anaerobic Digestion of Dairy and Swine Manure* (June 20, 2023), https://ww2.arb.ca.gov/sites/default/files/classic/fuels/lcfs/ca-greet/t1_biomethane_DSM_instruction_manual_v0620023.pdf. The Tier 1 calculator quantifies baseline emissions (of anaerobic lagoons and non-anaerobic storage) as well as emissions associated with the biogas control systems themselves (like emissions from venting events and emissions from effluent ponds), and other emissions not related to the biogas control system itself. The calculator then quantifies avoided methane by comparing baseline methane emissions to project methane emissions. Note that new models for the life cycle analysis are expected to be published for public comment on Tuesday, December 19, 2023. The Tier 2 pathway for manure biogas is simply a customized version of the full CA-GREET 3.0 model. As such, it requires far more input from the producer than the simplified Tier 1 pathway. Additionally, users can choose either a United States or IPCC reference scenario. If they choose a United States reference scenario, they can further specify a reference scenario by state.

ysis for manure biogas begins at manure storage in the lagoon. Beginning the life cycle analysis with manure storage leaves out all emissions that occur before storage: emissions from feed production, general dairy operations, enteric fermentation, and the collection and transportation of manure to lagoons. The justification for starting the life cycle analysis with manure storage in the lagoon is that the manure will be stored in lagoons regardless of the addition of an anaerobic digester incentivized by LCFS credits.[52] That is, CARB assumes a reference scenario based on liquid manure management systems with anaerobic lagoons, as discussed *supra*. Upstream emissions should be considered if CARB seeks to understand the impact of the LCFS on agricultural emissions. Excluding these emissions is justifiable to the extent that CARB limits use of the life cycle analysis to claims about transportation fuel reductions.

At the other end, the life cycle analysis model is bounded by the end-use of the energy generated, either the combustion of RNG as transportation fuel or as electricity. The life cycle analysis also excludes emissions from the storage and disposal of digestate,[53] the by-product of anaerobic digestion. The exclusion of digestate is justifiable if CARB also excludes emissions from manure land application in the reference scenario. An environmental scientist consulted for this research explained that forthcoming research at a single dairy found that emissions from land application and from digestate application are likely comparable. The scientist also stressed that a generalized comparative analysis of manure application versus digestate application would be extremely challenging to implement because emissions are dispersed and vary based on soil conditions, climate, and the specific pollutant studies.[54]

Focusing life cycle analyses on transportation fuels is an intentional and understandable choice by CARB given the intended function of the LCFS. CARB is required to "[c]onsider the significance of the contribution of each source or category of sources to statewide emissions of greenhouse gases."[55] Transportation is the largest source of greenhouse gas emissions in California at 38%.[56] Agriculture is responsible for 9% of emissions in California.[57] Because CARB focuses on transportation fuel life cycle emissions (and, by extension, assumes the existing system of dairying), the Board's decision not to include upstream emissions from dairy operations is justifiable. No life cycle analysis can include all processes and all systems. The exclusion of upstream emissions, however, remains justifiable *only so long as* CARB's focus remains fixed on transportation emissions. CARB should not claim reductions from dairying overall without having analyzed emissions upstream of manure storage.

However, CARB makes a great deal of the avoided methane from agriculture, in addition to the displacement of conventional transportation fuels. This is a key reason that LCFS credit values are so high. CARB also frequently touts emissions reductions from the dairy sector on the basis of

52 Jeongwoo Han, Marianne Mintz, and Michael Wang, *Waste-to-Wheel Analysis of Anaerobic-Digestion-Based Renewable Natural Gas Pathways with the GREET Model ANL/ESD/11-6* (waste is collected in both the reference case (current manure management) and the "new" AD cases.").

53 Anaerobic digester residue is eventually land-applied and still generates emissions, as one GREET study acknowledged. *Id.* That study explained that "62% of the C in the residue is assumed to become CO 2 , and the rest (38%) is assumed to remain stored in the soil." *Id.* That study further asserted that the impacts of anaerobic digester residue land application, "that is, synthetic fertilizer displacement and N2 O and NOx emissions—should be included in LCAs of AD pathways." *Id.* The solid digestate "may be recycled for animal bedding or as a soil amendment, but this is not considered in our analysis." Heidi Sieverding et al., *A Life Cycle Analysis (LCA) Primer for the Agricultural Community*, *supra* note 48.

54 Indeed, existing literature shows variation in emissions based on a number of factors including different methods of digestate storage and processing. Holly et al., for example, found that storage of digestate with limited oxygen increased nitrous oxide emissions. Holly et al., *Greenhouse Gas and Ammonia Emissions from Digested and Separated Dairy Manure During Storage and After Land Application*, 239 Ag., Ecosystems, and Env't 410 (Feb. 15, 2017), https://www.sciencedirect.com/science/article/pii/S0167880917300701. That study also concluded that "[nitrous oxide] from digester separated solids was much higher than the separated solids without digestion." *Id.*

55 Cal. Health & Safety Code § 38562.

56 Cal. Air Res. Board, Current California GHG Emission Inventory Data, https://ww2.arb.ca.gov/ghg-inventory-data.

57 *Id.*

the LCFS analysis. While the LCFS can estimate a total quantity of emissions captured by anaerobic digesters, the narrow transportation focus of the LCFS has allowed the agency to ignore the fact that this invention locks in the most highly emitting form of dairying, precluding broader reductions.

The dairy sector is responsible for more than half of California's methane emissions.[58] Making claims about reductions from the dairy sector requires a full analysis of dairy emissions. Yet in CARB's *Analysis of Progress Towards Achieving the 2030 Dairy and Livestock Sector Methane Emissions Targets*, the agency begins with primacy of digesters, rather than with a holistic analysis of dairy emissions.[59] CARB's narrative of its process reflects this, stating: "To understand what level of resources are needed to achieve the target, CARB staff looked at existing dairy methane emissions reduction efforts, including both grant programs that fund the initial capital costs and market-based programs that incentivize GHG emissions reductions or low carbon fuel production."[60] But existing emissions reduction efforts have been defined through the transportation lens of the LCFS, which assumes the perpetuation of California's most highly-emitting dairying model. This assumption should not be the starting point for CARB's dairy mitigation strategy.

There is a second broader critique of the limitations of a baseline scenario based on the status quo at a time when we need to decarbonize all sectors simultaneously. The choice is less between the status quo and anaerobic digesters but between anaerobic digesters and a host of other policy choices. Because the dairy digester intervention only evaluates how transportation emissions will change as a result, it risks locking in or increasing dairying emissions at a time when they, too, need to decline.

While relying on a static reference scenario is necessary in any single analysis to draw a meaningful comparison between two alternatives, we are in a time of major transition: We need to decarbonize all sectors—including agriculture—simultaneously, using multiple different tactics. This presents conceptual difficulties for a binary life cycle analysis comparing a static baseline and one potential intervention. The LCFS relies on a static reference scenario of "Current Manure Management" to find that this intervention is better, but it's an intervention that increases the value of manure while other interventions could decrease the value of the manure. The manure biogas life cycle analysis' reliance on a static baseline freezes the reference scenario, both in theory and practice, first by assuming its existence into the future and second by investing in transportation fuel reductions that rely on that status quo.

D. Key Takeways: Life Cycle Analysis Assumptions and Applications

- **We need to decarbonize all sectors—including both agriculture and transportation—simultaneously**. California policymakers should work to ensure that interventions in one sector are not locking in or increasing emissions elsewhere.

- **Because the LCFS focuses on transportation sector emissions, the fact that the dairy digester intervention locks in emissions-intensive practices in the dairy sector has been given little attention.** CARB's life cycle analysis for biogas-derived fuels assumes the ongoing presence of industrial-scale confinement dairies with liquid manure management systems, locking these systems in both in theory and practice. Because the life cycle

58 Cal. Air Res. Board, Analysis of Progress Toward Achieving the 2030 Dairy and Livestock Sector Methane Emissions Target (March 2022), https://ww2.arb.ca.gov/sites/default/files/2022-03/final-dairy-livestock-SB1383-analysis.pdf.

59 *Id.*

60 *Id.*

analysis uses this dairying model as its baseline scenario, only dairies that use this model are eligible for lucrative LCFS credits.

- **The LCFS rewards captured (or "avoided") methane. This means that the more emissions dairy operations generate, the more they can capture, the more reductions they can claim publicly, and the more revenue they obtain through LCFS credits.**

- **The life cycle analysis used for transportation fuels is not an appropriate analysis to apply when analyzing overall dairy emissions, because it excludes the bulk of emissions from dairy operations.** The LCFS life cycle analysis was designed to measure the change in transportation sector emissions; it should not be used as the starting point for CARB's broader dairy mitigation strategy.

- **Dairy emissions and leaks from biogas systems are not actively monitored to groundtruth the LCFS' bottom-up estimates for captured methane despite concerns about fugitive emissions.**

IV. Consolidation and LCFS Credits

Dairy industry stakeholders argue[61] that the trend towards consolidation in dairy predates and is independent of the adoption of digester technology and Low Carbon Fuel Standard (LCFS) incentives. This is correct. Consolidation in the dairy industry is a consistent, long-term trend that far predates the LCFS and the embrace of dairy digesters. This fact does not preclude the possibility that LCFS incentives for digesters contribute to that trend in a meaningful way. This section describes the history, geography, and major drivers of consolidation in the American dairy industry. We cannot draw clear conclusions about the impact of the LCFS yet—the data needed to evaluate its effects will be released later in 2024 in the 2022 USDA Agriculture Census. Understanding the drivers of consolidation and pressures on dairy operations still provides essential context for understanding the stakes of incentivizing dairy digesters over other potential interventions.

Among other impacts, dairy consolidation has resulted in the loss of thousands of small and mid-sized farms, contributed to the decline of rural economies and communities, and increased environmental and environmental justice concerns by densely concentrating operations in a few parts of the country. Consolidation matters in the context of the LCFS and the dairy digester push for several reasons:

- First, consolidation of the dairy industry set the stage for the dairy digester push. The consolidation trend has resulted in the dominance of ever-larger, industrial-scale operations over the smaller-scale dairies that were dominant as recently as the 1980s. These factory farms rely on manure lagoons to store the manure they generate, which generates methane emissions for the duration of storage.

- Second, the credits provided by the LCFS may impact the consolidation trend, by encouraging the growth of already-large operations or encouraging operations to merge in order to take advantage of the lucrative credits available for operations that can manage a biogas control system.

- Third, even if the LCFS does not directly incentivize operations to grow or merge, it provides an additional revenue stream for the large-scale operations where digesters are an appropriate intervention. This impact would

61 Ermias Kebreab, Frank Mitloenher, and Daniel A. Sumner, *Meeting the Call: How California is Pioneering a Pathway to Significant Dairy Sector Methane Reduction*, UCDavis CLEAR Center (December 2022), https://clear.ucdavis.edu/sites/g/files/dgvnsk7876/files/inline-files/Meeting-the-Call-California-Pathway-to-Methane-Reduction_0.pdf.

not necessarily be limited to California, as LCFS credits are available to dairies nationwide.

A. Dairy consolidation is a long-term trend.

The trend towards consolidation in dairy is unmistakable and far predates the adoption of the LCFS (adopted in 2009).[62] The trend is clear both nationally and in California. A 2020 USDA report using data from the most recent USDA Agricultural Census (2017) found that since at least the late 1980s, the average dairy herd size has risen consistently, and the number of dairy operations has decreased consistently.[63] The decline in dairies and increase in herd sizes reflects the loss of small and mid-sized farms as production has shifted toward much larger farms.[64] Not only have larger dairies proliferated during this period, but frontier of what is considered "large" has progressively increased.[65]

1. Dairy consolidation coincided with a decline of small farms in the Midwest and the East and growth in industrial-scale operations in the West.

The dairy industry has trended towards consolidation nationally, but the geography of consolidation has varied. The Midwest and the Northeast have "long had many small commercial dairy farms, while production in the major Western Dairy States has revolved around large farms."[66] As the industry has consolidated, the decline of small commercial dairy farms has been "concentrated in the Midwest and the Northeast and in four states in particular: Minnesota, New York, Pennsylvania, and Wisconsin."[67] Alongside the decline in Midwestern and Northeastern small commercial dairies, "[p]roduction has shifted to Western States and is concentrated in a smaller number of counties."[68] That is to say: the decline of small farms in the Midwest and the Northeast (as well as California's dwindling pasture-based operations in Marin and Sonoma Counties)[69] have fueled the growth of the industrial-scale dairies that populate California's Central Valley and other western states.

62 Cal. Air Res. Bd., *Session 9: Overview of Low Carbon Fuel Standard & Dairy/Swine Manure Fuel Pathways* (March 29, 2022), https://ww2.arb.ca.gov/sites/default/files/2022-04/dairy-ws-session-9-CARB.pdf.

63 Commercial dairies declined at an annual average rate of 4.2 percent from 1978 through 2017.The median herd size increased dramatically over this period as well. The report found that the midpoint herd size has risen consistently from 80 or more cows in 1987 to 1,300 cows in 2017. James M. MacDonald, Jonathan Law, and Roberto Mosheim, *Consolidation in U.S. Dairy Farming*, ERR-274 (July 2020), https://www.ers.usda.gov/webdocs/publications/98901/err-274.pdf (this number is for dairies with over 10 cows which closely correlates to dairies that sell milk.)

64 *Id.* at Report Summary. The small commercial farms of 10-99 cows that were typical in 1992 have seen "large and persistent declines." *Id.* at 10. These operations have decreased by "over 80 percent in 1992–2017 for farms with 10–49 cows and over 70 percent for those with 50–99 cows." *Id.* at 10. In 2017 they made up only 12.6 percent of U.S. dairies. *Id.* at 10. Large dairies, on the other hand, make up a larger share of the industry than ever before. The USDA report found that, "In 1992, the census counted 564 farms with at least 1,000 cows, and those farms accounted for less than 10 percent of all cows. Twenty-five years later, nearly 2,000 farms had herds of that size, and they accounted for 55 percent of U.S. inventory." *Id.* at 11.

65 However, the total number of farms with at least 2,000 cows doubled between the 1997 and 2002 censuses, and then nearly doubled again between the 2002 and 2012 censuses, with continuing increases since. The frontier—the size of a dairy farm that we would call "large"—keeps expanding." *Id.*

66 *Id.*

67 *Id.*

68 *Id.*

69 Greig Tor Guthey, Lauren Gwin, and Sally Fairfax, *Creative Preservation in California's Dairy Industry,* 93 Geo. R. 2 (April 2003), 171, https://www.jstor.org/stable/30033905.

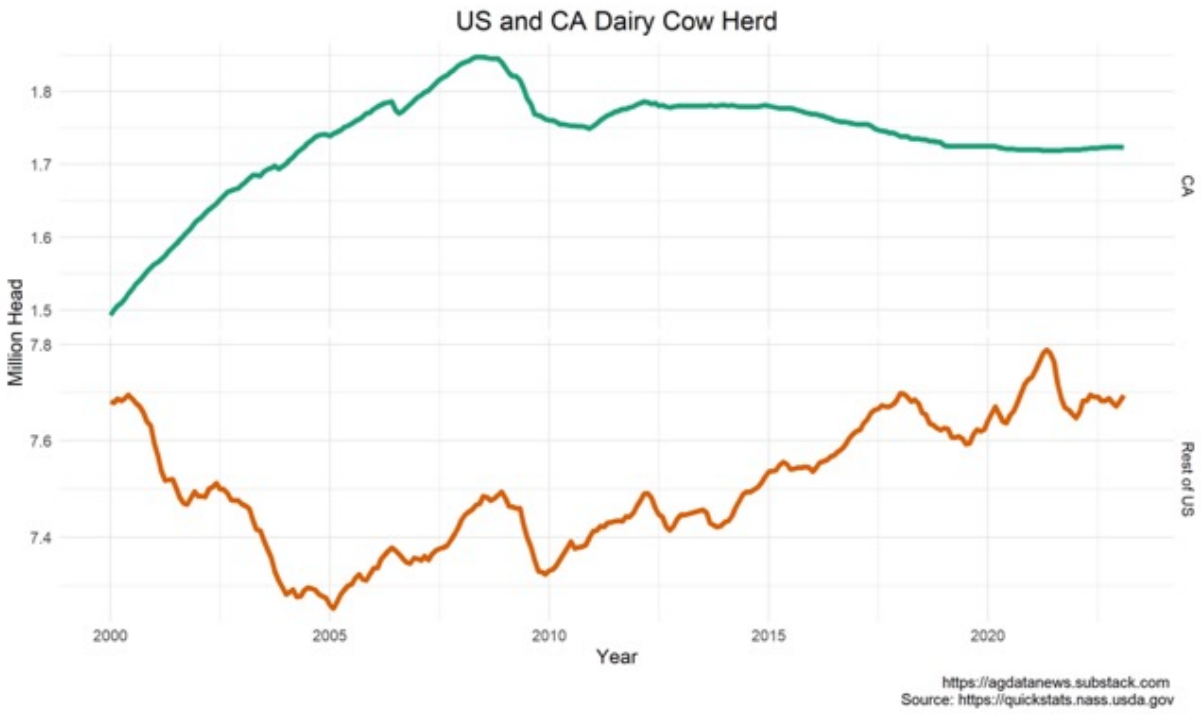


FIGURE 4 Via Aaron David Smith, Are Manure Subsidies Causing Farmers to Milk More Cows? (April 7, 2023), available at https://asmith.ucdavis.edu/news/are-digesters

The California dairy industry began consolidating before other major dairying states like Wisconsin and New York, generating pressure for other states to consolidate in order to compete with California's new mega-dairies. California surpassed Wisconsin as the top producer of milk nationally in 1993 and has held that position ever since.[70]

California led the way nationally in consolidating and industrializing the industry[71] for several reasons. The University of California provided essential research (as respective land grant universities did in other states); the intense urbanization pressures around Los Angeles County resulted in several cycles of "urban encroachment, farm relocation, and herd expansion" throughout the mid-century; and California's unique geography "created ideal conditions for growth, despite several setbacks related to land prices, water availability, and the relatively late start for the industry."[72]

The industrialization of California dairies was facilitated by University of California research into "breeding and genetic experimentation to increase the productivity of cows and milkfat content of the milk and the development of dairy-farm building plans that were structurally appropriate

70 Sophie Barrowman, *Transformations in California's Dairy Industry: Mapping Regional Variations in Milk Production and Operations,* Master of Arts Thesis, University of Cal. Davis Geo. Dep't, https://escholarship.org/uc/item/4tx1m87s (citing Sumner 2020).

71 In California, dairies are concentrated in the San Joaquin Valley, in particular in Tulare and Merced counties. The dairies in this region are "almost all confinement-style dairies." There are also some remaining dairies in western San Bernadino and Riverside Counties, but these areas have seen significant decline due to urbanization. North of San Francisco, in Marin, Sonoma, and Humboldt Counties, there is a small cohort of smaller-scale pasture-based and organic dairies. Daniel A. Sumner, California Agriculture: Dimensions and Issues, Chapter 6: California Dairy: Resilience in a Challenging Environment, 143, https://s.giannini.ucop.edu/uploads/pub/2021/01/21/chapter_6_dairy_2020.pdf.

72 Sophie Barrowman, *Transformations in California's Dairy Industry: Mapping Regional Variations in Milk Production and Operations,* Master of Arts Thesis, University of Cal. Davis Geo. Dep't, (citing Butler andWolf 2000). *See also* James Sterngold, *Urban Sprawl Benefits Dairies in California*, New York Times (Oct. 22, 1999), https://www.nytimes.com/1999/10/22/us/urban-sprawl-benefits-dairies-in-california.html. Other contributing factors included: "the geographic isolation of the state requiring sufficient in-state processing facilities; the large and diverse population creating demand and labor for the industry; and the early adoption, or rather invention, of dairy science technology." *Id.*

for California's warmer climate."[73] The combination of advances in breeding, the pressures of urbanization, and the introduction of drylot feeding by Dutch immigrants pushed industrialization forward, beginning with Los Angeles County.[74] While urban encroachment in the broader Los Angeles area pushed farms out of the region, farmers were often able to sell land at high prices to developers giving them the capital needed to build out newer, larger facilities, often in the Central Valley.

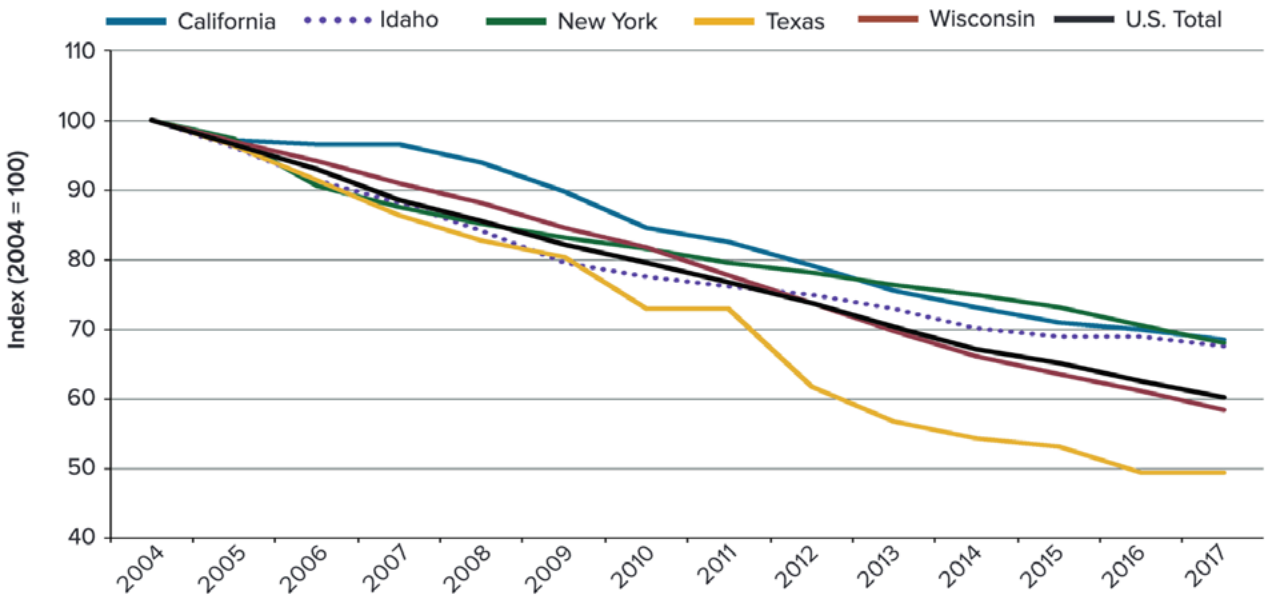
Drylot feeding (also known as zero-grazing) is the "practice of concentrating cows into a small acreage and bringing their food to them." This practice was "revolutionary" for the dairy industry in California.[75] It was well-suited to California and particularly to the Central Valley, because "the abundance of local agricultural by-products like sugar beets and citrus and the availability of cheap hay made drylot feeding affordable, actually increasing milk production per cow compared to grazing."[76] The abundance of agricultural by-products remains a major benefit to California's dairy industry today.

California's climate also contributed to the unprecedented growth of the state's dairy industry. A UC Davis marketing memo from 1984 aimed at changing eastern and midwestern dairies' perception of California dairies as "heartless corporate farms," explained that the climate also facilitated regular expansion: "Due to the ideal climate, cows do not need the elaborate shelter that is required in other parts of the U.S. That means that when times are good, California dairy farmers add cows. In contrast, dairy farmers in other areas of the U.S. must add facilities before they can add cows."[77] Traditional dairying states like New York and Wisconsin experience weather variation throughout the year that requires modifying their practices, including but not limited to housing.

The California dairy industry only benefitted from the loss of small farms in the Midwest and East, however, until other states, particularly other western states, adopted the scale and industry structure that had given California dairies a competitive edge. In 2004, California dairies had the largest herd size in the country. Since then (through 2017, at least, the most recent year for which we have consistent USDA data) other major dairying states have increased herd sizes dramatically to compete, or as Sumner asserts simply: "dairy industries in other states have become more like those in California."[78]

73 *Id.* citing Hutchison 1946.
74 *Id.* citing Gilbert and Wehr 2003.
75 *Id.* citing Gilbert and Wehr 2003.
76 *Id.*
77 Dr. John W. Siebert, *A Word from the Bad Guys*, UC Davis (Oct. 1984), http://s3-us-west-2.amazonaws.com/ucldc-nuxeo-ref-media/c709e8dc-9761-4850-bd9d-735f0d1092d9.
78 Daniel A. Sumner, California Agriculture: Dimensions and Issues, Chapter 6: California Dairy: Resilience in a Challenging Environment, 143, https://s.giannini.ucop.edu/uploads/pub/2021/01/21/chapter_6_dairy_2020.pdf.

Figure 6.4. Index of Number of Dairy Farms in California and Major Dairy States, 2004–2017



Source: USDA/NASS Quickstats. Available at: https://www.nass.usda.gov/Quick_Stats/

FIGURE 5 Via Daniel Sumner, California Agriculture: Dimensions and Issues (data sourced from USDA/NASS Quickstats), https://s.giannini.ucop.edu/uploads/pub/2021/01/21/chapter_6_dairy_2020.pdf.

2. *Drivers of consolidation include declining domestic demand, dismantling of supply management policies, trade policies that promote exports, and economies of scale.*

Major drivers of consolidation include declining domestic demand, changes to federal programs and subsidies, and economies of scale. Analyses of consolidation often point vaguely to "economic forces,"[79] but these economic forces have been constructed by policy choices. A Food and Power piece characterizes the problem like this:

> *Dairy farmers, particularly in the U.S. and Europe, are stuck in a cycle of consolidation and overproduction. Fewer, more powerful buyers, paired with declining domestic demand and dismantled supply management policies, have pushed the prices paid to farmers below their cost of production. In response, farmers seek to lower their costs per gallon and survive on high volumes. But as more farms seek a larger scale, milk production continues to increase, perpetuating oversupply, low milk prices, and a reliance on export markets.*[80]

The 2020 USDA report described "powerful cost incentives behind farm consolidation." Due to economies of scale, "larger farms are more likely to realize positive net financial returns to milk production..."[81] But economies of scale apply to most agricultural operations and the pace

79 See *e.g.* Ermias Kebreab, Frank Mitloenher, and Daniel A. Sumner, *Meeting the Call: How California is Pioneering a Pathway to Significant Dairy Sector Methane Reduction*, UCDavis CLEAR Center (December 2022), https://clear.ucdavis.edu/sites/g/files/dgvnsk7876/files/inline-files/Meeting-the-Call-California-Pathway-to-Methane-Reduction_0.pdf.

80 Claire Kelloway, *Fewer Global Dairy Corporations Drive Overproduction and Pollution, Harming Small Farmers, Report Finds* (June 18, 2020), Food & Power, https://www.foodandpower.net/latest/2020/06/18/fewer-global-dairy-corporations-drive-overproduction-and-pollution-harming-small-farmers-report-finds?rq=dairy.

81 For more on economies of scale, *see* James Macdonald, *Scale Economies Provide Advantages to Large Dairy Farms* (August 3, 2020), U.S.D.A. Econ. Res. Service, https://www.ers.usda.gov/amber-waves/2020/august/scale-economies-provide-advantages-to-large-dairy-farms/.

of dairy consolidation "far exceeds the pace of consolidation seen in most of U.S. agriculture."[82]

One of the major developments that exacerbated the trend towards consolidation was the embrace of export markets in the early 2000s. Historically,[83] the American dairy industry was focused on the domestic market.[84] Around the turn of the 21st century this began to change. A 2016 USDA report on the dairy export[85] market explains: "From 2004 to 2014, the value of U.S. dairy product exports more than quadrupled."[86] This was a "significant change for an industry previously focused primarily on domestic rather than international demand."[87]

According to the 2016 USDA report, exports increased due to increasing incomes in developing countries ("demand"), free trade agreements opening up new markets (the North American Free Trade Agreement in particular), market-based reforms in China, and finally, a reduction of "domestic support and export subsidies for dairy products in recent years, bringing about greater openness of world markets."[88]

At the domestic level, major changes came to longstanding price supports for dairy, which had long set floors on dairy prices. According to the 2016 USDA report: "The Milk Price Support Program (MPSP) was established by the Agricultural Act of 1949 and was amended several times over the years. Through the program, the Federal Government purchased dairy products in order to support milk prices at specified levels."[89] The purpose of the program (ultimately repealed in the 2014 Farm Act) was to correct for an oversupply of dairy that made it impossible for dairy farmers to adequately support themselves.

Removing the price supports that made smaller-scale dairying possible was necessary to embrace export markets but created incentives for consolidation. Today, American dairies "must compete aggressively for a share of consumer food budgets and for resources and investment capital," not just in the United States but globally.[90] The growth of the export market and broader globalization of the dairy industry has also "tended to emphasize the strength of multinational dairy firms."[91] At the level of the individual dairy operation, industrial-scale facilities are better able to operate in this landscape and contend with the greater and demand price volatility.

At the international level, the Uruguay Round of the General Agreement on Tariffs and Trade concluded in 1994 "with an agreement that fundamentally changed the treatment of national agricultural policies under the multilateral rules of global trade."[92] The Uruguay Round Agreement on Agriculture[93] brought national agricultural policies under the purview of the newly formed World Trade Organization, such that "trade-distorting policies" could be disciplined or constrained.[94]

82 *Id.*

83 Protectionism in agriculture has often been framed as a national security concern (or more recently as food sovereignty). These concerns remain very live today. See, e.g. Dr. Krista Versteeg, *It's Time to Talk about Food and Agricultural Security* (March 21, 2023), U.S. Dep't Homeland Sec. Science and Tech., https://www.dhs.gov/science-and-technology/news/2023/03/21/its-time-talk-about-food-and-agriculture-security.

84 Jess Cessna, Lindsay Kuberka, Christopher G. Davis, and Roger Hoskin, *Growth of U.S. Dairy Exports*, U.S.D.A. Econ. Res. Service (November 2016), https://www.govinfo.gov/content/pkg/GOVPUB-A93-PURL-gpo75564/pdf/GOVPUB-A93-PURL-gpo75564.pdf.

85 Note that dairy exports are typically dry milk or milk powder, which is "traded internationally at higher volumes than liquid milk products, since liquid products are bulky and often perishable, making them costly to ship and store." Powdered milks are often reconstituted in low-income countries, but are also common products in other dairy products and can be used as animal feed. Other dairy products traded internationally include cheese, infant formula, butter or butterfat products, whey products, casein products, and lactose. *Id.*

86 *Id.*

87 *Id.*

88 *Id.*

89 *Id.* at 21.

90 Donald Blayney and Mark Gehlhar, *U.S. Dairy at a New Crossroads in a Global Setting*, U.S.D.A. Econ. Res. Service, https://www.ers.usda.gov/amber-waves/2005/november/u-s-dairy-at-a-new-crossroads-in-a-global-setting/.

91 *Id.*

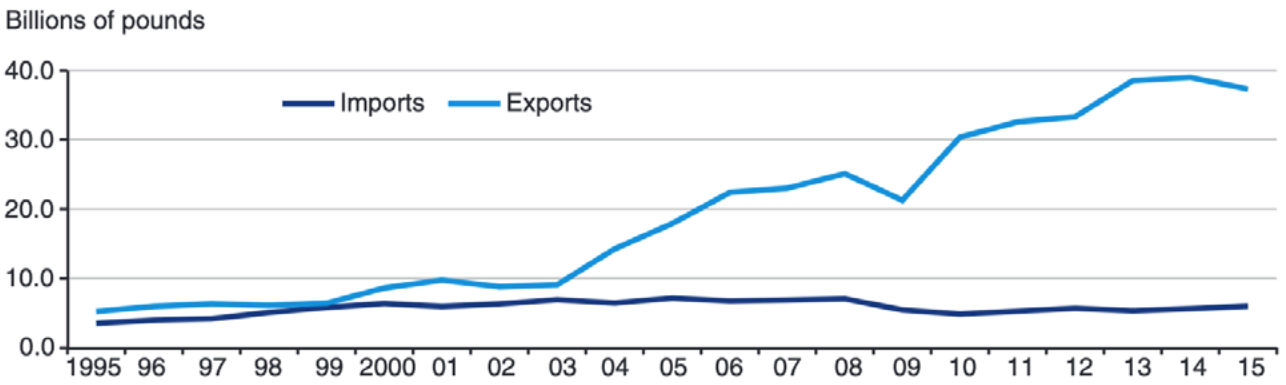
92 *Id.* quoting Burfisher, 2001. *See also* Don P. Balyney, Terry L. Crawford, and Christopher G. Davis, *Dairy Export Markets: Changing the Structure of US Dairy Demand*, 19 Int'l Food and Agribus. Mgmt Rev. B (2016), https://www.ifama.org/resources/Documents/v19ib/1220150087.pdf.

93 Agriculture became the most important issue in the failed Doha Round.

94 Donald Blayney and Mark Gehlhar, *U.S. Dairy at a New Crossroads in a Global Setting*.

Figure 11

U.S. imports and commercial exports of milk in all products on a skim-solids milk-equivalent basis



Sources: USDA/National Agricultural Statistics Service, USDA/Farm Service Agency, USDA/Foreign Agriculture Service, U.S. Department of Commerce Bureau of the Census, California Department of Food and Agriculture, USDA/Economic Research Service calculations. Numerous sources were used for conversion factors. See the workbook "Trade data conversion factors and sources" at http://www.ers.usda.gov/data-products/dairy-data.aspx.

FIGURE 6 Via Jess Cessna, Lindsay Kuberka, Christopher G. Davis, and Roger Hoskin, Growth of U.S. Dairy Exports, U.S.D.A. ECON. RES. SERVICE, supra note 84.

Implementation was phased in over a 6-year period that concluded in 2000 – 2001, just as U.S. dairy exports began dramatically increasing.

The growth of the U.S. dairy export market has not only accelerated consolidation but resulted in "greater variability in demand and prices."[95] California's dairy industry exports "about a third of all U.S. dairy exports, about twice its share of national production," making it particularly susceptible to the pressures of the global market, as will be discussed in more detail in the leakage section.[96]

B. Data that can be used to analyze the impact of the LCFS will become available in 2024.

The USDA consolidation report uses the most recent agriculture census data from 2017, but the LCFS adopted the inclusion of fuels from dairy and swine manure in 2017.[97] The use of fuels from dairy and swine manure in California appears to have taken off in earnest in 2018,[98] and therefore the impacts on the industry as a whole are not likely to be observable in the 2017 agriculture census data. (UC Davis agro-economist Aaron David Smith notes, "Data from the 2022 census will enable us to see whether the number of cattle on large farms has increased during the digester boom, but it will not be released until next year.")[99] USDA recently announced that the 2022 Agriculture Census will be released on February 13, 2024.[100]

95 *Id.*

96 Daniel A. Sumner, California Agriculture: Dimensions and Issues, Chapter 6: California Dairy: Resilience in a Challenging Environment, 143, https://s.giannini.ucop.edu/uploads/pub/2021/01/21/chapter_6_dairy_2020.pdf.

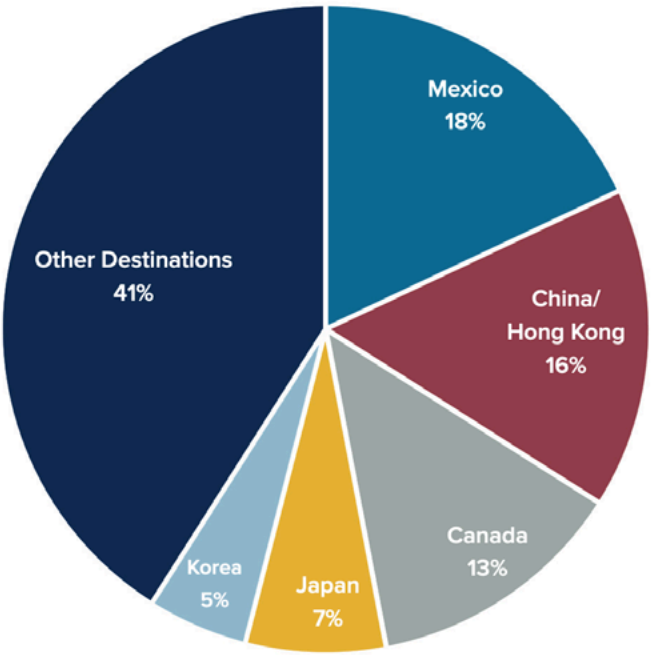
97 Cal. Air Res. Bd., *Session 9: Overview of Low Carbon Fuel Standard & Dairy/Swine Manure Fuel Pathways* (March 29, 2022), https://ww2.arb.ca.gov/sites/default/files/2022-04/dairy-ws-session-9-CARB.pdf but it says specifically a simplified calculator was adopted in 2019 and we know most applications are tier 2 anyway. The presentation says there were already 67 applied DSM pathways by Jan 1 2019. Table on slide 7 suggests credits first generated for dairy biomethane in 2017.

98 Cal. Air Res. Bd., *Session 9: Overview of Low Carbon Fuel Standard & Dairy/Swine Manure Fuel Pathways*.

99 Aaron David Smith, *Are Manure Subsidies Causing Farmers to Milk More Cows?* Ag Data News (April 7, 2023), https://asmith.ucdavis.edu/news/are-digesters.

100 U.S. Dep't of Ag., Agriculture Census, https://www.nass.usda.gov/AgCensus/.

Figure 6.10. California Dairy Product Destinations, Share of 2018 Exports



Source: University of California Agricultural Issues Center

FIGURE 7 Via Daniel A. Sumner, CALIFORNIA AGRICULTURE: DIMENSIONS AND ISSUES, Chapter 6: California Dairy: Resilience in a Challenging Environment, 143, https://s.giannini.ucop.edu/uploads/pub/2021/01/21/chapter_6_dairy_2020.pdf.

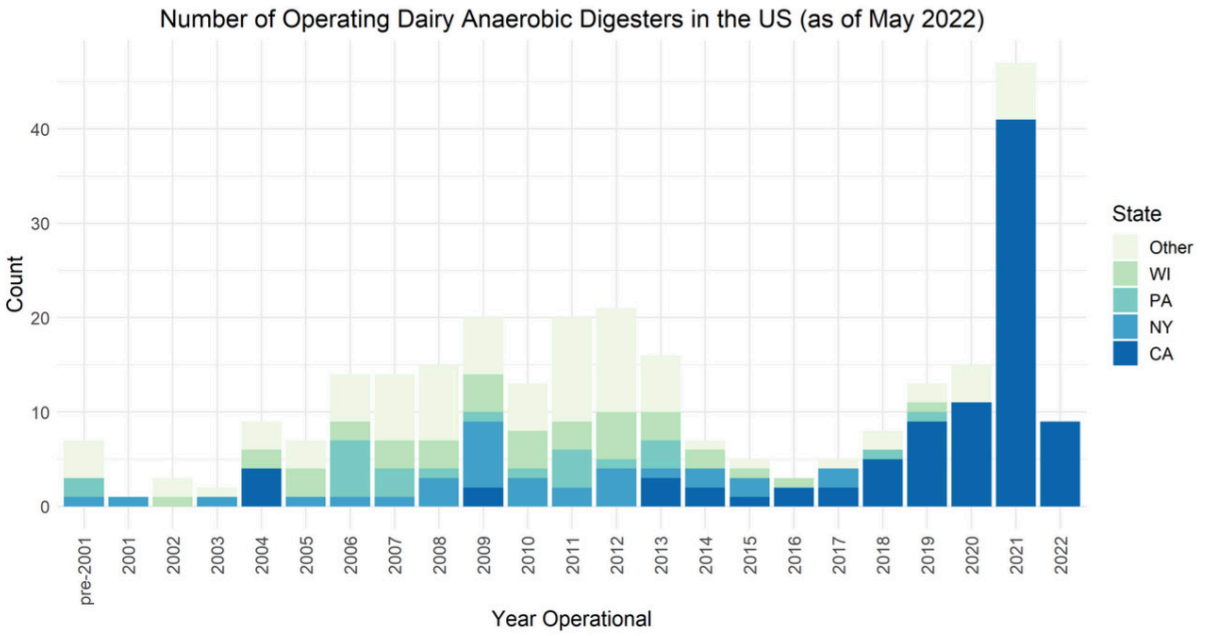


FIGURE 8 Via Aaron David Smith, Are Manure Subsidies Causing Farmers to Milk More Cows? (April 7, 2023), Ag Data News https://asmith.ucdavis.edu/news/are-digesters.

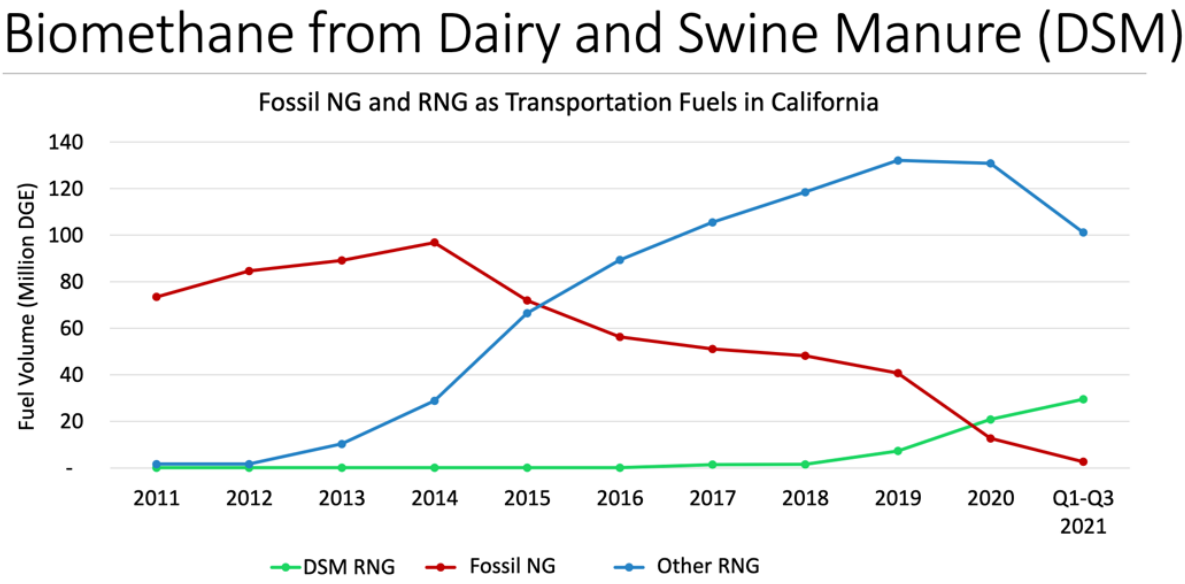


FIGURE 9 Via Cal. Air Res. Bd., Session 9: Overview of Low Carbon Fuel Standard & Dairy/Swine Manure Fuel Pathways (March 29, 2022), https://ww2.arb.ca.gov/sites/default/files/2022-04/dairy-ws-session-9-CARB.pdf.

C. Key Takeaways: Consolidation and LCFS Credits

- **The data required to analyze the impact of the LCFS on dairy consolidation will not be available until February 13, 2024.** The most recent Agriculture Census year is 2017, which is too early to show the effects of LCFS credits on California dairy. Any impact from the LCFS would likely be small, but dairy operations operate on slim margins so even a small shift in incentives could accelerate the pre-existing trend.

- **Dairy consolidation is a long-term trend driven by policy choices.** Small and mid-sized dairies in the Midwest and the East declined dramatically over past decades, as mega-dairies concentrated in the West, and particularly in California, have ballooned. There are many causes of consolidation including the dismantling of supply side management programs and the opening of export markets, which multiplied economies of scale.

- **There is a symbiotic relationship between industrialization, consolidation, and the push for dairy digesters.** Consolidation has resulted in fewer, ever-larger dairy operations. The larger operations become, the more manure they must manage and the more likely they are to rely on a manure lagoon. Dairy consolidation has set the stage for the digester push as the California dairy industry has become dominated by industrial-scale operations with manure lagoons.

- **Investing in industrial dairies further bolsters the competitive edge of these mega-operations at the expense of more sustainable dairying models and burdens environmental justice communities.** Smaller-scale dairies and pasture-based dairies have been fighting to preserve their competitive edge, but the LCFS provides credits that are generally only available to the largest dairies. Industrial dairying also contributes to and exacerbates ongoing environmental justice harms (the EPA states: "The San Joaquin Valley has some of the nation's worst air quality, fail-

ing to meet federal health standards for both ozone (smog) and particulate pollution").[101] And because industrial dairying has been historically prevalent in California, California environmental justice communities in the Central Valley have long experienced these harms.

V. Emissions Leakage Risk

Industry stakeholders assert that regulating methane from dairies[102] will push dairies out of business or out of state, exacerbating overall GHG emissions.[103] The movement of an industry and its emissions to another jurisdiction in order to avoid regulatory costs is called emissions leakage, and could present legal concerns.

AB 32 (2006) requires CARB to "minimize leakage to the extent feasible" in regulations promulgated under Parts IV and V of the Global Warming Solutions Act of 2006.[104] This includes the LCFS, promulgated under Part IV as an early action measure. The statute defines leakage as "a reduction in emissions of greenhouse gases within the state that is offset by an increase in emissions of greenhouse gases outside the state."[105] SB 1383 (2016) also requires CARB to "minimize and mitigate leakage to other states or countries as appropriate" in any potential regulation of dairy methane.[106]

The claim that regulating dairy methane will result in leakage has two parts that demand scrutiny. The first is the predictive assertion that if regulation is implemented, facilities will a) not be able to bear the costs of doing business and b) will be adequately mobile to move. The second is the premise that California leads the nation in "climate-smart dairy farming." If California dairies generate more emissions than dairies in other states,[107] outmigration of dairies won't necessarily result in equivalent or increased overall GHG emissions.

Additional political concerns are sometimes wrapped into the legal leakage claims. Generally, these arguments slip other value-laden claims about the loss of California dairy operations into the discussion, including the loss of jobs, the economic and cultural loss of the dairy industry, and sometimes implications that industry moving out-of-state will result in greater environmental degradation beyond GHG emissions. These important points bear discussion, but they are distinct from the legal emissions leakage argument.

The argument that methane regulation could lead to emissions leakage holds water if:

a) Other states are a more appealing place to operate than California;
b) The industry is adequately mobile to move;
c) The move would result in equivalent or a net increase in emissions.[108]

Legally, regulators are not required to prevent leakage altogether. They are required to "minimize" leakage in the context of the LCFS and to "minimize and mitigate" leakage in the context

101 U.S. Env't Prot. Agency, EPA Activities for Cleaner Air, https://www.epa.gov/sanjoaquinvalley/epa-activities-cleaner-air.
102 Excluding dairies from the LCFS should not result in inter-state leakage, because out-of-state dairies are currently eligible for LCFS credits. That is: there is no existing benefit to California dairies that CARB could remove at their expense relative to out-of-state operations. The claim the adoption of new regulations will result in leakage, however, deserves more attention.
103 A Dairy Cares comment letter, for example, argued: *"The analysis also shows that misguided efforts to change course by forced conversion to pasture-based operations, direct regulation of dairy farms, or limitations on dairy digester incentives will not only fail to achieve the desired greenhouse gas emission reductions but will exacerbate the problem by causing significant emissions "leakage". As demand for dairy products continues to increase across the U.S. and world, the dairy industry is likely to respond to costly direct regulation by leaving for states with less costly regulations and less commitment to climate protection."* The Dairy Cares website, for example, asserts: "California leads the nation in climate-smart dairy farming, and cows leaving results in a "leakage" of methane emissions."
104 Cal. Health & Safety Code § 38562 (b)(8).
105 Cal. Health & Safety Code § 38562 (b)(8).
106 Cal. Health & Safety Code § 39730.7.
107 I use climate-friendly, rather than climate-smart to convey an industry generating fewer GHG emissions. Climate smart is a term favored by industry that doesn't require overall emissions to decrease but simply for the industry to employ "smart" technologies. As such, it does the work of defining success on the industry's terms while conveying a more general sense of climate-friendly practices.
108 The leakage argument typically focuses exclusively on GHG emissions, but a consideration of other forms of pollution is appropriate as well.

of new dairy methane regulations pursuant to SB 1383. This discussion surveys research on leakage risk generally before evaluating each of the three criteria above and offering a final analysis of the risk of legal leakage if methane regulations are enacted or LCFS credits are diminished.

A. Leakage Risk Generally

Emissions leakage describes the movement of industry, and by extension that industry's emissions, out of one jurisdiction and into another in response to emissions regulation.[109] Leakage is a greater risk in industries that are "trade-exposed"[110] and in industries that are mobile. Trade-exposed industries are competing on the slim margins of global market and, if they are mobile, able to relocate with relative ease.

There is very little evidence that leakage in response to emissions regulation is common in practice.[111] Despite significant theoretical backing for leakage, research has consistently found virtually no evidence of emissions leakage.[112] A CARB-commissioned analysis from 2016 found that most early empirical studies on the trade effects of pollution control regulations established "no relationship, or a counter-intuitive positive relationship, between energy costs and net imports."[113] One "more sophisticated" study determined that "for most industries, environmental compliance costs have been too small to affect trade flows in an economically significant way."[114] One explanation for the low rates of leakage is the effective use of various policy tools to mitigate leakage risk.[115] These tools will be discussed further below in the legal analysis section.

The concept of leakage rests on an idealized notion of a frictionless global market. In practice, uprooting industries comes with its own costs and global markets have not operated as seamlessly as in economics textbooks. Research has found that risk of leakage is linked to the measure of industry's mobility. The Fowlie et al. study cited above found that while more mobile industries are indeed susceptible to leakage, "pollution intensity is positively correlated with [industry's] measures of immobility."[116] That is: more mobile industries are susceptible to leakage but the most polluting industries tend to be the most immobile.

Additionally, while regulation can result in a decline of in-state industry, typically only a portion of the decline in in-state production ends up migrating out-of-state.[117] A different CARB analysis on leakage risk from several food sectors, including cheese processing, found that a $20 million carbon compliance cost in California

109 Meredith L. Fowlie, Mar Reguant, and Stephen P. Ryan, *Measuring Leakage Risk* (May 2016), https://ww2.arb.ca.gov/sites/default/files/cap-and-trade/meetings/20160518/ucb-intl-leakage.pdf. A 2016 CARB-commissioned analysis on mitigating leakage characterizes the basic concern as follows: "An increase in relative operating costs can, in turn, adversely impact the ability of regulated firms to compete in a global market. If this shifts production outside the regulated jurisdiction, any associated increase in emissions can undermine the effectiveness of regional policies."

110 RFF uses the term "trade-exposed industry" and one RFF reports notes that highly emitting industries and industries highly exposed to international competition are particularly prone to leakage. Juha Siikamäki, Clayton Munnings, Jeffrey Ferris, and Daniel Morris, *Climate Policy, International Trade, and Emissions Leakage,* Resources for the Future, https://media.rff.org/documents/RFF-Bck-EmissionsLeakage.pdf. See also *Mitigating Emissions Leakage in Incomplete Carbon Markets,* 9 J. of the Ass'n of Env't and Res. Econ. 2, 307-343, 2022.

111 Meredith L. Fowlie, Mar Reguant, and Stephen P. Ryan, *Measuring Leakage Risk* (May 2016), *supra* note 109, at 8.

112 Michael Grubb *et al., Carbon Leakage, Consumption, and Trade*, 47 Ann. R. of Env't and Res. 753 (Sept. 2022), https://www.annualreviews.org/doi/pdf/10.1146/annurev-environ-120820-053625 (Studies find no evidence that climate policies lead to carbon leakage, but this is partly due to shielding of key industrial sectors, which is incompatible with deep decarbonization."); Florian Misch and Philippe Wingender, Revisitng Carbon Leakage, IMF Working Papers, 207 (Aug. 6, 2021), https://www.elibrary.imf.org/view/journals/001/2021/207/article-A001-en.xml ("The large body of the existing theoretical literature (which we review in the Appendix) has not reached consensus on the approximate magnitude or even the sign of carbon leakage... The empirical literature is smaller, and the results mostly imply that carbon leakage is limited.")

113 *Id.;* A 2015 report on the European Union's Emissions Trading System found "no evidence for production displacement," "no evidence for future 'carbon leakage' risk, and that "industry confirm[ed] lack of 'carbon leakage' risk." Carbon Market Watch, *Carbon Leakage Myth Busters* (Oct. 2015), https://carbonmarketwatch.org/wp-content/uploads/2015/10/CMW-Carbon-leakage-myth-buster-WEB-single-final.pdf.

114 *Id.*

115 *Commentary: What is Carbon Leakage? Clarifying Misconceptions for a Better Mitigation Effort*, London School of Econ. And Poli. Sci. (Dec. 8, 2021), https://www.lse.ac.uk/granthaminstitute/news/what-is-carbon-leakage-clarifying-misconceptions-for-a-better-mitigation-effort/.

116 *Id.*

117 Meredith L. Fowlie, Mar Reguant, and Stephen P. Ryan, *Measuring Leakage Risk* (May 2016), *supra* note 109 (about 1/6th of production decline moves out of state).

would lead to production decrease of .05% of the California cheese supply or 525.07 metric tons. That study further concluded that for cheese, 57% of that .05% California decrease would move out of state, resulting in a production leakage of 301.83 metric tons.[118] (Note that cheese processing is distinct from dairying, so these numbers, while instructive generally, are not directly on point for our purposes.)[119]

The food processing leakage study explained that emissions leakage can be determined from these production leakage numbers by "adjusting the market transfer effect for the relative emissions-intensity of the plants acquiring and losing market."[120] The authors refrained from making concrete predictions for cheese processing emissions leakage, instead citing variability in practices. They did, however, suggest that California food processing relies more on natural gas while other states rely more on coal, so some emissions leakage would likely occur in that sector.[121]

Overall, the research on emissions leakage suggests that the risk of major production leakage—of entire industries moving out of state—is low. Instead, depending on the costs of newly imposed regulation, the more likely outcome is a small decline in California production and some portion of that decline shifting out-of-state. Moving alone (production leakage), even because of emissions regulation, is not necessarily emissions leakage. Operations must move because of emissions regulation and must, in their new jurisdiction, emit as much or more methane as they had in California. In the context of dairy, the relevant comparison would be whether the practices of out-of-state dairies are more- or less-carbon intensive than in-state dairies.

It is impossible to predict what the costs of regulation and the attendant decline in California production might be, since no methane regulation for dairy has been proposed by CARB. In terms of LCFS credits, it is extremely unlikely that change to LCFS crediting would result in emissions leakage. Emissions leakage is causal[122] and depends on regulatory asymmetries, but LCFS credits are available to dairy operations nationally. This means a change in LCFS crediting would not result in the kind of regulatory asymmetries that cause leakage.

B. Relative Mobility of California Dairies

One study defines mobility as "an inherent characteristic of industry, which is closely related to the industry's own production and technical attributes, and reflects the ability of the industry to transfer flexibly among regions."[123] Measures of industry mobility appear to be relatively less studied than regulatory impacts on competitiveness, but one CARB-commissioned analysis used capital intensity as a proxy for immobility.[124] A study of Chinese industry mobility further identified several key measures of mobility including sunk costs, asset specificity, and difficulty of labor

118 Dr. Stephen F. Hamilton, Dr. Ethan Ligon, Dr. Aric Shafran, and Dr. Sofia Villas-Boas, *Production and Emissions Leakage from California's Cap-and-Trade Program in Food Processing Industries: Case Study of Tomato, Sugar, Wet Corn and Cheese Markets* (May 9, 2016), https://ww2.arb.ca.gov/sites/default/files/cap-and-trade/meetings/20160518/calpoly-food-process-leakage.pdf.

119 The CARB analysis was conducted for food processing sectors, rather than agriculture, because food processing is covered by cap-and-trade. CARB has pioneered efforts to reduce leakage in its cap-and-trade program.

120 Dr. Stephen F. Hamilton, Dr. Ethan Ligon, Dr. Aric Shafran, and Dr. Sofia Villas-Boas, *Production and Emissions Leakage from California's Cap-and-Trade Program in Food Processing Industries: Case Study of Tomato, Sugar, Wet Corn and Cheese Markets* at 43.

121 In the cheese processing plant study, the authors looked at general food processing statistics and assumed that, "[f]or the case of California food processors, the typical plant operates on natural gas; however, global food processing plants including those in other U.S. states rely on other sources such as coal and fuel oil." As a result, the authors suggested generally that food processing outmigration would result in increased net emissions, though they qualified that with the need for more specific data. *Production and Emissions Leakage from California's Cap-and-Trade Program in Food Processing Industries: Case Study of Tomato, Sugar, Wet Corn and Cheese Markets* at 43.

122 *Commentary: What is Carbon Leakage? Clarifying Misconception for a Better Mitigation Effort*, *supra* note 115.

123 Jianmin Dou and Xu Han, *How Does the Industry Mobility Affect Pollution Industry in China: Empirical Test on Pollution Haven Hypothesis and Porter Hypothesis*, 217 J. Cleaner Prod. 105 (April 20, 2019), https://www.sciencedirect.com/science/article/pii/S0959652619301647?casa_token=w8DPvD0fDUEAAAAA:fCh8su48J0KAzSBZXru34w404UX2TyDro5xOoaHLJ6SiVTjZABtruzpOAZ4Afn1xYu6ftyhdXw#bib41 (citing Stem 2007).

124 Fowlie et al., *Measuring Leakage Risk*, *supra* note 109 ("Capital intensity serves as a proxy for immobility; highly capital-intensive firms tend to be harder to relocate.")

force transfer.[125] The same study found generally that more mobile industries are more likely move in response to regulation, while less mobile industries are more likely to innovate.

Industrial-scale confinement dairies are highly capital intensive (and intensification of capital, land, and animals is one of the major trends in dairying in recent decades).[126] Barns and lagoons require significant, long-term investments that become sunk costs. The addition of digesters makes these operations even more capital intensive and less likely to move. Livestock itself is mobile, but like other highly polluting industries, industrial dairies cannot simply pick up and move anywhere. They are limited to areas that are zoned for agriculture and where the addition of thousands of cows and their waste will not be challenged by local communities. Industrial-scale facilities relying on export markets must consider proximity to processing facilities and/or to ports, as well as attendant freight costs. Labor force transfer could impose additional challenges. The National Milk Producers Federation states "[e]ven as technology become a greater park of agriculture, much of dairy farming remains labor-intensive."[127] The dairy labor supply is currently tight. The industry is facing labor shortages "with no foreseeable end in sight."[128]

C. Relative Appeal of Other States

The likelihood of production leakage depends on whether other states' practices and environments—regulatory and otherwise—make them more appealing than California. There is a lot of talk about how challenging the landscape is for California dairies[129]; however, the dairy industry in California is doing relatively well compared to other states. California has remained the top milk producer in the country since 1993.[130] California houses one in five of the nation's cows and produces one fifth of the milk produced in the United States.[131] Dairy farming is the leading agricultural commodity in California, generating $7.57 billion cash receipts from milk (in 2021) and handily sells more milk than any other state.[132] The export value of California dairy was $2.5 billion dollars in 2021.[133] In the most recent agriculture census, Tulare County alone had $1.8 billion in milk sales—5% of milk sales nationally—and four out of five of the top counties for milk sales were in California.[134] None of these statistics suggest a baseline environment that is significantly worse for dairy operators in California than in other states.

There has been a slight decline in California production and cow inventories from 2007-2017

125 Jianmin Dou and Xu Han, *supra* note 123.

126 Sara D. Short, *Characteristics and Production Costs of U.S. Dairy Operations*, US Dep't of Ag. Econ. Res. Service (February 2004), https://www.ers.usda.gov/webdocs/publications/47156/28499_sb974-6_1_.pdf?v=0; Milena Bojovic and Andrew McGregor, *Review of Megatrends in the Global Dairy Sector: What are the Socioecological Implications*, 40 Ag. And Human Values, 373 (2023), https://link.springer.com/article/10.1007/s10460-022-10338-x.

127 Nat'l Milk Prod. Fed., Labor and Immigration, https://www.nmpf.org/issues/labor-rural-policy/labor-and-immigration-reform-efforts/.

128 Taylor Leach, *Dairy Farmers Face Labor Challenges Never Seen Before*, Dairy Herd Mgmt. (Dec 6., 2022), https://www.dairyherd.com/news/labor/dairy-farmers-face-labor-challenges-never-seen.

129 A Congressional Research Service report on emissions leakage explains, "There is every incentive for any industry facing a cost increase from carbon policies to claim that its competitive position could be diminished, thereby justifying special consideration by the government." Larry Parker and John Blodgett, *"Carbon Leakage" and Trade: Issues and Approaches*, Congressional Res. Service (Dec. 19, 2008), https://www.everycrsreport.com/files/20081219_R40100_1464249ac98c462316e637e26ca75217dd95a47c.pdf.

130 Cal. Dep't Food and Ag., California Dairy Pressroom and Resources, Real California Dairy Facts, https://www.californiadairypressroom.com/Press_Kit/Dairy_Industry_Facts.

131 *Id.*

132 *Id.*; U.S. Dep't of Ag., *2017 Ag. Census Highlights: Dairy Cattle and Milk Production*, https://www.nass.usda.gov/Publications/Highlights/2019/2017Census_DairyCattle_and_Milk_Production.pdf.

133 Cal. Dep't of Food and Ag., *California Agricultural Exports 2021-2022*, https://www.cdfa.ca.gov/Statistics/PDFs/2022_Exports_Publication.pdf.

134 U.S. Dep't of Ag., *2017 Ag. Census Highlights: Dairy Cattle and Milk Production*, https://www.nass.usda.gov/Publications/Highlights/2019/2017Census_DairyCattle_and_Milk_Production.pdf.

(the year of the most recent USDA agriculture census), with production and inventory "rising noticeably in Idaho and in the Plains States of Texas, Kansas, and South Dakota."[135] Attrition of California dairy herds and gains in nearby states suggest that California is losing some of the comparative advantage it possessed for the past few decades, but does not validate claims[136] that such migration would be prompted by emissions regulation. Migration is already occurring with no emissions regulations on the books. The fact that the industry is already migrating suggests that hypothetical future emissions regulations would not be the sole cause of such migration, diminishing the case for leakage. There may be broader concerns about the environmental impacts of dairies moving out of state, but these concerns are distinct from the legal concern around emissions leakage.

Some of the commonly identified issues for California dairies include environmental regulation, drought, milk prices, fluctuating demand for dry milk (one of California's major exports),[137] and labor shortages.[138] A 2010 survey found that the top three concerns for both California and Wisconsin dairy operators were: environmental regulations, volatile milk prices, and high prices of inputs.[139] The remainder of this section will briefly survey these concerns.

1. Environmental Quality Regulation

Environmental regulations unrelated to GHG emissions will not influence whether an out-of-state move will result in GHG emissions leakage, but they can impact how appealing that initial move is. California's regulation of air and water quality are comparable to other agricultural states.

Like all states, California is subject to the federal Clean Water Act. At the federal level, the Clean Water Act does not require discharge permits (under the National Pollution Discharge Elimination System (NPDES) program) as a matter of course for agricultural operations.[140] Instead, permits are only federally required where operations are shown to have discharged. It can take extensive documentation of violations of the Clean Water Act and can entail multiple enforcement actions before a NPDES permit is required.

NPDES permitting authority is generally delegated to states. In California, NDPES permits are issued by Regional Water Control Boards. Accord-

135 A Dairy Cares comment letter on LCFS virtual community meetings states, "The regulatory burdens and resulting high cost of doing business in California and resulting economics of dairy production in a national market are driving consolidation, not the presence of LCFS incentives." Michael Boccadero, *Dairy Cares Comments on LCFS Virtual Community Meetings*, *available at* https://ww2.arb.ca.gov/approved-comments?entity_id=28876.

136 A UC Davis report, for example, asserts that "Ongoing attrition and consolidation in the state's dairy sector is evidence of leakage risk." While attrition is an indication of the general health of the industry, that is unrelated to the causal analysis of emissions leakage, which asks whether emissions regulations specifically have shifted or increased net emissions. Ermias Kebreab, Frank Mitloehner, and Daniel A. Sumner, *Meeting the Call: How California is Pioneering a Pathway to Significant Dairy Methane Reduction*, UC Davis CLEAR Center (Dec. 2022), https://clear.ucdavis.edu/sites/g/files/dgvnsk7876/files/inline-files/Meeting-the-Call-California-Pathway-to-Methane-Reduction_0.pdf.

137 Jeff Daniels, *Outside States to California Dairy Farmers: We Have Water*, CNBC (Feb. 10, 2015), https://www.cnbc.com/2015/02/10/california-drought-states-tempt-california-dairy-farms--we-have-water.html ("The USDA economist said it's not just the drought and high cost of feed that has been hurting California dairy producers but a decline in the dry milk market that's been "a big export market for them. They've taken a disproportionate hit on that market. Strong dollar is contributing and China has retreated from the market.")

138 Dave Natzke, *State of the Dairy 2022: California in a 'State' of its Own,* Progressive Dairy (March 10, 2022), https://www.agproud.com/articles/54489-state-of-the-dairy-2022-california-in-a-state-of-its-own ("Outside of milk markets, Raudabaugh splits California dairy farmers into two major burden-carrying groups: those facing water woes and those encountering labor shortages.")

139 Andre de Witte, Jessica Nowak, Frederike Schierholz, and Birthe J. Lassen, *Dairy Farming in Wisconsin and California: Different Challenges –Different Future?* The Snapshot Survey (Spring 2010) http://www.agribenchmark.org/fileadmin/Dateiablage/B-Dairy/Misc/10_Snapshot_USA.pdf.

140 In the early decades of the Clean Water Act, agricultural activities were deemed nonpoint sources. In the early 2000s, CAFOs of a certain size were designated as point sources and therefore were required to seek permits. Prompt litigation brought by the pork industry, however, resulted in a rebuttable presumption that CAFOs do not discharge and are therefore not federally required to obtain National Pollutant Discharge Elimination System (NPDES) permits (though states can still require them). In 2022, a large group of advocates petitioned EPA to rescind the rebuttable presumption that CAFOs do not discharge but EPA did not act on the petition. *Earthjustice Petition to U.S. EPA to Adopt a Rebuttable Presumption that Large CAFOs Using Wet Manure Management Systems Actually Discharge Pollutants Under the Clean Water Act* (October 2022s), *available at* https://earthjustice.org/wp-content/uploads/cafopresumptionpetitionfinal_oct2022.pdf.

ingly, much of the important water quality regulation occurs at the regional level.[141] Today, Central Valley Regional Water Control Board Order No. R5-2013-0122 applies to most dairies.[142] Order No. R5-2013-0122 requires existing dairies to enroll (unless they are not eligible because they have recently expanded). Dairies must submit waste and nutrient management plans and participate in groundwater monitoring to ensure they are in compliance.[143] Since the general order, new and expanding dairies in the region have been issued individual permits.[144] California's Porter-Cologne Water Quality Control Act also requires operations that discharge waste that could impact the quality of state waters to be permitted. (In 2022, only about 7% of California's 1,083 CAFOs were required to have NDPES permits; the rest were permitted under state general orders.)

The Central Valley's water quality permitting is not particularly onerous relative to permitting regimes in other agricultural states. In some respects, it is more lax, particularly given the concentration of CAFOs spreading waste in the Central Valley. For example, Order No. R5-2013-0122 allows dairy operations to apply potassium and phosphorus in excess of agronomic rates unless application causes "adverse impacts," at which point operations are to stop application.[145] This is a weaker standard than under federal regulations and in other states.[146] The Order generally does not require operations to submit their waste management plans to the permitting agency for review; nor are operations required to make their nutrient waste management plans available for public review.[147] By contrast, both Idaho and Texas require nutrient management plans to be approved by a regulating agency and South Dakota requires nutrient management plans to be made available for public review.[148] Industry complaints about water quality permitting are not unique to dairies in California. They are ubiquitous in many western dairying states.[149]

Air emissions like ammonia, volatile organic compounds (VOCs), and particulate matter from

141 Statewide Water Quality Regulations for Confined Animal Facilities, Subchapter 2. Confined Animals, https://www.waterboards.ca.gov/centralvalley/water_issues/confined_animal_facilities/program_regs_requirements/dairy/dairyreg.pdf. The Central Valley Regional Water Control Board had just required NPDES permits for dairies under Order No. R5-2010- 0118, and the order was then revised to reflect the decision in National Pork Producers Council v. Environmental Protection Agency. National Pork Producers Council, et al v. United States Environmental Protection Agency (5th Cir 2011) 635 F 3d 738. It was replaced with Order R5-2011-0091. Cal. Water Boards, Central Valley Region, Confined Animal Facilities – Dairy Program Regulations and Requirements, https://www.waterboards.ca.gov/centralvalley/water_issues/confined_animal_facilities/program_regs_requirements/dairy/.

142 Cal. Regional Water Quality Control Board, Central Valley Region, Order R5-2013-0122, Reissued Waste Discharge Requirements General Order for Existing Milk Cow Dairies.

143 *Id*.

144 Eamon Norman, *Cal. Air Res. Bd. Workshop: Air Quality Regulations for Dairies in the San Joaquin Valley* (March 29, 2022), https://ww2.arb.ca.gov/sites/default/files/2022-04/dairy-ws-session-2-SJVAPCD.pdf; Attachment C: Permitting Requirements for Dairies in California, https://www.waterboards.ca.gov/northcoast/water_issues/programs/dairies/pdf/AttC_Summary_of_Permitting_at_Dairies.pdf; Cal. Regional Water Quality Control Board, Central Valley Region, Order R5-2007-0035: Waste Discharge requirements General Order for Existing Milk Cow Dairies, California Regional Water Quality Control Board.

145 Cal. Regional Water Quality Control Board, Central Valley Region, Order R5-2013-0122, Reissued Waste Discharge Requirements General Order for Existing Milk Cow Dairies at C-11.

146 Earthjustice Petition at 49, *supra* note 140.

147 *Id*.

148 Farmers Assuring Responsible Management, Nutrient Management Fact Sheet: South Dakota (March 2021), https://nationaldairyfarm.com/wp-content/uploads/2023/01/NMP-Fact-Sheet-South-Dakota.pdf; Farmers Assuring Responsible Management, Nutrient Management Fact Sheet: Texas (January 2021) https://nationaldairyfarm.com/wp-content/uploads/2021/09/NMP-Fact-Sheet-Texas.pdf.

149 In Utah: Catherine Merlo, *Western Water Woes: Dairies Grapple with Uncertain Supplies, Ever-Tougher Regulations,* Dairy Herd Management (May 3, 2010), https://www.dairyherd.com/news/western-water-woes-dairies-grapple-uncertain-supplies-ever-tougher-regulations (Mike Kohler, the executive director of Dairy Producers of Utah, which represents 90% of the state's 245 dairies and 90,000 milk cows, argued that water-quality regulations most important issue to dairies there: "The problem isn't obtaining water but managing manure under an increasingly aggressive Environmental Protection Agency."); In New Mexico: *Id.* ("State legislation passed last year required New Mexico's Water Quality Control Commission to identify specific requirements for discharging dairy wastewater to protect groundwater quality. The Environment Department says more than 65% of New Mexico's 150 dairies have polluted groundwater beneath their facilities."; In Texas: Texas Comm'n on Env't Quality, *Interoffice Memorandum: Commission Approval for Proposed Rulemaking Land Application and Disposal of Dairy Waste Docket No: 202301229-RUL* (Oct. 20, 2023), *available at* https://www.tceq.texas.gov/downloads/rules/current/23139321_pex.pdf; In Idaho: *Watering Idaho: Is the Dairy Industry Putting Rural Drinking Water at Risk*, Boise State Public Radio News (Sept. 21, 2016), https://www.boisestatepublicradio.org/environment/2016-09-21/watering-idaho-is-the-dairy-industry-putting-rural-drinking-water-at-risk (On the requirement that dairies have waste management plans); In Washington: Courtney Flatt, *WA Dairies Must Do More to Clean Up Their Act, Judges Rule*, Northwest Public Broadcasting (July 13, 2021), https://crosscut.com/environment/2021/07/wa-dairies-must-do-more-clean-their-act-judges-rule .

dairies are a major concern generally and even more so in the Central Valley.[150] The state regulatory regime for air pollution is entwined with California's State Implementation Plans (SIPs), which are required to remedy the San Joaquin Valley's decades-long nonattainment of federal air quality standards under the Clean Air Act.

In 2003, SB 700 was passed to resolve a conflict between California and federal law. One of the changes the law made was to remove an air permitting exemption for agricultural operations. California now treats large dairy operations like other large sources of air pollutants and makes these farms subject to air district permits if emissions exceed half of a major source threshold.[151] In practice, 96% of dairies in the San Joaquin Valley obtain air permits.[152] The regulation of CAFOs as stationary sources is distinctive and a response to the San Joaquin Valley's severe air quality issues and the dairy industry's role in generating emissions. At least some research suggests that "air quality regulations have not raised farm costs significantly" for California dairies.[153]

California does not currently regulate GHG emissions from dairies, though CARB has the authority to do so as of January 2024. Industry stakeholders and even reporters often describe SB 1383 as imposing a regulatory burden on dairies.[154] But SB 1383 imposes no affirmative obligations on dairies currently. Instead, the law sets industry-wide targets and mandates that *CARB* implement a strategy to meet those targets.[155] Still, the potential for future methane regulations on dairies is viewed as a negative and statewide methane regulations on dairies are undoubtedly less likely to be promulgated in some other major western dairying states than in California.

2. Drought

Drought and overall lack of water resources in California presents serious challenges to the state's dairy industry.[156] Adequate water is important to irrigate feed crops (alfalfa is very water intensive) and to manage the flush systems many California dairies rely on. The lack of water is also a problem for manure spreading at agronomic rates—if there's no water to grow crops, there is no crop to uptake the nutrients and spreading could result in groundwater contamination. Geoff Vanden Heuvel of the California Milk Producer Council observes: "Because the predominant method of manure disposal or utilization as it was, was fertilizer on crops, which if the water supply becomes limited to grow those crops, then that creates a problem."[157]

150 A. Rotz et al., *Environmental Assessments of United States Dairy Farms*, J. of Cleaner Prod. 315 (2021) 128153, https://www.sciencedirect.com/science/article/pii/S0959652621023714 (Ammonia in particular is one of the most serious harms from dairies: "dairy farms may emit as much as 24% of that [ammonia] estimated for the whole country.")

151 SB 700 (Florez, 2003).

152 Eamon Norman, *Cal. Air Res. Bd. Workshop: Air Quality Regulations for Dairies in the San Joaquin Valley* (March 29, 2022), https://ww2.arb.ca.gov/sites/default/files/2022-04/dairy-ws-session-2-SJVAPCD.pdf.

153 Josué Medllín-Azuara et al., *Assessment of California Crop and Livestock Potential to Adapt to Climate Change (Prepare for California's Fourth Climate Change Assessment)*, Publication number: CCCA4-CNRA-2018-018, University of California, Davis and University of California, Merced (2018), https://www.energy.ca.gov/sites/default/files/2019-11/Agriculture_CCCA4-CNRA-2018-018_ADA.pdf.

154 *See, e.g.* A UC Davis blog asserting that the dairy sector "is mandated to reduce methane emissions by 40% by 2030." *California Dairy Sector Poised for Climate Neutrality by 2030, per US Davis Research*, UC Davis CLEAR Center (May 2, 2023) https://clear.ucdavis.edu/news/california-dairy-sector-poised-climate-neutrality-2030-uc-davis-researchers; An agriculture trade publication writes that SB 1383 "require[es] livestock and dairy operations to reduce manure methane emissions by 40% by 2030." Dave Natzke, *State of Dairy 2022: California in a 'State' of its Own*, Progressive Dairy (March 10, 2022), https://www.agproud.com/articles/54489-state-of-the-dairy-2022-california-in-a-state-of-its-own.

155 ENVIRONMENTAL PROTECTION—POLLUTION—REDUCTION, 2016 Cal. Legis. Serv. Ch. 395 (S.B. 1383) (WEST) ("This bill would require the state board, no later than January 1, 2018, to approve and begin implementing that comprehensive strategy to reduce emissions of short-lived climate pollutants to achieve a reduction in methane by 40% ... below 2013 levels by 2030, as specified.")

156 *See, e.g. Are California Farmers Really Leaving for Greener Pastures?* Dairy Herd Management (Dec. 23, 2022), https://www.dairyherd.com/news/business/top-10-stories-2022-are-california-farmers-really-leaving-greener-pastures ("RaboResearch started exploring g the idea of dairy cows migrating toward the center of the country a couple years ago. The Reason? Water issues in the West, as well as a way to be closer to an abundance of feed. And Rabo says today, that scenario is already playing out.")

157 *California Water Crisis Challenges Dairy, Vanden Heuvel Says*, Nat'l Milk Prod. Federal Dairy Defined Podcast (Sept. 12, 2022), https://www.nmpf.org/california-water-crisis-challenges-dairy-vanden-heuvel-says/.

While drought and inadequate water is first and foremast a climactic problem, California's system of water use is often viewed as another source of burdensome regulation by dairy operators.[158] State regulators have to step in in order to manage the water supply and protect the state's water resources. Overdrawn basins have had to submit implementation plans under the Sustainable Groundwater Management Act of 2014.[159] Combined with drought years, this has put increasing pressure on dairies, particularly in the southern San Joaquin Valley.[160]

At least one state (Iowa) touted its "abundant water" at California's dairy expo in an attempt to entice dairy operators to move.[161] But drought and water resources issues generally are also major concerns in many of the western dairying states where California dairy operations might be likely to move.[162]

3. *Milk Prices*

Milk prices are an essential part of what makes a given state more or less appealing to dairy operations. About 75% of U.S. milk production is covered the Federal Milk Marketing order (FMMO).[163] The FMMO applies to and establishes minimum uniform prices for the exchange of milk from dairy operations to dairy processers within specific areas.[164] There are 11 different FMMO regions in the United States. Historically, California set its prices in a separate but similar program,[165] but joined the FMMO in 2018.[166] California comprises its own region in the FMMO. At least some dairy operators seem to think the FMMO has improved California milk prices relative to the old system.[167] There has also been pushback to the new system.[168]

Under both systems, California's milk prices have been relatively low. Daniel Sumner asserts that California's relatively low milk prices stem from its role as a net exporter and the cost pressure on milk processers here. He cautiously predicts that, because these specific pressures are unlikely to change in the near future, "a return to rapid growth of California milk production seems unlikely. However, the inherent strengths of the California dairy industry remain. Therefore, it also seems unlikely that significant aggregate declines in California milk production are on the horizon."

158 *Id.* ("It's a combination of droughts, but also what we call manmade drought.")

159 *Id.* ("And then those agencies in critically overdrafted basins, which is most of the Central Valley, had a requirement that by January 31 of 2020, they had to submit a plan that would show how that area was going to become sustainable by the year 2040.")

160 *Id.* "And in the Southern San Joaquin Valley, south of Fresno is just naturally drier than the northern part of the Central Valley. And so it's facing kind of the crunch quicker than maybe other areas, but we have a lot of dairy in the Southern San Joaquin Valley."

161 Karen Bohnert, *Dairy's Future, Who Will the Top Dairy States Be in the Next Decade*, Dairy Herd Management (August 31, 2021), https://www.dairyherd.com/news/dairy-production/dairys-future-who-will-top-dairy-states-be-next-decade (The Dairy Iowa banner here at the expo touts the state's "abundant land, water, feed and forage supply." It also cites a "positive business climate," among other things."); Jeff Daniels, *Outside States to California: We Have Water,* CNBC (Feb. 10, 2015), https://www.cnbc.com/2015/02/10/california-drought-states-tempt-california-dairy-farms--we-have-water.html.

162 Catherine Merlo, *Western Water Woes: Dairies Grapple with Uncertain Supplies, Ever-Tougher Regulations,* Dairy Herd Management (May 3, 2010) https://www.dairyherd.com/news/western-water-woes-dairies-grapple-uncertain-supplies-ever-tougher-regulations.

163 *Federal Milk Marketing Orders: An Overview,* Cong. Res. Serv. (June 15, 2022), https://sgp.fas.org/crs/misc/R45044.pdf.

164 U.S. Dep't of Ag., *An Oveview of the Federal Milk Marketing Order Program*, https://www.ams.usda.gov/sites/default/files/media/DairyFMMOBooklet.pdf.

165 Cal. Dep't of Food and Ag., *Milk Pricing in California*, https://www.cdfa.ca.gov/dairy/pdf/Milk_Pricing_in_CA.pdf.

166 7 CFR 1051, 26547-26556 *available at* https://www.federalregister.gov/documents/2018/06/08/2018-12245/milk-in-california-federal-milk-marketing-order-promulgation; *USDA to Hear Proposals on Federal Milk Pricing System*, Paso Robles Press (Aug. 18, 2023) https://pasoroblespress.com/special-sections/agriculture/usda-to-hear-proposals-on-federal-milk-pricing-system/. In 2022, the average Class I price in California was $25.74. This was higher than in the Pacific Northwest area (by about 20 cents) and in the Central area (by 12 cents). It was lower than in the Southwest area (by about 90 cents) and in Arizona (by about twenty cents). U.S. Dep't of Ag, Class I Milk Price, https://www.ams.usda.gov/sites/default/files/media/ClassIPrices2022.pdf.

167 Geoff Vanden Heuvel, *California's Milk Price Has Shown Improvement*, Hoard's Dairyman (March 24, 2022), https://hoards.com/article-31723-californias-milk-price-has-shown-improvement.html.

168 Dave Natzke, *State of the Dairy 2022: California in a 'State' of its Own*, Progressive Dairy (March 10, 2022), https://www.agproud.com/articles/54489-state-of-the-dairy-2022-california-in-a-state-of-its-own/ ("Since joining the FMMO system at the end of 2018, dairy cooperatives in California gained far more economic flexibility, especially as it relates to pooling, weakening the farmer safety net, she explained.")

4. *Demand, Trade Exposure, and California's Comparative Advantage*

California carved out its place in the national market by pioneering industrial drylot dairies, but newer dairying states in the West and some older dairying states in the Midwest, like Wisconsin, have now adopted the California model, eroding California's competitive advantage. Traditional dairying states have followed the pattern of consolidation and increased herd sizes to an extent since the early 2000s; however, they've also made greater progress in milk yields. One analysis suggests that traditional dairying states may have focused gains on milk yields rather than increases in herd sizes to the extent of modern states, like California, because of a more stringent regulatory environment:

> *The fact that milk yield in traditional states grew more rapidly after the introduction of genomic testing in dairy genetics suggests that genetics may have played a role in the observed yield increase. It is also possible that, due to zoning and environmental regulations, traditional dairy states are simply more limited in their ability to grow cow numbers. Having exhausted their ability to grow production through cow numbers, they are instead turning to improving yield. This mirrors a larger trend in US crop production where output growth is driven mostly through productivity gains rather than putting more acres into production.*[169]

The overall dairy herd size nationally also appears to be leveling off.[170] Demand for fluid milk is down among younger people[171] and the dairy industry saw a major change[172] in demand nationally and major price fluctuations[173] over the course of the COVID-19 pandemic. This included a "relative shift towards production of storable dairy products." This shift may have helped fuel the gradual move towards the center of the country. Milk production was historically concentrated on the coasts because the perishability of milk required the cows to be near market. This is changing as the dairy industry shifts away from fluid milk.[174]

California's role as a net exporter[175] also results in relatively greater trade exposure and

169 Jared Hutchins and Joe Janzen, *Production Trends in the US Dairy Sector*, FarmDocDaily (Oct. 30, 2023), https://farmdocdaily.illinois.edu/2023/10/production-trends-in-the-us-dairy-sector.html.

170 *Id.* ("In the past two years, cow numbers have begun to level off, perhaps reacting to uncertainty the ability and willingness of the supply chain to continue to accept the volume of milk that it does. It may also be that the total number of dairy cows in the country is reaching a long-run, stable level. This is especially the case if zoning and environmental regulation prevent modern dairy states from expanding cow numbers as they have in the past two decades. If growth in the US dairy herd does level off, we may even see modern dairy states follow the lead of the traditional states and drive growth through yield improvement rather than more cows.")

171 Kim Severson, *Got Milk? Not This Generation*, N.Y. Times (April 4, 2023), https://www.nytimes.com/2023/04/04/dining/milk-dairy-industry-gen-z.html.

172 *Dairy Supply Chains Will Need to Adjust as Consumer Behavior Changes*, Cal. Dairy (July 15, 2020), https://californiadairymagazine.com/2020/07/15/dairy-supply-chains-will-need-to-adjust-as-consumer-behavior-changes/.

173 The large fluctuations in the cheese and all-milk prices seen in Figures 4 and 5 underlie the broader effect of the COVID-19 pandemic on dairy prices. Daniel A. Sumner, Tristan M. Hanon, and Scott Somerville, *Effects of the COVID-19 Pandemic on the Western Dairy Industry,* Western Econ. Forum (June 2021), https://ageconsearch.umn.edu/record/311305/?ln=en.

174 *As California Farmers are Pressed, Dairy Cows Flee for Texas and Arizona,* The Bullvine (Sept. 21, 2022), https://www.thebullvine.com/news/as-california-farmers-are-pressed-dairy-cows-flee-for-texas-and-arizona/. ("According to Boccadoro, milk production has been moved to the Midwestern states as a result of a decline in the demand for fluid milk and a rise in the demand for cheese, yogurt, butter, whey protein, and other milk-related products. Since the pandemic started in 2020, demand for dairy products has grown by 2000%.")

175 This section has focused on inter-state rather than international outmigration. That said, it is notable that the United States is a net exporter of dairy. Int'l Dairy Foods Ass'n, The Importance of Trade for U.S. Dairy, https://www.idfa.org/trade. A UC Davis blog asserts: "While the rise in greenhouse gas emissions in developing countries is largely due to domestic growth, it's no secret that companies from wealthy countries set up factories in foreign countries to cut costs and avoid regulations, thus further contributing to global pollution." In the context of dairy, however, recent years have seen a surge in U.S. dairies catering specifically to the Chinese export market. Agricultural exports to China and the value of agricultural exports has increased every year since 2018, rather than vice versa. U.S. Dep't of Ag. Foreign Ag/Serv., Record U.S. FY 2022 Agriculture Exports to China (Jan. 6, 2023), https://fas.usda.gov/data/record-us-fy-2022-agricultural-exports-china; Amanda Lockwood, *Everything to Know Before Exporting to China*, Dairy Foods, https://www.dairyfoods.com/articles/96607-everything-to-know-before-exporting-to-china. China is the leading importer of nearly every major dairy product. Aidan Connolly, *China is Sneezing, Will it Give the U.S. Dairy Industry a Cold*, Dairy Herd Management (Nov. 29, 2023), https://www.dairyherd.com/news/business/china-sneezing-will-it-give-us-dairy-industry-cold. In recent years, western states have seen the growth of export-only factor dairies. Lynne Terry, *While Small Dairy Farms Shut Down, This Mega-Dairy is Shipping Milk to China*, Civil Easts (Nov. 27, 2018), https://civileats.com/2018/11/27/while-small-dairy-farms-shut-down-this-mega-dairy-is-shipping-milk-to-china/. Moreover, the U.S. dairy industry's major competitors in the Chinese market are the European Union and New Zealand, not developing countries. U.S. Dairy Export Council Staff, *Slow Whey Demand in China Holds Back U.S. Dairy Exports in July*, The U.S. Dairy Exporter Blog (Sept. 7, 2023), https://blog.usdec.org/usdairyexporter/slow-whey-demand-in-china-holds-back-us-dairy-exports-in-july-0. While new emissions regulations could (and probably would) influence these trends, the baseline situation is one in which the U.S. already is better situated to produce and export.

consistently lower prices than the national average.[176] Given this role, tariffs imposed on U.S. dairy products by Mexico and China during the Trump administration may have taken a disproportionate toll on California dairies.[177] As in the discussion of consolidation above, however, the data here is largely from the 2017 USDA Agriculture Census and so will not show the impacts of the LCFS. Additionally, Chinese demand has decreased in recent years, depressing global milk prices.[178] As a net-exporter, California has been particularly impacted as dry milk prices have fallen.[179]

There are also factors that cut against departure for California dairies. California's location on the West Coast and the Central Valley's proximity to urban markets have long been important to the industry. One analyst argued, "California has the second largest population in the country. You need to have milk close to the population, and because there's already infrastructure there, there will always be dairy in California."[180]

The California dairy industry is unlikely to find that other states can replicate the benefits of the Central Valley without any of the perceived challenges. One analyst suggested: "I think we'll continue to see consolidation in the dairy industry in California, the smaller herds are going to really have a tough time of it like they have for the last 10 or 15 years. I still think we'll see some producers migrate out, but it'll continue, I think to be a trickle. I'm not sure that it's going to accelerate significantly."[181]

D. Emissions Implications of Dairies Moving Out of State

Production leakage does not necessarily entail emissions leakage, the focus of the legal leakage concerns. Production leakage only results in emissions leakage where the state that hosts the influx of new dairy operations has a more highly emitting dairy industry and model. Emissions from different dairying models vary based on the regulatory regime, but also from the practices commonly employed, standard operation size, soil characteristics, and regional climate.[182]

Some stakeholders assume that California has a stricter regulatory regime for dairies in California and that California dairies emit fewer GHGs. But California currently does not regulate methane from dairies. Anaerobic digesters capture emissions, but they capture emissions from the high baseline generated by industrial-scale facilities.

There is little evidence that California's baseline model of dairying—confinement-based operations with liquid manure management—emits fewer GHGs than other models. On the contrary, confinement dairies with liquid manure

176 Daniel A. Sumner, California Agriculture: Dimensions and Issues, *Chapter 6: California Dairy: Resilience in a Challenging Environment*, https://s.giannini.ucop.edu/uploads/pub/2021/01/21/chapter_6_dairy_2020.pdf ("But, the lower California prices are due to the fact that California is a net exporter of milk products to the rest of the United States and the world, and not because of identified deficiencies in government regulations.")

177 Michael Hiltzik, *Column: California's Dairy Farmers Were Struggling to Regain Profitability. Then Came the Trade Wars*, L.A. Times (October 26, 2018), https://www.latimes.com/business/hiltzik/la-fi-hiltzik-caltrump-dairy-20181026-story.html.

178 Zahra Tayeb, *Economic Slump Means a Glass of Milk Could Soon Cost a Lot Less*, Business Insider (Aug. 3, 2023), https://www.businessinsider.com/china-economy-milk-powder-prices-fall-demand-slump-2023-8.

179 Tracy Withers, *Milk Powder Price Sinks to Three-Year Low as Dairy Demand Wanes*, BNN Bloomberg (Aug. 1, 2023), https://www.bnnbloomberg.ca/milk-powder-price-sinks-to-three-year-low-as-dairy-demand-wanes-1.1953649.

180 *Are California Farmers Leaving for Greener Pastures?* Dairy Herd Management (Dec. 23, 2022), https://www.dairyherd.com/news/business/top-10-stories-2022-are-california-farmers-really-leaving-greener-pastures.

181 *Id*. *See also* quote from Mike North in the same article ("Mike North of ever.ag says dairy farmers who are in a water deficit area may be forced to relocate, but he says there will always be dairy cows in California. However, consolidation is something he thinks will continue to happen in the state, largely due to the drought. "What's happening is the people that are water threatened may be looking to reduce their herd, but producers who aren't water threatened are buying their cattle and quotas. So, you won't see the number of dairy cattle in California dramatically drop," says North").

182 Rotz et al. ("No clear trends were found that indicated that a given management approach or farm size consistently provided lower environmental footprints. Often differences occurred due to differences in soil characteristics and climate, so a management approach that produces lower footprints for one environmental metric in one region may not function well for other metrics or locations. For example, NH3 and other manure emissions can be a concern for open lot dairies in the west with long-term manure storage, whereas nutrient runoff and water quality issues are often the greater concern for eastern farms using tie stall and free stall barns with less or no storage of manure.")

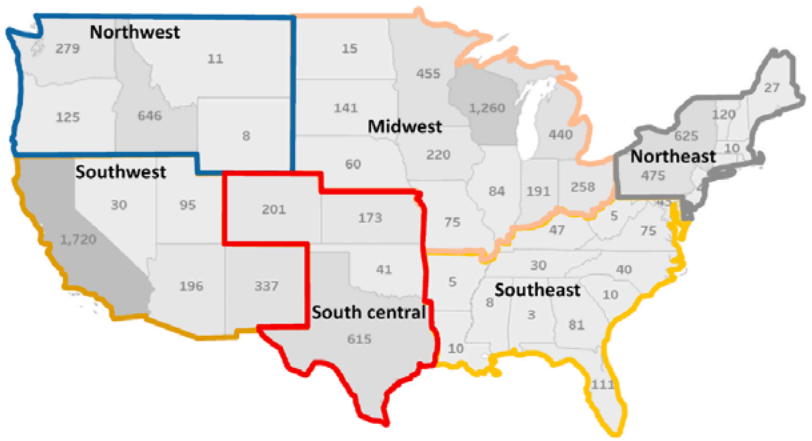


Fig. 1. Dairy regions of the United States used in our evaluation of the environmental footprints of dairy farms. Numbers are thousands of dairy cows in each state (NASS, 2020).

Table 1
Number of each type of dairy farm simulated to represent each region of the U.S.

Region	Amish	Organic	Grazing	Semiconfined	Confined <1000 cows	Confined 1000+ cows
Northeast	1	2	4	6	4	3
Southeast	0	0	5	9	4	2
Midwest	1	2	2	3	8	4
South central	0	1	2	3	6	8
Northwest	0	1	2	0	5	12
Southwest	0	1	1	0	1	17

FIGURE 10 Via A. Rotz et al., Environmental Assessment of U.S. Dairy Farms, supra note 150.

management systems are associated with higher emissions than other dairying systems.[183] This model is more common in the Southwest, and in California in particular, than in other parts of the country.[184] The dairying practices associated with the lowest GHG intensity are smaller grazing operations, which are primarily found in the East and the Midwest.[185]

The adoption of anaerobic digesters significantly reduces the GHG intensity of the California dairying model by capturing emissions generated by the long-term storage of liquified manure in lagoons. But it reduces the emissions from a high baseline relative to other common dairying models. Additionally, while anaerobic digesters capture emissions from manure lagoons, they do not address environmental harms, including but not limited to GHG emissions, beyond the lagoon.

Confinement-based dairies rely heavily on purchased feed. According to the Rotz et al. analysis, about 67% of the total fossil energy consumption by dairies nationally was used to

183 The study also determined that each of these farm management styles resulted in different environmental footprints generally and GHG emissions specifically. The results of the study provide insight into both the leakage discussion and the broader concerns about the LCFS: "Farms with the lowest intensity were often smaller grazing operations with little or no long-term storage of manure. For example, five grazing dairies in the northeast had a mean footprint of 0.88 kg CO2e/kg FPCM. Larger dairies that used an anaerobic digester also had below average intensities (0.69–0.87 kg CO2e/kg FPCM). Dairies with the greater intensity were often confinement operations with long-term liquid manure storage (i.e., large lagoons or retention ponds), particularly in the warmer regions of the country (six operations in the southwest averaged 1.09 kg CO2e/kg FPCM). Often the greatest intensities were associated with dairies that had lower FPCM production per cow along with the use of long-term manure storage." A. Rotz et al., *Environmental Assessments of U.S. Dairy Farms*, J. of Cleaner Prod. 315 (2021) 128153, https://www.sciencedirect.com/science/article/pii/S0959652621023714.

184 One study that determined the environmental footprint of dairy nationally found that the largest confinement dairies were found in the southwest region, where dairies were concentrated in California. The northwest region also had similar concentrations of the largest confinement operations but the other regions had a more varied breakdown, that typically included some smaller confinement operations, semiconfined operations, grazing, and organic operations.

185 A. Rotz et al., *Environmental Assessment of U.S. Dairy Farms*.

produce feed. About 97% of blue water consumption by dairies nationally was used to produce feed. Confinement-based dairies typically lack adequate land to spread manure regularly, necessitating long-term storage of manure which results in greater GHG and ammonia emissions.

The geography and climate of the southwestern region also influences environmental impacts in California, particularly when paired with the dominant model of confinement dairying. The amount of freshwater withdrawals varies regionally, but is highest in the Southwest. Overall, less water is consumed in regions that produce most of their feed on the farm without irrigation. Dairies on the West Coast rely heavily on irrigated feed crops.[186]

In terms of NOx emissions, "portions varied across the country, with less NH3 emission and greater NO3 loss in the eastern regions and greater NH3 emission and less NO3 loss in the dry conditions of the west."[187] In terms of GHG emissions, "manure contributed a lower proportion in the Northeast (17%) due to cooler temperatures and less use of long-term storage, and manure contributed a greater portion in the Southwest (28%) due to warmer temperatures and more use of long-term storage (IPCC, 2006a; Rotz, 2018). The enteric CH4 portion was also greater in the two eastern regions (47%) due to greater use of forage in cow diets."[188]

A comparison between California, as the nation's top dairy producing state, and Wisconsin, the second, illustrates California's role as leading the industrialization of dairy. California dairies are larger and the industry is more consolidated than in Wisconsin. A 2010 survey of California and Wisconsin farmers found that "While farms in Wisconsin are mostly medium-sized family farms, Californian farms operate on a much larger scale but are still owned by the family."[189] In 2014, Wisconsin had almost seven times more licensed dairy herds than California, but the average herd size was about 10 times smaller than the average herd size in California.[190] California first surpassed Wisconsin in dairy production in 1993 after a period of rapid growth and concentration in California (increasing production from 16.6 billion pounds of milk in 1988 to 22.9 billion pounds in 1993).[191] As discussed, the pressures of urbanization in Southern California in the early 1990s resulted in the loss of dairies in that region, but it also allowed them to sell their land at very high prices which they could use to build larger operations in the Central Valley.[192]

There is little evidence to suggest the baseline system of dairying in California is more climate-friendly or environmentally friendly than dairying nationally. However, the states the industry would be most likely to move to may not reflect the national average either. The states that have seen the most dairy growth in recent years are other western states adopting the California model of confinement-based operations with liquid manure management. Therefore, their practices may be similar to the practices of California dairies and, it is likely that they have fewer incentives for digesters, which is the primary method of reducing emissions from these dairies without otherwise altering practices. LCFS credits are available to any operation in the continental

186 Rotz et al. ("The lowest consumers were farms in the Midwest, Northeast, and Southeast regions that produced most of their feed on the farm without irrigation. The greatest consumers were farms in the Northwest and Southwest that relied almost entirely on irrigated feed crops.")

187 *Id.*

188 *Id.*

189 André de Witte, Jessica Novak, Freiderike Schierholz, and Birthe J. Lassen, *Dairy Farming in Wisconsin and California: Different Challenges — Different Future?* Snapshot Survey (Spring 2010), http://www.agribenchmark.org/fileadmin/Dateiablage/B-Dairy/Misc/10_Snapshot_USA.pdf.

190 *Wisconsin vs. California Dairy System Adaption*, University of Wisconsin Food Production Systems and Sustainability, https://kb.wisc.edu/dairynutrient/375fsc/page.php?id=48427.

191 John Oncken, *The Milk Continues to Flow*, Wis. State Farmer (Jan. 27, 2021), https://www.wisfarmer.com/story/opinion/columnists/2021/01/27/milk-continues-flow-california-and-wisconsin/6664991002/.

192 *Id.* ("Of course, they did not just move their 500 to 1000 cows. Instead, they built new and bigger and the strip from Bakersfield north to Sacramento sprouted new dairies, many of them 2,000 to 5,000 cows in size and all housed in freestall barns (copied from the new dairies being built in the Midwest) and away from the mud and rains of the corral type housing used in their former location.").

United States through book-and-claim accounting and federal incentives to support the construction of digesters are available, but California also offers substantial assistance for digester construction in the form of loans and grants.

E. Legal Leakage and Mitigation Measures

The nature of the leakage risk depends on the specific approach to GHG regulation, but several policy tools are available to reduce the likelihood of leakage generally. The primary tools are production incentives/output-based rebating and border climate adjustments.

Border climate adjustments "impose a fee on imported energy-intensive and trade-exposed products and a refund for exports of the same products."[193] They have been challenging to implement in practice.[194] Border climate adjustments are unlikely to be feasible for intra-American leakage, because they would impose a carbon tax on imports from other states, almost certainly generating litigation under the Dormant Commerce Clause.

Output-based rebates "consist of payments to energy-intensive and trade-exposed firms based on their production."[195] They have been found to "significantly reduce simulated emissions leakage."[196] Output-based rebating is similar to free allocations of emissions allowances, such as those used by California's cap-and-trade program.[197] Allocating allowances to regulated industry in the cap-and-trade program is intended to give enterprises time to transfer to less GHG-intensive technologies but also to prevent leakage. The level of allocations "will decline over time to settle at a level needed to prevent leakage."[198]

Output-based rebating has two side effects that make it important to carefully target subsidies to the industries actually at risk of leakage: "First, an opportunity cost is incurred when allowances are allocated for free or tax revenues are recycled to industrial producers. Second, output-based rebating dilutes the carbon price signal received by firms receiving the subsidy."[199]

While these tools have been effective in preventing leakage in other jurisdictions, it's crucial that they accurately target sectors seriously at risk of leakage. It's not clear that this is the case for dairy—further empirical research would be required. Moreover, the effectiveness of these policies in preventing leakage is due to the fact that they shield "key industrial sectors, which is incompatible with deep decarbonization."[200]

In the context of dairies, CARB would have to more deeply analyze how methane regulations would influence dairy operator behavior—in the absence of a specific regulation, it's challenging to determine whether it would actually prompt dairies to leave beyond the pre-existing decline. If it was determined that methane regulations were going to prompt industry departure, this kind of rebate could be carefully tailored to, for example, compensate dairies just enough to make the costs of leaving unappealing. Such rebates could also be tied to ongoing compliance with methane regulations.

In addition to the policy tools designed to address emissions leakage, policymakers should also consider that trade-exposure is one of the major leakage risk factors. The major changes

193 Noah Kaufman, John Larsen, Ben King, and Peter Marsters, *Output-Based Rebates: An Alternative to Border Carbon Adjustments for Preserving US Competitiveness*, Columbia Center on Global Energy Policy, https://www.energypolicy.columbia.edu/wp-content/uploads/2020/12/OBR-commentary-designed-v5-12.01.20.pdf.

194 *Mitigating Emissions Leakage in Incomplete Carbon Markets*, 9 J. of the Ass'n of Env't and Res. Econ. 2, 307-343 (2022).

195 Noah Kaufman, John Larsen, Ben King, and Peter Marsters, *Output-Based Rebates: An Alternative to Border Carbon Adjustments for Preserving US Competitiveness*, Columbia Center on Global Energy Policy, https://www.energypolicy.columbia.edu/wp-content/uploads/2020/12/OBR-commentary-designed-v5-12.01.20.pdf.

196 *Mitigating Emissions Leakage in Incomplete Carbon Markets* at 4, *supra* note 194.

197 Cal. Air Res. Board, *Proposed Regulation to Implement the California Cap-and Trade Program Part I, Vol. 1*, https://ww2.arb.ca.gov/sites/default/files/barcu/regact/2010/capandtrade10/capisor.pdf#page=56

198 *Id.*

199 *Id.*

200 Michael Grubb et al., *Carbon Leakage, Consumption, and Trade*, 47 Ann. R. of Env't and Res., 753 (Sept. 2022), https://www.annualreviews.org/doi/pdf/10.1146/annurev-environ-120820-053625.

to the dairy industry's export market over the past few decades have, therefore, increased the risk of leakage. As discussed, the opening of the export market also contributed to price depression and consolidation in the dairy industry. There are several farmer-led movements in the Northeast and the Midwest calling for a return of supply-side management programs specifically in order to preserve a healthy dairy industry and to reduce the environmental harms associated with confinement dairying.[201] This push is in line with the recent political trends, including resurgence in interest in industrial policy[202] and bipartisan pushback[203] against the free-trade line that has dominated U.S. politics for several decades.

The impact of free trade agreements makes it challenging to address the export market and supply-side management issue that has contributed to depressed milk prices, but it should prompt a deeper consideration of how California dairying can both be economically robust and sustainable into the future. These concerns should be especially important given the need to consider food security and the resilience of regional food systems in the face of climate change.

Overall, the likelihood of methane regulation and certainly of any changes to LCFS crediting running afoul of the legal requirement that CARB minimize leakage is low. Each step in the process—that dairies would leave the state in large numbers, that they would generate significantly more emissions out-of-state, and that CARB would not have policy options to minimize these events—is unlikely.

F. Key Takeaways: Emissions Leakage Risk

- **Research tells us that leakage is much less likely in practice than in theory.** Most of the literature on leakage suggests that it is very limited in practice. The textbook economics that envisions leakage imagines a frictionless global market, but uprooting industries incur additional costs that operators may not be willing to bear. Additionally, there are effective mitigation measures available that are commonly employed to reduce leakage risk. Multiple studies have found that while compliance costs can result in small in-state decreases, only a portion of those decreases are accounted for by moves out of state. For more on the risk of leakage in practice, see the CARB-commissioned *Mitigating Leakage Risk.*

- **Leakage risk is also closely tied to industry mobility. Industrial-scale dairying is capital-intensive, requires substantial sunk costs, and is facing a labor shortage, all of which erect barriers to mobility.** Dairy is more mobile than oil and gas production, which requires location at the source of fossil fuels; however, several characteristics of industrial-scale dairies are impediments to mobility.

201 Northeast Farmers Calling for a new supply-side model for organic dairy: *Northeast Dairy Task Force, Recommendations to USDA* (Dec. 16, 2021), https://agriculture.vermont.gov/sites/agriculture/files/Northeast%20Dairy%20Task%20Force%20-%20Recommendations%20to%20USDA.pdf; Wisconsin Farmer Union's Dairy Together advocating for supply management: Sarah E. Loloyd, *Dairy Together: Building a Farmer-Led Movement for Supply Management,* Disparity to Parity, https://disparitytoparity.org/dairy-together-building-a-farmer-led-movement-for-supply-management/ ("The vicious cycle of too much milk, leading to low prices, where only bigger and bigger farms can survive, which then leads to more milk produced, continues to speed up... A coordinated supply response is needed."); National Family Farm Coalition advocating for supply management: Kathryn Anderson, *Supply Management, Parity Prices, and Ecological Thinking as the Foundation for a Practice Agriculture System*, Disparity to Parity, https://disparitytoparity.org/supply-management-parity-prices-and-ecological-thinking-as-the-foundation-for-a-practical-agriculture-system/ ("Supply management and parity pricing directly mitigate environmental impacts by reducing the total volume of production. Importantly, supply management also indirectly improves agriculture's ecological footprint by 1) allowing the small and mid-scale farms that are best suited for diverse and ecological farming to thrive and 2) providing sufficient income for farmers to invest in conservation and regenerative practices.").

202 Anshu Siripurapu and Noah Berman, *Is Industrial Policy Making a Comeback?* Council on Foreign Relations, (Sept. 18, 2023), https://www.cfr.org/backgrounder/industrial-policy-making-comeback.

203 *See, e.g.* John Harwood, *Bipartisan Support for Free Trade Has Been Left Behind as the 2020 Race Barrels Ahead*, CNBC (Sept. 20, 2019), https://www.cnbc.com/2019/09/20/republicans-and-democrats-oppose-free-trade-in-2020-white-house-race.html; Washington Post Editorial Board, *A Bipartisan Retreat on Trade*, Wash. Post (July 31, 2019), https://www.washingtonpost.com/opinions/a-bipartisan-retreat-on-trade/2019/07/31/5473185a-b2f0-11e9-951e-de024209545d_story.html; Mohamed Younis, *Sharply Fewer in U.S. View Foreign Trade as Opportunity,* Gallup (March 31, 2021), https://news.gallup.com/poll/342419/sharply-fewer-view-foreign-trade-opportunity.aspx.

- **California's Central Valley still offers many benefits to dairy operators. Many of the challenges facing California dairies exist nationally or in other western states.** Dairies have struggled nationally for decades, but California has remained the top dairy producer in the country since 1993. On most metrics, California's dairy industry is the most successful in the country. While there are real challenges facing California dairies, many of these challenges are also facing dairies nationwide (like the ongoing trend towards consolidation) or in other western states (like drought and access to adequate water). Dairy operators may find policymakers less likely to directly regulate methane in Texas or in Kansas, but by moving, they would lose benefits like close proximity to urban markets and ports, cheap by-product feed, proximity to major transportation corridors, a milder climate etc.

- **While there has been a decline in California dairy operations in recent years, this movement is caused by a range of pre-existing factors.** Emissions leakage is a causal phenomenon. Outmigration followed by increased net emissions is only leakage if it was caused by emissions regulation. If anything, the fact that the industry has been moving out of state *prior* to any emissions regulations diminishes the likelihood that emissions regulations alone will cause outmigration and attendant emissions leakage. There are other valid and important concerns about the outmigration of dairy operations, but the legal leakage issue is not raised by these departures in the absence of any emissions regulation. Some of the reasons dairies have left California include: California slowly losing its competitive edge as other western states adopt its model of industrial-scale dairying, lack of reliable access to water, increased feed and manure management costs, and increased urbanization pressures.

- **The industry moving out of state ("production leakage") on its own does not necessarily result in emissions leakage. Despite stereotypes of California as a strict environmental regulator, it's not assured that dairies would emit more GHGs if they moved to other states.** Emissions leakage occurs when emissions regulations push and industry and their emissions out of state. This means emissions leakage requires that net emissions stay the same or increase as the result of the move. California-style dairies, however, generally have higher baseline emissions overall and per-cow than small and mid-sized dairies. California pioneered the most industrialized and highest emitting model of dairying in the country. California-style industrialized dairies are proliferating nationally, but they still are not the norm in many "traditional" dairying states, where smaller-scale, lower-emitting models remain more common. It's unlikely that California dairies would move to traditional dairying states, but if they did, net emissions could actually be reduced.

- **Mega-dairies outside of California are increasingly likely to employ anaerobic digesters.** California's main contribution to mitigation of dairy emissions has been the push for dairy digesters. The incentives provided by LCFS credits are available to any dairy operation nationally that plugs into a common carrier pipeline or the grid, however, not just California dairies. This means the LCFS does not incentivize climate-friendly behavior in California more than in any other state. Where California does have an edge is in grant funding for digesters through the

DDRP program. Other states have comparable programs. While other states' programs are less-well funded, this may reflect in part the fact that no state has more industrial dairies than California. Federal funding for digesters is also available, as is private funding.[204]

California dairies are more likely to relocate to other "modern" dairying states in the West, which have generally attempted to replicate California-style mega-dairies. Many of these states are also embracing digesters now, sometimes with the help of California-based companies like Brightmark (which has digester projects in South Carolina, Iowa, Michigan, Washington, Wisconsin, Florida, New York, and South Dakota)[205] and California Bioenergy (which has about 50 projects in California and has recently ventured to South Dakota).[206] A few indications of the surge in digesters in states that would be likely destinations for dairies exiting California:

- In Idaho, a "goldrush" to build dairy digesters specifically due to LCFS credits;
- In Washington, an "explosion of growth" and $22 million public investment in dairy digesters based on a CARB report touting its success;
- In Iowa, a "huge uptick" in dairy digesters from 2022 to 2023
- In Arizona, dairy digesters are a "hot investment;"
- In South Dakota, $150 million in private funding from California Bioenergy goes to three new dairy digester clusters in 2023;
- In Kansas, one of the top states for dairy growth, Shell is constructing a dairy digester;
- In Oregon, where "manure is big business," public funds and a Biomass Tax Credit program have incentivized digesters.

- **California regulators are obligated to minimize emissions leakage to the extent reasonable, not to ensure zero leakage.** Legally, CARB is only required to minimize or mitigate leakage, and there are policy tools available to help do this, like carefully designed output-based rebates. More generally, the dairy market is global, so leakage is possible from virtually any jurisdiction seeking to regulate dairy emissions. The question should be whether the amount of emissions leakage is so great as to frustrate the emissions reductions sought by the regulation.

204 *See, e.g.* Sarah Zimmerman, *Environmental Groups Blast USDA for Extending Climate Funding to Dairy Digesters*, Ag. Dive (Nov. 2, 2023), https://www.agriculturedive.com/news/climate-activists-digesters-dairy-biofuels-usda-ira/698611/; Grace van Deelan, Emma Foehringer Merchant, *Just Two Development Companies Drive One of California's Most Controversial Climate Programs: Manure Digesters*, Inside Climate News (Sept. 20, 2022), https://insideclimatenews.org/news/20092022/just-two-development-companies-drive-one-of-californias-most-controversial-climate-programs-manure-digesters/.

205 *Brightmark Energy to Build Its First Dairy RNG Project in South Dakota*, Bioenergy Int'l (Feb. 6, 2020) https://bioenergyinternational.com/brightmark-energy-to-build-its-first-dairy-rng-project-in-south-dakota/.

206 California Bioenergy, Projects, https://calbioenergy.com/projects/.

207 Michael Boccadero, *Dairy Cares Comment Letter on LCFS Virtual Community Meetings* (June 14, 2023) ("The LCFS is a Necessary Measure to Reach the SB 1383 Targets. Removing Dairies would Lead to Significant, Unavoidable Impacts.").

VI. California's Climate Targets and Credits for Dairy Digesters

Some[207] have argued that California cannot meet its climate targets without LCFS incentives for biogas from dairy manure. The implication is that by eliminating LCFS incentives for biogas, advocates would jeopardize climate progress. More specifically, the argument is that reducing incentives will make dairies less likely to construct biogas control systems and, as a result, methane from existing manure lagoons will continue to be vented. This section examines the two relevant sets of targets—California's overall climate targets established under SB 32 and California's 2030 methane targets set by SB 1383—and evaluates the extent to which this claim is accurate.

A. California's Overall Climate Targets

California's most recent update to the Scoping Plan calls to cut greenhouse gas emissions by 48 percent below 1990 levels by 2030 and 85 percent below 1990 levels by 2045.[208] The Scoping Plan "approaches decarbonization from two perspectives: (1) managing a phasedown of existing energy sources and technology and (2) ramping up, developing, and deploying alternative clean energy sources and technology over time."[209]

Short lived climate pollutants,[210] like methane, account for "about one-third of the cumulative GHG emissions reductions the State is relying on to achieve the statewide 2030 GHG emissions target established under SB 32."[211] The dairy and livestock sectors contribute more than half of the state's methane emissions.

B. California's Dairy Methane Targets

The three largest sources of methane emissions in California are the dairy and livestock industry, landfills, and oil and gas systems.[212] CARB took early action measures to address landfills and oil and gas directly (the Landfill Methane Regulation, Cal. Code of Regs., tit. 17, §§ 95460, et seq. and the Oil and Gas Methane Regulation, Cal. Code of Regs., tit. 17, §§ 95665–77) but declined to do so for the dairy and livestock sectors.

The SLCP Strategy's approach to dairy and livestock was characterized by CARB as a "carrot-then-stick" approach, prioritizing voluntary, incentive-based mechanisms in early years to "overcome technical and market barriers."[213] In the 2022 Scoping Plan CARB explained, "Under this "carrot-then-stick" strategy, incentives are replaced with requirements as the solutions become increasingly feasible and cost-effective."[214] Theoretically, the stick element could be implemented as of January 2024, per SB 1383. However, CARB has not indicated it intends to begin rulemaking on this issue.

SLCP reductions are "necessary to achieve the State's 2030 GHG emissions target, as described in the 2017 Scoping Plan Update, as well as the mid-century carbon neutrality goal."[215] The 2017 Short-Lived Climate Pollutant Reduction Strategy included a target of 40% reduction in total methane emissions as well as a separate 40 percent reduction in methane specifically from dairy and

208 Cal. Air Res. Board, *Press Release 22-44: California releases final proposal for world-leading climate action plan that drastically reduces fossil fuel dependence, slashes pollution* (Nov. 16, 2022), https://ww2.arb.ca.gov/news/california-releases-final-2022-climate-scoping-plan-proposal.

209 Cal. Air Res. Board, *2022 Scoping Plan for Achieving Carbon Neutrality* (November 16, 2022), https://ww2.arb.ca.gov/sites/default/files/2022-11/2022-sp.pdf.

210 Short lived climate pollutants include black carbon (soot), methane (CH4), and fluorinated gases (F-gases, including hydrofluorocarbons [HFCs]). Cal. Air Res. Board, *2022 Scoping Plan* at 222.

211 Cal. Air Res. Board, *Analysis of Progress Toward Achieving the 2030 Dairy and Livestock Sector Methane Emissions Target* (Final) (March 2022), https://ww2.arb.ca.gov/sites/default/files/2022-03/final-dairy-livestock-SB1383-analysis.pdf.

212 Cal. Air Res. Board, *2022 Scoping Plan, supra* note 209.

213 *Id.*

214 *Id.*

215 Cal. Air Res. Board, *Analysis of Progress Toward Achieving the 2030 Dairy and Livestock Sector Methane Emissions Target, supra* note 211.

livestock operations.[216] California's target of a 40 percent methane reduction below 2013 levels for the dairy and livestock sector by 2030 constitutes a reduction of 9 million metric tons carbon dioxide equivalent (MMTCO2e).[217]

California is not on track to meet these targets for dairy and livestock even with the LCFS incentives. The progress report projects that the dairy and livestock sector will achieve "just over half of the annual methane emissions reductions necessary to achieve the target by 2030 through modifications to manure management systems—primarily using anaerobic digesters—and additional reductions through decreases in animal populations."[218] The SB 1383 progress report concludes that, to meet SB 1383 targets, "approximately 230 additional digesters may be needed, at a cost between $0.7 and $3.9 billion depending on the types of technologies selected."[219] The report also finds, on the other hand, that "based on currently funded projects and reduction trends observed to date, staff's analysis indicates that the State would be unable to achieve the 2030 dairy and livestock sector target through deployment of alternative manure management practices alone."[220] That is, according the CARB's projections, California cannot meet its goals with just digesters or with just alternative manure management practices.

The intra-agency Dairy and Livestock Greenhouse Gas Emissions working group, which consisted of CARB, CDFA, California Energy Commission, and CPUC principals, convened three stakeholder subgroups in 2017 and 2018. Subgroup 1 provided recommendations on non-digester manure management practices, Subgroup 2 provided recommendations on overcoming barriers to implementing livestock digester projects, and Subgroup 3 provided recommendations on research needs related to dairy and livestock emissions reductions. CARB has pursued dairy digester projects as the Board's primary tool to reduce dairy emissions since the recommendations were made final in 2018.[221] Subgroup 3 published a Dairy research Prospectus to Achieve California's SB 1383 Climate Goals.[222]

Beginning January 1, 2024, CARB has authority to regulate GHG emissions from agriculture, "provided that CARB, in consultation with CDFA, determine the regulations are technologically and economically feasible, cost-effective, include provisions to minimize and mitigate potential leakage, and include an evaluation of the achievements made by incentive-based programs."[223] "SB 1383 intends to prioritize the use of voluntary and incentive-based measures to achieve those reductions before regulations are implemented"; however, the progress report projects that California is on track to reach less than half of dairy and livestock reduction targets by 2030.[224] Additionally, the progress report concludes that meeting targets will "require implementation of additional methane emissions reductions strategies, and continued collaboration among agencies and other stakeholders," but the Board has made no indication that it intends to initiate rulemaking.[225]

216 Cal. Air Res. Board, *2022 Scoping Plan, supra* note 209.
217 Cal. Air Res. Board, *Analysis of Progress Toward Achieving the 2030 Dairy and Livestock Sector Methane Emissions Target*, *supra* note 211.
218 Cal. Air Res. Board, *Analysis of Progress Toward Achieving the 2030 Dairy and Livestock Sector Methane Emissions Target*.
219 *Id.*
220 *Id.*
221 In addition to reductions from digesters, CARB's projections include "a continued annual animal population decrease of 0.5 percent per year through 2030." Cal. Air Res. Board, *2022 Scoping Plan.* A UC Davis report cited *supra* also assumes ongoing herd attrition. It's not clear how assumptions of herd attrition interact with claims that leakage is imminent—this is an area for future research.
222 Cal. Air Res. Board, Dairy and Livestock Subgroup #3, *Dairy Research Prospectus to Achieve California's SB 1383 Climate Goals* (Nov. 26, 2018), https://ww2.arb.ca.gov/sites/default/files/classic/cc/dairy/dsg3/dsg3_final_dairy_air_research_prospectus_11-26-18.pdf.
223 Cal. Air Res. Board, *Analysis of Progress Toward Achieving the 2030 Dairy and Livestock Sector Methane Emissions Target*.
224 *Id.*
225 *Id.*

C. Key Takeaways: California's Climate Targets and Credits for Dairy Digesters

- **Dairy digesters are necessary for California to achieve its GHG reduction targets at this point, but so are a range of non-digester interventions that have not been seriously pursued.** Methane captured by digesters accounts for most of the reductions counted towards the methane reduction targets for dairy and livestock, but even with these large reductions California is not on track to meet targets for dairy and livestock. California policymakers should look to the report by the 2018 CARB-convened working group on non-digester tactics to reduce dairy methane emissions to understand alternative, more holistic approaches to reduce GHG emissions from dairies.

- **CARB will not be able to accurately assess and select interventions if it relies on the LCFS life cycle analysis for manure biogas to analyze dairy emissions.** The life cycle analysis CARB uses measures the carbon intensity of transportation fuels produced from manure biogas, not the carbon intensity of milk (this is discussed at length in the carbon intensity discussion). A holistic life cycle analysis of milk produced on California dairies and feed production would prompt different kinds of interventions, since more emissions are generated from enteric fermentation than from manure management. The life cycle analysis for transportation fuels used by the LCFS *assumes* the dairy industry is static—the dependent variable in that analysis is the change in transportation fuel from conventional fuels to manure-derived biogas. This is a valid assumption to make in the context of a transportation program, like the LCFS, but should not drive the broader strategy to achieve emissions reductions from the dairy industry. California policymakers should be considering a suite of options to reform and support the dairy industry transition to a less-emitting model.

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Nitrous Oxide Production from Cattle and Swine Manure

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REVIEW

Nitrous oxide production from cattle and swine manure

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Abstract The aim of this review is to summarize the current knowledge of nitrous oxide (N_2O) production from manure. The article investigates the scientific literature regarding N_2O emissions according to different factors, such as microclimate, season, manure composition, microbial population, management, storage conditions, and type of digestion. Nitrous oxide is formed through the microbiological processes of nitrification and denitrification. The amount of N_2O produced from manure storage depends on type of manure management. The anaerobically stored farm yard manure (FYM) emitted more N_2O emissions than the composted FYM. The anaerobic storage of liquid manure reduces N_2O production. Covering the slurry store (SLR) with a chopped straw increased N_2O emissions. Finally, emission factors from manure treatment and management are listed in table.

Keywords: nitrous oxide, manure, slurry, housing

Introduction

Contemporary agriculture is characterized by the intensive production of livestock in confined facilities and land application of stored waste as an organic fertilizer. Animal agriculture potentially contributes up to 50 % of total agricultural nitrous oxide (N_2O) emissions (Klein de and Eckard 2008). The anthropogenic greenhouse gas emission from animal manure is estimates on 20 % of N_2O (Sommer and Moller 2000).

N_2O emissions from nitrogen (N) excreted as animal waste alone could be as much as 30–50 % of the global agricultural N_2O emissions, suggesting that the contribution of animal agriculture to total agricultural N_2O emissions could be in excess of 50 % when including emissions from N fertilizer use (Oenema et al 2005; Klein and Eckard 2008). N_2O emissions occur high when N fertilizers are used for production of concentrates to feed the animals, as well as from excretal returns (Davidson 2009; Petersen and Sommer 2011).

N_2O is produced during several microbial processes in the nitrogen (N) cycle of terrestrial and aquatic systems. Typically, 70 % to 90 % of the N ingested by herbivores is excreted, either during grazing or via application of manure collected outside grazing periods (Schils et al 2013). Housed animals excrete as dung and urine according to Paustian et al (2004) 80 to 95 % of the N in their diet, and some proportion of this N is emitted as N_2O during collection, storage, and application. Ruminants excrete between 75 and 95 % of the N they ingest, with excess dietary N increasingly excreted in the urine, while dung N excretion remains relatively constant (Castillo et al 2000; Eckard et al 2007).

In animal husbandry, N_2O emissions are associated with manure management and the application and deposition of manure in crop or pasture land. Manure treatment can be an important source of N_2O emissions, accounting for an estimated 5 % of global N_2O emissions (Owen and Silver 2015). Major agricultural manure emission sources are reported to be N_2O from poultry sheds and from beef feedlots (Pratt et al 2014).

Collected manure may be handled in solid (farmyard manure, deep litter) or liquid form (slurry with typically 1 % to 10 % of dry matter) (Schils et al 2013). Dung and urine are often separated to solid stacked manure and slurry (SLR), with or without subsequent composting of the stacked manure and (anaerobic or aerobic) treatment of the SLR. In other production systems, effluent from barns is transferred into open anaerobic ponds (lagoons) where the effluent is typically stored for many months, with the potential of generating large quantities of emissions (McGahan et al 2016).

N_2O is released from excrement and urine excreta, from SLR applied for crop or pasture production, and aerobic and anaerobic degradation of livestock waste in the lagoons and dry manure pile (Saggar et al 2004; Fabbri et al 2007; Borhan et al 2011; Redding et al 2015).

Formation N_2O

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The various pathways of N_2O formation could describe for apply to the manure environment, but the potential for N_2O emissions will depend on manure management practice. Manure contains most elements necessary for stimulating soil nitrification and denitrification processes that form N_2O. These processes are transient, depending on the amount and form of available N (NH_4^+ or NO_3^-), soil oxidation–reduction potential, degradable carbon (C) sources, soil temperature, water content, and microbial population (Montes et al., 2013). Poor correlations between N_2O efflux and soil physicochemical variables and fertilizer loading rate point to the complexity of interacting factors affecting N_2O production and emission (Whalen 2000).

The main sources of N_2O from agriculture are nitrification and denitrification processes in soil. Farms primarily emit N_2O arising mainly from nitrogen fertilizer (organic manures or inorganic fertilizers) application to soil, direct N deposition by grazing animals, or manure storages (Whalen et al 2000; Crosson et al 2011; Adler et al 2015). Nitrous oxide can also be produced indirectly when manure N is lost through volatilization as NH_3, NO, and N_2O and is nitrified and denitrified in soil following redeposition (Montes et al 2013). The smaller contributions from barn floors, where both aerobic and anaerobic conditions can exist (Chianese et al 2009; Van Middelaar et al 2013; Eckard et al 2003).

The major N_2O contributor is normally the denitrification process under anaerobic conditions, but nitrification under aerobic conditions may also contribute. Nitrification and denitrification rates are affected by numerous soil and climatic or seasonal factors (Monaghan and Barraclough 1993; Chadwick et al 2000; de Klein and Eckard 2008). The rate of formation and emission of N_2O varies through time with changes in the porosity, moisture content, temperature, amount of solids in the manure, and N or dietary protein content of the soil or manure substrate (Külling et al 2001; Kebreab et al 2006; Chianese et al 2009; Li et al 2014). Anaerobically stored solid manure emitted much more N_2O than the compost (Amon et al 1998a). Chadwick et al (2000) also reported that immediate emissions of N_2O from the beef manure was likely due to rapid nitrification of ammonium or denitrification of nitrate already in the manure.

Most of the N_2O resulting from manure is produced in manure-amended soils through microbial nitrification under aerobic conditions and partial denitrification under anaerobic conditions, with denitrification generally producing the larger quantity of N_2O (Montes et al 2013). Nitrogen in liquid manure is mostly in the form of ammonium (NH_4^+) and organic N, and though anaerobic lagoons are generally anaerobic, aerobic conditions which could promote denitrification exist at inlets. Other N_2O formation reactions are also possible, such as denitrification of nitrate (NO_3^-) (Owen and Silver 2015).

Mahimairaja et al (1995) examined the denitrification loss of N from fresh poultry and animal (dairy, sheep, pig and horse) manures, and from poultry manure during composting with different amendments. The results indicated that during denitrification, the amount of N_2 produced is generally greater than that of N_2O. The ratio of N_2O:N_2 varied from 0.09 to 0.21.

Factors affecting N_2O releasing

When fecal matter is excreted by animals, it undergoes a series of reactions such as decomposition, hydrolysis, nitrification, denitrification, fermentation etc., from which N_2O can be produced. Based on the principles of thermodynamics and reaction kinetics, these reactions are commonly controlled by a group of environmental factors such as temperature, moisture, stacking, density, litter addition, mixing, composition, and aerobic decomposition during storage of the manure, also redox potential, pH, substrate concentration gradient, etc. (Oenema et al 2005; Yamulki 2006; Kebreab et al 2006; Li et al 2012; Rzeźnik and Mielcarek 2016). The influencing factors appeared to be also the manure removal frequency, dry matter content, and time deposit of the manure (Fournel et al 2012). After 6 weeks of storage N_2O emission from farmyard manure (FYM) and deep litter manure reached a maximum (Külling et al 2002).

N_2O emissions are strongly correlated with all these parameters (Mihina et al 2012; Owen and Silver 2015). This suggests that in FYM, at least a portion of the N_2O fluxes were derived from denitrification, which requires the same general environmental conditions as methanogenesis (warm temperatures, abundant labile C, anaerobic conditions) (Owen and Silver 2015).

One main factor influencing the amount of N_2O emissions seems to be the manure temperature. This would explain why under summer conditions the emission rates of N_2O are different than under winter conditions (Jungbluth et al 2001). Sommer and Moller (2000) studied composting of pig deep litter during a 4-month period. Emissions of N_2O were only significant in the low temperature phases. N_2O was also produced in the center both initially and after the temperature of the compost had dropped to below 45 °C (Sommer and Moller 2000).

The initial C: N ratio and dry matter content of the stored FYM are also the most important factors affecting N_2O emissions. The greater C content in the organic FYM compared with the conventional FYM corresponded to a reduction in total N_2O emission (Yamulki 2006). N_2O emissions increase with the N content of waste, the extent to which waste is allowed to become aerobic (allowing the

initiation of nitrification-denitrification reactions) and the length of storage (Mosier et al 1998). Further, owing to interactions between available C and N sources in the correct oxidation form, semi-permeable manure storage covers can enhance N_2O formation (Hansen et al 2009; Nielsen et al 2010; Gerber et al 2013).

Table 1 N2O production and emission factors from manure storage facilities (per animal)

Cattle manure, without covering; 0.78 mg.m^{-2} h^{-1} (Ross et al 1999, cited by Jungbluth et al 2001).
Manure, summer, 3.5 t, winter, 7 t; anerobically stored vs. composted, 3 times per week, ODC, 74.7 g.t^{-1} vs. 49.8 g.t^{-1} (Amon et al 1998a).
Cattle manure (housing, storage, spreading); ODC, FTIR; yearly average 0.62 g.LU^{-1}.d^{-1} (Amon et al 1998b, cited by Amon et al 2006a).
Dairy solid manure system; 25.8 mg.LU^{-1}.h^{-1} (Amon et al 1999; cited by Amon et al 2006a).
Dairy liquid manure system; 25.4 mg.LU^{-1}.h^{-1} (Amon et al 1999; cited by Amon et al 2006a).
Dairy SLR, storage, 1200 m^3; winter, TDL; 14 mg.m^{-3}.d^{-1} (Hensen et al 2006).
12 Brown Swiss, 52 DIM, 637 kg LBW, 30,9 kg MY, individual stalls, slatted floor, TMR, 4 MS (DL, SLR, urine-rich SLR, FYM); 7 wks, TDL; according MS: 9.3 ng.m^{-2}.s^{-1}, 5.6 ng.m^{-2}.s^{-1}, 12.1 ng.m^{-2}.s^{-1}, 556.4 ng.m^{-2}.s^{-1}; (DL, SLR, FYM) 42 mg.d^{-1}, 12 mg.d^{-1}, 886 mg.d^{-1} (Külling et al 2001).
Pig manure, without covering; from containers (0,5 m^3) closed for 1 h gas measurement, summer, GC; 0.67 mg.m^{-2}.h^{-1} (Ross et al 1999, cited by Jungbluth et al 2001).
Pig manure, with straw covering; from containers (0,5 m^3) closed for 1 h gas measurement, summer, GC; 0.95 mg.m^{-2}.h^{-1} (Ross et al 1999, cited by Jungbluth et al 2001).
Pig manure, without covering; winter, FMC, GC; 0.35 mg.m^{-2}.h^{-1} (Ross et al 1999, cited by Jungbluth et al 2001).
Pig manure, with straw covering, winter, FMC, GC; 0.30 mg.m^{-2}.h^{-1} (Ross et al 1999, cited by Jungbluth et al 2001).
160 fattening pigs, uncovered SLR vs. covered SLR; warm, FC; after 50 days, 23 g.m^{-3} vs. 30 g.m^{-3}; after 200 days, 119 g.m^{-3} vs. 114 g.m^{-3} (Amon et al 2007).
160 fattening pigs, uncovered SLR, covered SLR; cold, FMC; after 50 days, 36 g.m^{-3} vs. 18 g.m^{-3} (Amon et al 2007).
Fattening pigs; FS housing, anaerobic effluent pond, short hydraulic retention tank; 2x30 ds; N_2O from housing and pond, or below the detection limits, total emissions from the short hydraulic retention tank: winter 0.001 mg N_2O-N.LU^{-1}.d^{-1}, summer 5.9 mg N_2O-N.AU^{-1}.d^{-1} (McGahan et al., 2016).
3 fattening pigs farms; SLR lagoons; every M, MBIGA; lagoon concentration 636.8 mg NH_4-N kg^{-1}, 201.0 mg NH_4-N kg^{-1}, 236.6 mg NH_4-N kg^{-1}, 0.3 kg N_2O-N ha^{-1} d^{-1}, 0.4 kg N_2O-N ha^{-1} d^{-1}, 0.0 kg N_2O-N ha^{-1} d^{-1} (Harper et al 2004).
Manure, fattening pigs, DL, stored 113 ds; every wk, RC (tent), GC; d 11: 28 mg N_2O-N.kg DM^{-1} d^{-1}, after d 40: 6 mg N_2O-N.kg DM^{-1} d^{-1} (Wolter et al 2004).

The increase in manure organic matter accelerates soil metabolism, depleting oxygen, triggering denitrification and N_2O emissions (Hristov et al 2013; Gerber et al 2013). On the contrary, anaerobic digestion, or separation of manure solids, lowers the organic content of manure, which generally results in lower emissions of N_2O (Clemens et al 2006; Velthof and Mosquera 2011; Gerber et al 2013). Manure affects the balance between NH_3 and N_2O emissions. This interaction may be positive (e.g., both emissions are reduced by an airtight cover during storage and stimulated by composting), or negative (e.g., direct N_2O emissions from soil will potentially increase if losses of NH_3 are prevented during storage or field application) (Petersen and Sommer 2011). N_2O release from stored manure was low when NH_3 was high (Külling et al 2002).

The amount of N_2O produced from manure storage depends on the amount of N excreted and duration of storage (Merino et al 2011). Solid manure rich in high fiber bedding material has a high porosity that promotes aerobic fermentation, and heat, which can stimulate N_2O emissions (Petersen et al 1998). Also, the higher the density the lower the emission of N_2O (Oenema et al 2005). However, covering delayed aeration of the stored manure; this reduced internal heat production, degradation of organic matter, and emission of greenhouse gases and ammonia (Hansen et al 2006). At the study of Sommer and Moller (2000) was production of N_2O restricted to the surface layers during the thermophilic phase of composting (Sommer and Moller 2000). Brown et al (2000) found that the mean N_2O-N fluxes were between 0 and 0.33 g N m^{-2} d^{-1}, and N_2O was only generated in samples from the top two layers of the dairy FYM pile. Manure samples from the 30 to 45 cm depth were adjusted by amendment with chopped straw to 70, 75, and 80 % water content. These samples produced twice as much N_2O-N as the unamended samples.

Slurry separation reduces emissions if losses during storage of the solid fraction can be kept on a low level (Amon et al 2006b). At the study of Hansen et al (2006), emissions of N_2O from an uncovered and covered heap of solid manure separated from pig SLR were compared, and related to the oxygenation level inside the manure heap. Approximately 15 % of the initial nitrogen content of the solids separated was found to be lost when the separated solids were stored uncovered. Almost 5 % of the initial N content was found to be lost as N_2O. Emissions of N_2O were reduced by 12 %, when the manure heap was covered with

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an airtight material. The oxygenation level inside heaps of solids separated from pig SLR was found to influence the production and emission of greenhouse gases during the storage period (Hansen et al 2006).

In contrast, in liquid manure lagoons particulate organic matter is a physical barrier against gas exchange when a surface crust forms (Petersen and Sommer 2011). Anaerobic digestion is in fact an effective means to reduce greenhouse gas emission (Amon et al 2006a). However, the anaerobically stored FYM emitted more N_2O emissions than the composted farm yard manure (Amon et al 1998a; Amon et al 2001).

Covering the SLR store with a layer of chopped straw increased greenhouse gas emissions mainly by increasing N_2O emissions. When liquid manure stored as anaerobic SLR, N_2O emission is low, but NH_3 and CH_4 emissions are high, depending on the cover of the slurry and mixing rate (Oenema et al 2005). N_2O emissions can occur from SLR when a dry crust is formed on the surface with combination of anaerobic and aerobic micro-sites (Philippe and Nicks 2013). Therefore, straw cover and SLR aeration showed negative environmental effects (Amon et al 2006b).

Natural surface crusts may develop into a porous matrix with high O_2 availability that harbors an active population of aerobic microorganisms. The occurrence of NO_2^- and NO_3^- in the crusts also indicate the presence of actively metabolizing NH_3^- oxidizing bacteria (Nielsen et al 2010). The floating crust is important because it provides a substrate that spans anaerobic and aerobic environments, where N_2O production can occurs (Petersen and Sommer 2011).

Floating crusts on manure storages are environments with intense microbial activity, and microbial processes are governed by the extent of oxic conditions that are governed by the moisture of the crust. Hansen et al (2009) study investigated whether physical properties of the crust or crust microbiology had an effect on the emission of the N_2O when crust moisture was manipulated (dry, moderate, and wet). However, an increase in N_2O emission was observed in all crusted treatments exposed to anoxia, and this was probably a result of denitrification based on NO_x that had accumulated in the crust during oxic conditions.

Comparison of manure types

The type of manure can be crucial factors in reducing the extent of nitrogen lost (Bell et al 2016). The amount of N_2O produced from manure storage depends on type of manure management (Yamulki 2006; Merino et al 2011; Rzeźnik and Mielcarek 2014). Total manure emissions are the product of the amount of N excreted during storage multiplied by the associated emission factor for that manure management system and animal population (Crosson et al 2011).

A lower dietary protein content furthermore reduced N_2O emission rates in most manure types but increased CH_4 emission from urine-rich SLR. In deep litter manure, characterized by the highest C: N ratio, emission rates of total N, N_2O values were intermediate. Substantial emission of N_2O occurred with FYM. C: N ratio of manure was shown to be suitable to predict total N loss during storage in all manure types whereas urine N proportion and manure pH were only of use with liquid manures (Külling et al 2002).

Amon et al. (1998b) compared N_2O emission in solid and liquid manure management systems. In the tie-stall housing of dairy cows no differences were found between a SLR based and a straw based system. Only deep litter systems with straw showed higher N_2O emissions. This reflected the higher microbial biomass content and approximately neutral pH at FYM field (Mogge et al 1999).

N_2O synthesis needs close combination of aerobic and anaerobic areas. These heterogeneous conditions are not met within SLR but deep litter (Philippe and Nicks 2013). Therefore, for waste of a given N content, anaerobic lagoons will result in the least N_2O emissions whereas solid storage and dry-lot handling will promote emissions (Paustian et al 2004). The anaerobic nature of liquid manure systems reduces N_2O production (Kebreab et al 2006).

Majority of swine production systems use anaerobic or liquid-slurry systems for waste holding or disposal (Harper et al 2000). A model has been developed to predict pig manure evolution (mass, dry and organic matter, and N contents) and related gaseous emissions nitrous oxide (N_2O) from pig excreta up to manure stored before spreading. This model simulates contrasted management systems, including different options for housing (slatted floor or deep litter), outside storage of manure and treatment (anaerobic digestion, biological N removal processes, SLR with straw and solid manure composting (Rigolot et al 2010).

The results of Fournel et al (2012) showed that liquid manure from deep-pit housing systems produces greater emissions of nitrous oxide (N_2O) than natural and forced dried manure from belt housing systems. The study of Cabrera et al (1994) on N_2O emissions from poultry litter compared pellets or fine particles. Cumulative emission of N_2O was slightly higher for pelletized (6.8 % of applied N) than for fine-particle litter (5.5 %). Authors indicate that the effect of poultry litter physical characteristics on N_2O emissions can be expected to vary depending on the soil water regime (Cabrera et al 1994).

Application method

N_2O emissions are strongly dependent on the method and timing of fertilizer application. Manure incorporation

increased N_2O emissions and yield for the perennial system, but both effects were dependent on the interannual weather variability and crop growth (Webb et al 2014). High temperatures, high wind speed and low rainfall immediately following manure application promote emissions from manures containing a high amount of readily available N. Emissions of N_2O were significantly affected by the timing of manure application, with greatest N_2O emissions measured from manures applied and incorporated into bare soil in warmer and wetter autumn conditions. Mean annual N_2O emissions across all manure treatments were greater from autumn (2 kg N_2O–N ha^{-1}) than spring (0.35 kg N_2O – N ha^{-1}) applications (Bell et al 2016).

The more frequent soil application may increase N_2O emissions, if application occurs during prolonged periods with warm temperature, wet soil and low plant-N uptake. Therefore, a combination of decreased storage time in warm weather and extended winter storage is a viable option in many regions (Hristov et al 2013; Gerber et al 2013). Following field application, infiltration of liquid is influenced by manure organic matter, and retention of ammoniacal N at the soil surface will enhance NH_3 volatilization (Petersen and Sommer 2011).

Final considerations

Farms emit N_2O arising mainly from manure application to soil, faces deposition by grazing animals, or manure storages. The various pathways of N_2O formation described above also apply to the manure environment, but the potential for N_2O emissions will depend on manure management practice. Nitrification and denitrification rates of manure are affected by numerous soil and climatic or seasonal factors.

Emissions of N_2O are significantly affected by the timing of manure application, with greatest N_2O emissions measured from manures applied and incorporated into bare soil in warmer and wetter autumn conditions. Straw cover, floating crust and aeration of slurry showed negative environmental effects. An extended review revealed that more data are needed to better quantify emissions from manure management.

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References

Adler AA, Doole GJ, Romera AJ, Beukes PC (2015) Managing greenhouse gas emissions in two major dairy regions of New Zealand: A system-level evaluation. Agricultural Systems, 135:1–9.

Amon B, Amon T, Boxberger J, Pöllinger A (1998a) Emissions of NH3, N2O and CH4 from composted and anaerobically stored farmyard manure. In: Martinez J, Maudet MN (eds) Management Strategies for Organic Wastes in Agriculture. FAO European Cooperative Research Network on Recycling of Agricultural, Municipal and Industrial Residues in Agriculture; Ramiran, pp 209–216.

Amon B, Boxberger J, Amon T, Zaussinger A, Pöllinger A (1998b) Emissions of NH3, N2O and CH4 from a tying stall for milking cows during storage of farmyard manure and after spreading. In Martinez J, Maudet MN (eds) Management Strategies for Organic Wastes in Agriculture. FAO European Cooperative Research Network on Recycling of Agricultural, Municipal and Industrial Residues in Agriculture; Ramiran, pp 269–278.

Amon B, Amon T, Boxberger J, Alt Ch (2001) Emissions of NH3, N2O, and CH4 from dairy cows housed in a farmyard manure tying stall (housing, manure storage, manure spreading). Nutrient Cycling Agroecosystems, 60:103–113.

Amon B, Kryvoruchko V, Amon T, Zechmeister-Boltenstern S (2006a) Methane, nitrous oxide and ammonia emissions during storage and after application of dairy cattle slurry and influence of slurry treatment. Agriculture Ecosystems & Environment, 112:153–162.

Amon B, Kryvoruchko V, Moitzi G, Amon T (2006b) Greenhouse gas and ammonia emission abatement by slurry treatment. International Congress Series, 1293:295–298.

Amon B, Kryvoruchko V, Frohlich M, Amon T, Pollinger A, Mosenbacher I, Hausleitner A (2007) Ammonia and greenhouse gas emissions from a straw flow system for fattening pigs: housing and manure storage. Livestock Science, 112:199–207.

Bell MJ, Hinton NJ, Cloy JM, Topp CFE, Rees RM, Williams JR, Misselbrook TH, Chadwick DR (2016) How do emission rates and emission factors for nitrous oxide and ammonia vary with manure type and time of application in a Scottish farmland? Geoderma, 264:81–93.

Borhan MS, Capareda S, Mukhtar S, Faulkner WB, McGee R, Parnell Jr. CB (2011) Determining Seasonal Greenhouse Gas Emissions from Ground Level Area Sources in a Dairy Operation in Central Texas. Journal of Air and Waste Management, 61:786–795.

Brown HA, Wagner-Riddle C, Thurtell GW (2000) Nitrous oxide flux from solid dairy manure in storage as affected by water content and redox potential. Journal of Environmental Quality, 29:630–638.

Cabrera ML, Chiang SC, Merka WC, Pancorbo OC, Thompson SA (1994) Nitrous-oxide and carbon-dioxide emissions from pelletized and nonpelletized poultry litter incorporated into soil. Plant and Soil, 163:189–195.

Castillo AR, Kebreab E, Beever DE, France J (2000) A review of efficiency of nitrogen utilisation in lactating dairy cows and its relationship with environmental pollution. Journal of Animal and Feed Sciences, 9:1–32.

Chadwick DR, Pain BF, Brookmann SKE (2000) Nitrous oxide and methane emissions following application of animal manures to grassland. Journal of Environmental Quality, 29:277–287.

Chianese DS, Rotz CA, Richard TL (2009) Simulation of nitrous oxide emissions from dairy farms to assess greenhouse gas reduction strategies. Transactions the ASABE, 52:1325–1335.

Clemens J, Trimborn M, Weiland P, Amon B (2006) Mitigation of greenhouse gas emissions by anaerobic digestion of cattle slurry. Agriculture, Ecosystems & Environment, 112:171–177.

Crosson P, Shalloo L, O'Brien D, Lanigan GJ, Foley PA, Boland TM, Kenny DA (2011) A review of whole farm systems models of greenhouse gas emissions from beef and dairy cattle production systems. Animal Feed Science and Technology, 166–167:29–45.

Davidson EA (2009) The contribution of manure and fertilizer nitrogen to atmospheric nitrous oxide since 1860. Nature Geoscience, 2:659–662.

Eckard RJ, Chen D, White RE, Chapman DF (2003) Gaseous nitrogen loss from temperate grass and clover dairy pastures in south eastern Australia. Australian Journal of Agriculture Research, 54:561–570.

Eckard RJ, Chapman DF, White RE (2007) Nitrogen balances in temperate perennial grass and clover dairy pastures in south-eastern Australia. Australian Journal of Agriculture Research, 58:1167–1173.

Fabbri C, Costa A, Guarino M, Valli L, Mazzotta V (2007) Ammonia, Methane, Nitrous Oxide and Particulate Matter Emissions from Two Different Buildings for Laying Hens. Biosystems Engineering, 97:441–455.

Fournel S, Pelletier F, Godbout S, Lagacé R, Feddes J (2012) Greenhouse Gas Emissions from Three Cage Layer Housing Systems. Animals, 2:1–15.

Gerber PJ, Hristov AN, Henderson B, Makkar H, Oh J, Lee C, Meinen R, Montes F, Ott T, Firkins J, Rotz A, Dell C, Adesogan AT, Yang WZ, Tricarico JM, Kebreab E, Waghorn G, Dijkstra J. Oosting S (2013) Technical options for the mitigation of direct methane and nitrous oxide emissions from livestock: a review. Animal 7, 2:220–234.

Hansen MN, Henriksen K, Sommer SG (2006) Observations of production and emission of greenhouse gases and ammonia during storage of solids separated from pig slurry: Effects of covering. Atmospheric Environment, 40:4172–4181.

Hansen R, Nielsen D, Schramm A, Nielsen L, Revsbech N, Hansen M (2009) Greenhouse gas microbiology in wet and dry straw crust covering pig slurry. Journal of Environmental Quality, 38:1311–1319.

Harper LA, Sharpe RR, Parkin TB (2000) Gaseous nitrogen emissions from anaerobic swine lagoons: ammonia, nitrous oxide, and dinitrogen gas. Journal of Environmental Quality, 29:1356–1365.

Harper LA, Sharpe RR, Parkin TB, Visscher de A, Cleemput van O, Byers FM (2004) Nitrogen Cycling through Swine Production Systems: Ammonia, Dinitrogen, and Nitrous Oxide Emissions. Journal of Environmental Quality, 33:1189–1201.

Hristov AN, Oh J, Firkins J, Dijkstra J, Kebreab E, Waghorn G, Makkar HPS, Adesogan AT, Yang W, Lee C, Gerber PJ, Henderson B, Tricarico JM (2013) Mitigation of methane and nitrous oxide emissions from animal operations: I. A review of enteric methane mitigation options. Journal of Animal Science, 91:5045–5069.

Jungbluth T, Hartung E, Brose G (2001) Greenhouse emissions from animal houses and manure stores. Nutrients Cycling Agroecosystem, 60:133–145.

Kebreab E, Clark K, Wagner-Riddle C, France J (2006) Methane and nitrous oxide emissions from Canadian animal agriculture: A review. Canadian Journal of Animal Science, 86:135–158.

Klein de CAM, Eckard RJ (2008) Targeted technologies for nitrous oxide abatement from animal agriculture. Australian Journal of Experimental Agriculture, 48:14–20.

Külling DR, Henzi HK, Krober TF, Neftel A, Sutter F, Lischer P, Kreuzer M (2001) Emissions of ammonia, nitrous oxide and methane from different types of dairy manure during storage as affected by dietary protein content. Journal of Agricultural Science, 137:S235–250.

Li C, Salas W, Zhang R, Krauter C, Rotz AC, Mitloehner F (2012) Manure-DNDC: a biogeochemical process model for quantifying greenhouse gas and ammonia emissions from livestock manure systems. Nutrient Cycling in Agroecosystems, 93:163–200.

Li J, Shi Y, Luo J, Zaman M, Houlbrooke D, Ding W, Ledgard S, Ghani A (2014). Use of nitrogen process inhibitors for reducing gaseous nitrogen losses from land-applied farm effluents. Biology and Fertility of Soils, 50:133–145.

Mahimairaja S, Bolan NS, Hedley MJ (1995) Denitrification losses of N from fresh and composted manures. Soil Biology and Biochemistry, 27:1223–1225.

McGahan EJ, Phillips FA, Wiedemann SG, Naylor TA, Warren B, Murphy CM, Griffith DWT, Desservettaz M (2016). Methane, nitrous oxide and ammonia emissions from an Australian piggery with short and long hydraulic retention-time effluent storage. Animal Production Science, 56:1376–1389.

Merino P, Ramirez-Fanlo E, Arriaga H, del Hierro O, Artetxe A, Viguria M (2011) Regional inventory of methane and nitrous oxide emission from ruminant livestock in the Basque Country. Animal Feed Science and Technology, 166-167:628–640.

Middelaar Van CE, Berentsen PBM, Dijkstra J, De Boer IJM (2013) Evaluation of a feeding strategy to reduce greenhouse gas emissions from dairy farming: The level of analysis matters. Agricultural Systems, 121:9–22.

Mihina S, Kazimirova V, Copland TA (2012) Technology for farm animal husbandry. 1st Edition. Nitra: Slovak Agricultural University. 99 p.

Mogge B, Kaiser EA, Munch JC (1999) Nitrous oxide emissions and denitrification N-losses from agricultural soils in the Bornhoved Lake region: influence of organic fertilizers and land-use. Soil Biology and Biochemistry, 31:1245–1252.

Monaghan RM, Barraclough D (1993) Nitrous oxide and dinitrogen emissions from urine-affected soil under controlled conditions. Plant and Soil, 151:127–138.

Montes F, Meinen R, Dell C, Rotz A, Hristov AN, Oh J, Waghorn G, Gerber PJ, Henderson B, Makkar HPS, Dijkstra J (2013) Mitigation of methane and nitrous oxide emissions from animal operations: II. A review of manure management mitigation options. Journal of Animal Science, 91:5070–5094.

Mosier AR, Duxbury JM, Freney JR, Heinemeyer O, Minami K (1998) Assessing and mitigating N_2O emissions from agricultural soils. Climatic Change, 40:7–38.

Nielsen D, Schramm A, Revsbech N (2010) Oxygen distribution and potential ammonia oxidation in floating liquid manure crusts. Journal of Environmental Quality, 39:1813–1820.

Oenema O, Wrage N, Velthof G, Groenigen JW, Dolfing J, Kuikman P (2005) Trends in Global Nitrous Oxide Emissions from Animal Production Systems. Nutrient Cycling in Agroecosystems, 72:51–65.

Owen JJ, Silver WL (2015) Greenhouse gas emissions from dairy manure management: a review of field-based studies. Global Change Biology, 21:550–565.

Paustian K, Babcock B, Kling C, Hatfield J, Lal R, McCarl B, McLaughlin S, Post WM, Mosier A, Rice C, Robertson GP, Rosenberg NJ, Rosenzweig C, Schlesinger WH, Zilberman D (2004) In Agricultural Mitigation of Greenhouse Gases: Science and Policy Options; Council on Agricultural Science and Technology (CAST); Report #R141, ISBN 1- 887383-26-3.

Petersen SO, Lind AM, Sommer SG (1998) Nitrogen and organic matter losses during storage of cattle and pig manure. Journal of Agricultural Science, 130:69–79.

Petersen SO, Sommer SG (2011) Ammonia and nitrous oxide interactions: roles of manure organic matter management. Animal Feed Science and Technology, 166:503–513.

Philippe FX, Nicks B (2013) Emissions of ammonia, nitrous oxide and methane from pig houses: Influencing factors and mitigation techniques. In Reconciling livestock management to the environment - Applying Best Available Technique (BAT): From the lab to the farm. European Workshop: Reconciling the environment with livestock management, du 19 au 20 mars 2013, IRSTEA, Rennes, France. 10 p.

Pratt C, Redding M, Hill J, Shilton A, Chung M, Guieysse B (2014) Good science for improving policy: greenhouse gas emissions from agricultural manures. Animal Production Science, 55:691–701.

Redding M, Devereux J, Phillips F, Lewis R, Naylor T, Kearton T, Hill CJ, Weidemann S (2015) Field measurement of beef pen manure methane and nitrous oxide reveals a surprise for inventory calculations. Journal of Environmental Quality, 44:720–728.

Rigolot C, Espagnol S, Robin P, Hassouna M, Beline F, Paillat JM, Dourmad JY (2010) Modelling of manure production by pigs and NH3, N2O and CH4 emissions. Part II: effect of animal housing, manure storage and treatment practices. Animal, 4:1413–1424.

Rzeźnik W, Mielcarek P (2014) Comparison of greenhouse gas emissions during summer from deep litter and fully-slatted piggery. Agricultural Engineering, 151:169-177.

Rzeźnik W, Mielcarek P (2016) Greenhouse Gases and Ammonia Emission Factors from Livestock Buildings for Pigs and Dairy Cows. Polish Journal of Environmental Studies, 25:1-9.

Saggar S, Bolan NS, Bhandral R, Hedley CB, Luo J (2004) A review of emissions of methane, ammonia and nitrous oxide from animal excreta deposition and farm effluent application in grazed pastures. New Zealand Journal of Agricultural Research, 47:513–544.

Schils RLM, Eriksen J, Ledgard SF, Vellinga TV, Kuikman PJ, Luo J, Petersen SO, Velthof GL (2013) Strategies to mitigate nitrous oxide emissions from herbivore production systems. Animal, 7:29–40.

Sommer SG, Moller HB (2000) Emission of greenhouse gases during composting of deep litter from pig production - effect of straw content. Journal of Agricultural Science, 134:327–335.

Velthof GL, Mosquera J (2011) The impact of slurry application technique on nitrous oxide emission from agricultural soils. Agriculture, Ecosystems & Environment, 140:298–308.

Whalen SC, Phillips RL, Fischer EN (2000) Nitrous oxide emission from an agricultural field fertilized with liquid lagoonal swine effluent. Global Biogeochemical Cycles, 14:545-558.

Whalen SC (2000) Nitrous Oxide Emission from an Agricultural Soil Fertilized with Liquid Swine Waste or Constituents. Soil Science Society of America Journal, 64:781–789.

Webb J, Thorman R, Fernanda-Aller M, Jackson D (2014) Emission factors for ammonia and nitrous oxide emissions following immediate manure incorporation on two contrasting soil types. Atmospheric Environment, 82:280–287.

Wolter M, Prayitno S, Schuchardt F (2004) Greenhouse gas emission during storage of pig manure on a pilot scale. Bioresource Technology, 95:235–244.

Yamulki S (2006) Effect of straw addition on nitrous oxide and methane emissions from stored farmyard manures. Agriculture, Ecosystems & Environment, 112:140–145.

Abbreviations

C = carbon
CCH = closed chamber
CO_2 = carbon dioxide
CV = coefficient of variation
d = day
ds = days
DIM = days in milk
DL = deep litter
DM = dry mater
ds = days
FC = flux chamber
FMC = floating measuring chamber
FS = fully slatted
FTIR = Fourier transform infrared spectroscopy
FYM = farmyard manure
GC = gas chromatography
h = hour
LBW = live body weight
LU = live unit (500 kg of LBW)
M = month
MBIGA = mass balance method from 24 h gas sampling
MC = measuring chamber
MY = milk yield
MS = manure system
N = nitrogen
NH_3 = ammonium
ODC = open dynamic chamber
RC = respiration chamber
SLR = slurry
TDL = Tuneable Diode Laser absorption spectrometer
TMR = total mixed ration
yr = year
yrs = years
wk = week
wks = weeks

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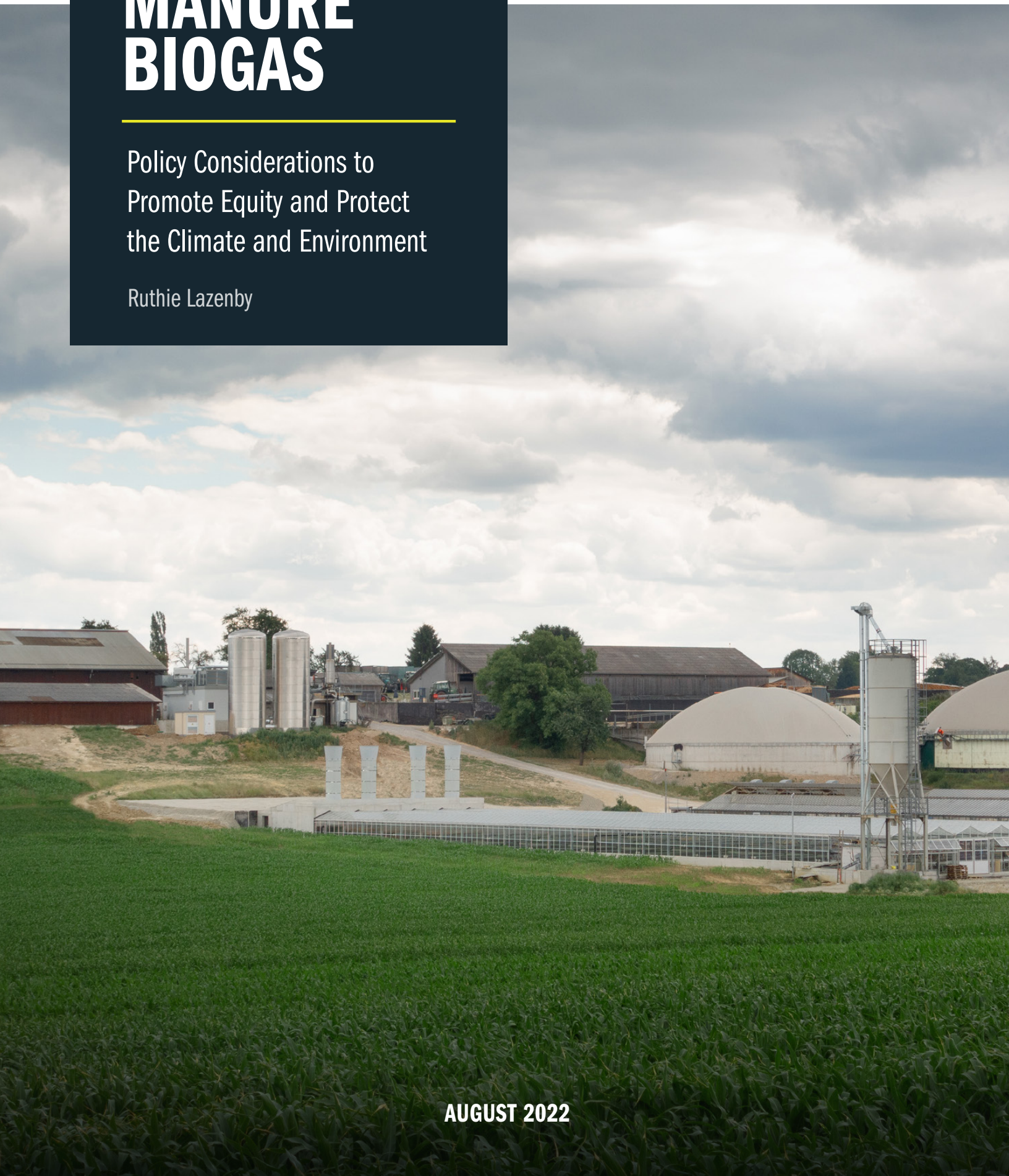
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RETHINKING MANURE BIOGAS

Policy Considerations to Promote Equity and Protect the Climate and Environment

Ruthie Lazenby

VERMONT LAW & GRADUATE SCHOOL
CENTER FOR AGRICULTURE & FOOD SYSTEMS



AUGUST 2022



AUTHORS & ACKNOWLEDGMENTS

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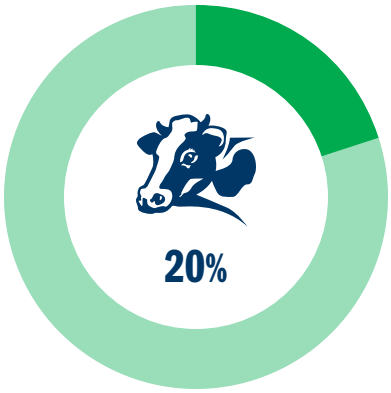


INTRODUCTION

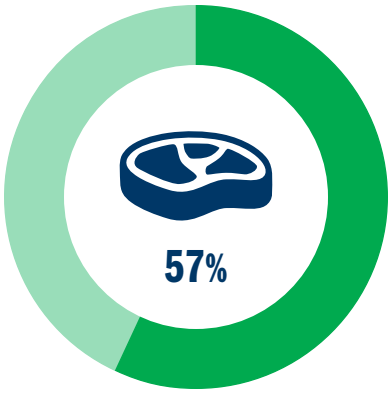
THE WORLD IS ON TRACK TO EXCEED A 2° C INCREASE DURING THE 21ST CENTURY, an outcome scientists have described as catastrophic.[1] Direct impacts on the food and agriculture sectors will be far-reaching.[2] Already, climate-related impacts to farming include "observed changes in extremes such as heatwaves, heavy precipitation, droughts, and tropical cyclones."[3] These changes impact both crop and livestock production. Experts predict that further warming will continue to dramatically affect the "global water cycle and its variability, global monsoon precipitation and the severity of wet and dry events."[4]

In regions like eastern North Carolina, home to the United States' top two pork producing counties,[5] producers will experience more regular hurricanes of greater magnitude.[6] California's Central Valley, which provides cropland for over 250 different crops[7] and houses 80 percent of the state's milk cows,[8] already relies on the second most over-pumped aquifer in the nation while facing substantially drier conditions as a result of climate change.[9] These impacts will disproportionately harm vulnerable populations[10] in addition to historically marginalized farmers, who will be the first to lose their livelihoods.[11] Climate change will force agriculture to adapt—either now, through innovation to mitigate increased warming, or later, as regional climates become incompatible with existing models of food production.[12]

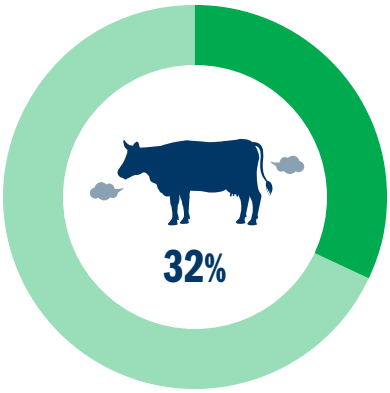
It is clear that the food and agriculture sector will bear significant impacts from climate change, but this sector is also a major contributor of greenhouse gas (GHG) emissions. Animal agriculture, in particular, is responsible for approximately 20 percent of global GHG emissions and 57 percent of food related emissions.[13] Animal agriculture's primary contributions to climate change result from methane and nitrous oxide emissions. Methane has a global warming potential 28 to 36 times that of carbon dioxide on a 100-year timescale and nitrous oxide has a global warming potential 265 to 298 times that that of carbon dioxide on a 100-year timescale.[14] Moreover, while emissions from the energy sector have decreased as a result of emission reduction policies, GHG emissions from agriculture have increased over recent decades with this trend projected to continue.[15] Consequently, addressing emissions from agriculture is increasingly critical.



Percent of global greenhouse gas emissions caused by animal agriculture



Percent of global food-based emissions caused by animal agriculture



Percent of global methane emissions caused by livestock manure and enteric fermentation

Source: Food in the Anthropocene: the EAT-Lancet Commission on Healthy Diets from Sustainable Food Systems, THE LANCET

One approach to reducing atmospheric GHGs from livestock involves capturing emissions from manure through the use of anaerobic digesters.[16] Proponents of this approach herald it as a win-win. Manure biogas systems reduce GHG emissions by capturing GHGs that would otherwise be emitted and can displace the use of fossil fuels. Additionally, this new fuel source (biogas) creates a new revenue stream from a former waste product. In a 2017 press release announcing federal funding to help farmers construct biogas systems, the United States Department of Agriculture (USDA) articulated the conventional wisdom of the emissions reduction claim, stating:

> "Anaerobic digesters actually provide two-fold greenhouse gas reduction. First, they capture methane that otherwise would be emitted from the manure into the atmosphere. . . . Second, by utilizing the trapped biogas as a renewable energy source, digesters displace the need for additional fossil fuels."[17]
>
> **– LAURA MELLING**

While these claims sound promising, they omit important nuance. **Animal agriculture generates emissions throughout the operation—from land conversion to enteric fermentation (the emissions generated from ruminant burps), to transportation.** It is imperative that policymakers and others recognize that manure biogas systems reduce emissions from only one part of this system—manure management. At the same time, manure biogas systems rely on the ongoing production of large quantities of livestock manure—the source of manure management emissions—to function. Espousing these systems to the exclusion of other emissions mitigation measures can foreclose the potential to make important modifications throughout the livestock life cycle. Ultimately, this reinforces current conventional models of livestock production at the expense of farmers using more sustainable production models.

Currently, policymakers are dedicating increasing amounts of public funding and attention to manure biogas as compared to other policy interventions that can reduce livestock emissions. Recently, the American Biogas Council suggested that the US could support at least another 13,740 potential new biogas systems, including 8,300 on farms, in addition to 4,000



What is Methane?

"Methane is produced as part of normal digestive processes in animals. During digestion, microbes resident in an animal's digestive system ferment food consumed by the animal. This microbial fermentation process, referred to as enteric fermentation, produces CH4 as a byproduct, which can be exhaled or eructated by the animal. The amount of CH4 produced and emitted by an individual animal depends primarily upon the animal's digestive system, and the amount and type of feed it consumes."

Source: Inventory of US Greenhouse Gas Emissions and Sinks (1990-2020), Environmental Protection Agency

What is Enteric Fermentation?

"Enteric fermentation is fermentation that takes place in the digestive systems of animals. In particular, ruminant animals (cattle, buffalo, sheep, goats, and camels) have a large "fore-stomach," or rumen, within which microbial fermentation breaks down food into soluble products that can be utilized by the animal."

Source: AP-42: Compilation of Air Emissions Factors, Environmental Protection Agency

What are Biosolids?

"Biosolids are a product of the wastewater treatment process. During wastewater treatment the liquids are separated from the solids. Those solids are then treated physically and chemically to produce a semisolid, nutrient-rich product known as biosolids. The terms 'biosolids' and 'sewage sludge' are often used interchangeably."

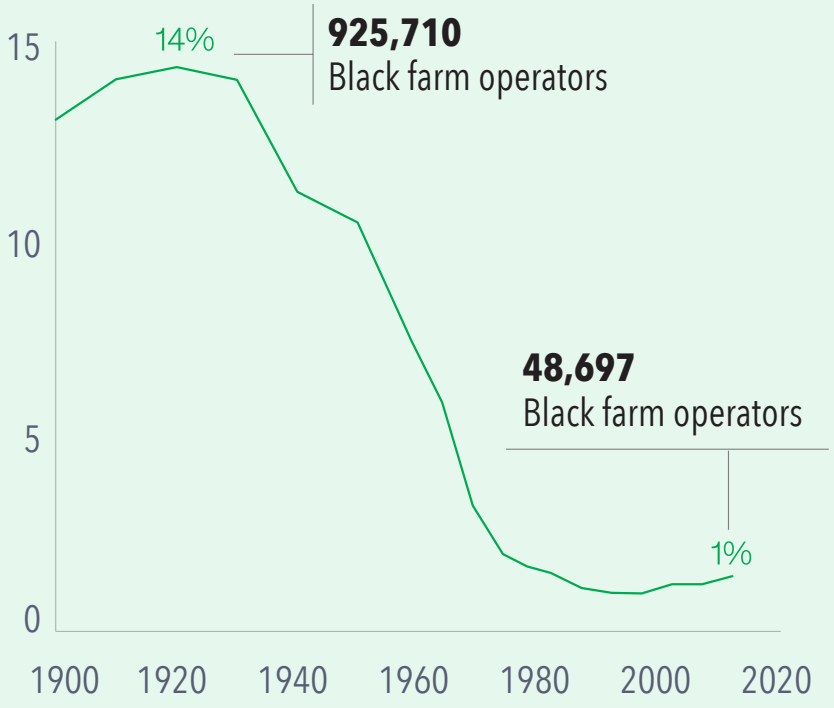
Source: Environmental Protection Agency

for wastewater, 1,000 for food scraps, and 440 for landfills.[18] Biogas systems are expensive to construct and operate. They require substantial investment into long-lasting, durable infrastructure such as pipeline interconnections and facilities upgrades. As more public and private resources are dedicated to this infrastructure, the incentives to continuing using these systems will increase.

To date, many discussions on the benefits of manure biogas fail to account for the concerning and negative implications associated with widespread adoption of manure biogas systems. For example, the climate implications resulting from the need for these systems to engage in long-term production of massive quantities of livestock manure (or other biosolids) to recoup the fixed upfront costs of installation and continued revenue generation is rarely addressed. To illustrate this point, the public programs subsidizing production and sale of biomethane from these operations provide incentives for the ongoing production of the core input—livestock manure—even as climate scientists warn that greater reductions from animal agriculture are necessary.[19] Promoting widespread investment in and adoption of manure biogas systems will inevitably impact livestock agriculture for years, if not decades, into the future, creating potential barriers for more substantial and systemic climate mitigation measures for the sector.

Moreover, because manure digesters are typically feasible only for industrial-scale livestock operations, the largest confined animal feeding operations will reap the financial and public relations benefits that accompany the installation of digesters. This is not a new trend: today and historically, large-scale commercial operations have benefited from the lion's share of federal funding for agriculture. Due to decades of discriminatory lending by USDA,[20] the majority of these operations are owned by white farmers.[21] Racism and discriminatory lending by the federal government over the past century has resulted in a dramatic loss of Black-owned land and farms across the board (one recent analysis calculated this dispossession to total $326 billion).[22] This disparity is even more pronounced for larger agricultural operations.[23] However, in some parts of the country, the substantial environmental impacts generated by these larger agricultural operations disproportionately harm Black, Indigenous, and communities of color.[24]

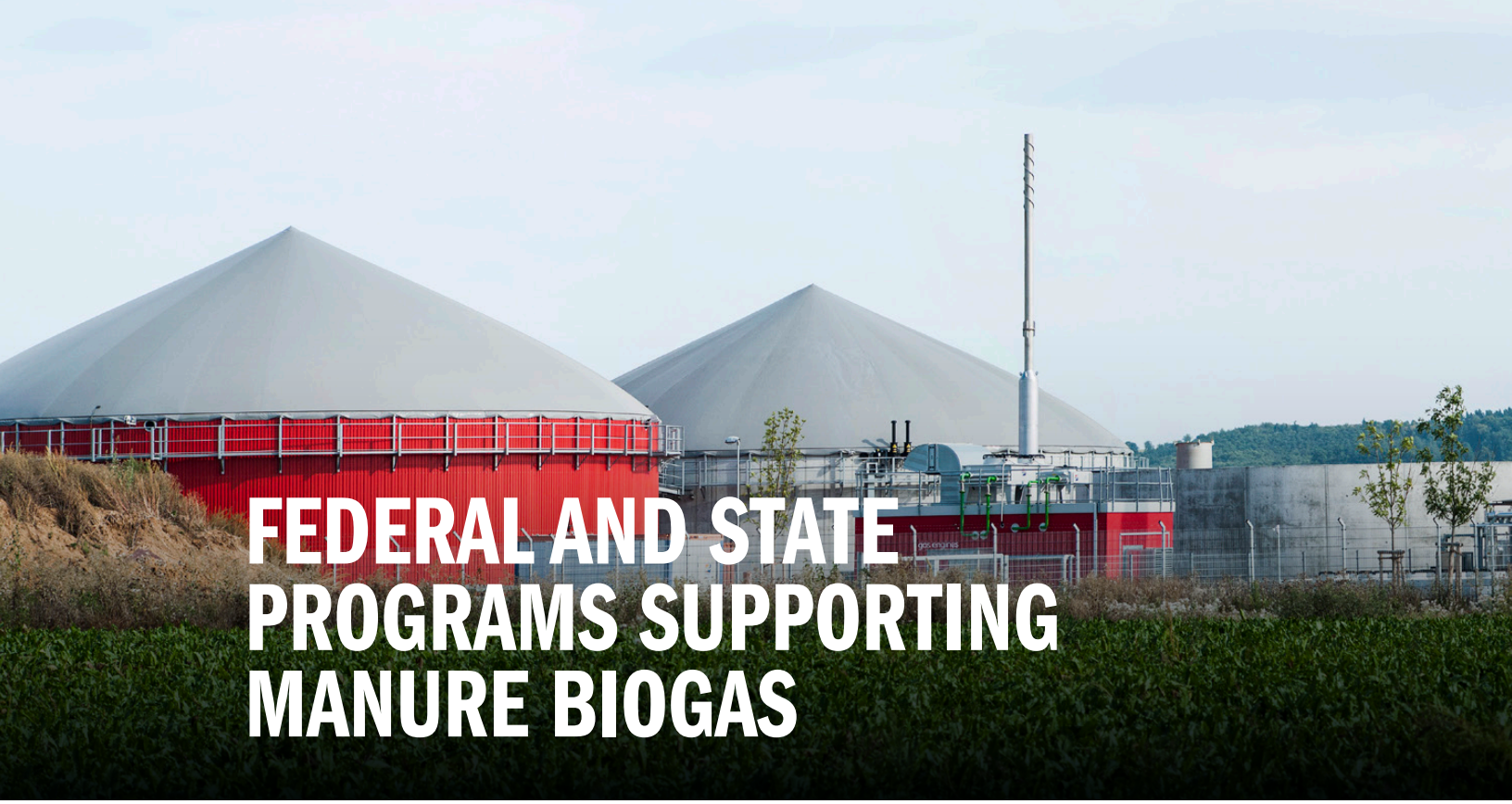
The share of Black farmers has declined significantly over the last century. Today just 1.4 percent of farmers identify as Black.



Source: Black farmers in the US: The opportunity for addressing racial disparities in farming, McKinsey & Company

Anaerobic digesters, in contrast to alternative mitigation measures, are an appealing means to reduce livestock emissions in industrial animal agriculture because they require no change to the structure of conventional livestock operations and manure management. On the contrary, these systems function by ensuring the continuity of both the existing system and its beneficiaries. This fails to consider and plan for the systemic changes needed in conventional operations and manure management due to the current, near, and long-term impacts of climate change.[25] Consequently, policymakers should immediately begin to proactively plan for the future by assessing the full range of suitable mitigation measures and supporting those that will provide for long-term sustainability and climate mitigation. As part of this process, policymakers must also critically evaluate the environmental justice impacts to neighboring communities and equity implications of elevating biogas systems over other mitigation measures.

This report analyzes and evaluates the extensive adoption and support of manure anaerobic digesters with a specific focus on the resulting equity implications, a goal explicitly aligned with two executive orders issued by the Biden Administration—Executive Order 14008: Tackling the Climate Crisis at Home and Abroad[26] and Executive Order 13985: Advancing Racial Equity and Support for Underserved Communities Through the Federal Government.[27] The report begins by surveying existing funding opportunities for manure biogas systems and the fuels they produce. It then addresses the direct environmental impacts of installing and operating these systems, including a brief discussion about the methodology used to account for life cycle emissions. The next section evaluates alternative methods to reduce livestock emissions, indirect environmental impacts of adopting manure biogas as the primary means to reduce GHG emissions from livestock operations, and the equity impacts. The report concludes with a set of recommendations for policymakers and regulators as they consider the role this technology should play in shifting livestock agriculture toward a more equitable, just, and climate-smart model.



FEDERAL AND STATE PROGRAMS SUPPORTING MANURE BIOGAS

THE BIDEN ADMINISTRATION HAS CONSISTENTLY EMPHASIZED ITS COMMITMENT TO CLIMATE-SMART AGRICULTURE and tasked a number of federal agencies with collecting input from stakeholders and developing plans to address the climate crisis.[28] USDA was directed to submit a report to the administration laying out an "agricultural and forestry strategy."[29] In USDA's 90-Day Progress Report on Climate-Smart Agriculture and Forestry,[30] the agency embraced the president's "focus on developing a climate-smart agriculture and forestry strategy that employs proven conservation practices," announced plans to reduce methane from livestock,[31] and significantly funded research efforts targeted at these reductions.[32] With this new momentum, policy attention and interest in manure biogas has never been greater due to the perception that it provides an easy solution to reduce atmospheric emissions without requiring significant changes to the conventional industrial livestock model. This section surveys many of the existing and overlapping funding sources and incentive programs for manure biogas.

Grants & Loans Covering Start-Up Costs

Direct financial support for anaerobic digester systems is available to livestock facilities in the form of grants and loans. At the federal level, the Rural Energy for America Program (REAP) provides guaranteed loan financing and grant funding for the construction of biogas systems.[33] Federal funds for biogas systems can also be obtained through USDA's conservation programs—the Environmental Quality Incentives Program (EQIP), the Conservation Stewardship Program (CSP), and the newer Conservation Loan Program (CLP).[34] While these conservation and energy programs are the most important sources of federal funds for manure biogas, many other programs support the development of the industry. The 2018 Farm Bill's Energy Title alone includes the Biorefinery, Renewable Chemical, and Biobased Product Manufacturing Assistance Program;[35] the Bioenergy Program for Advanced Biofuels;[36] Biomass Research and Development Program;[37] the Biodiesel Fuel Education Program;[38] and the Carbon Utilization and Biogas Education Program.[39]

USDA encourages livestock operations to "stack" multiple programs. In 2015, USDA stated:

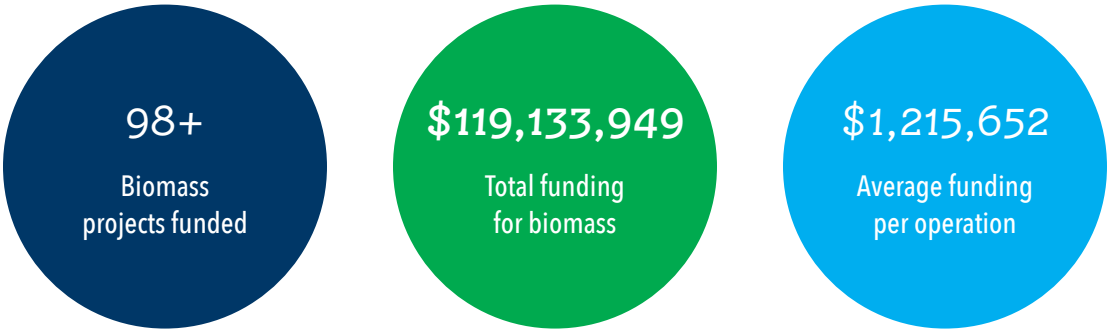
> To coordinate and maximize the potential assistance programs, Rural Development (RD) and Natural Resources Conservation Service (NRCS) met and developed a working partnership to deliver USDA services to producers interested in getting an anaerobic digester for their farming operation…. When "stacking," both RD and NRCS funding mechanisms can be used to assist in funding a project but each has limitations; for instance, the $450,000 cap on EQIP encompasses financial assistance for any practice that the producer wants to implement during the life of the Farm Bill.[40]

The report encourages the 50-50 use of EQIP and REAP funds and provides a detailed breakdown of estimated costs, where the two programs cover the total $1,778,950 required to construct the digester system.

Some states provide a similar suite of programs to fund the installation of manure biogas systems. In California, for example, the Dairy Digester Research & Development Program (DDRDP) provides funding for the installation of dairy digesters.[41] There are many smaller programs that offer grants, such as the Minnesota Department of Agriculture's Methane Digester Loan Program.[42]

The federal 1603 program, "Payments for Specified Energy Property in Lieu of Tax Credits,"[43] provides grants to reimburse businesses for a portion of the cost of installing certain energy projects, including anaerobic digesters on farms.[44] The 1603 program's creation as part of the American Recovery and Reinvestment Act in 2009 was "motivated by difficult economic conditions and the perceived lack of tax-equity capacity to support renewable energy projects" eligible for the tax credits discussed below.[45] While most 1603 funding has gone to wind and solar projects,[46] the program has provided funding for at least 98 projects designated "biomass (open loop, livestock)" for a total of $119,133,949.00 or an average of $1,215,652.54 per operation.[47]

1603 PROGRAM:
Payments for Specified Energy Property in Lieu of Tax Credits



Private investment is also available to livestock operations seeking funding to install digester systems. As public programs to subsidize manure biogas production proliferate, the industry has become increasingly appealing to private investors. A March 2021 report by Stifel Equity Research laid out the prospects for manure biogas as follows:

> We are bullish on the fundamentals of renewable natural gas (RNG) as it is positive for the environment (net negative carbon form of energy post-combustion), it is economic today (10-60 percent project IRRs), and offers immense growth potential (IEA projects an 18x increase in supply by 2040).[48]

The report noted that the current optimistic forecast for investors is closely linked to the enormous policy supports for this technology:[49]

> The combination of policy ([CA] Senate Bill 1383, requiring reductions in short-lived climate pollutants) and regulatory incentives (both federal and state) have driven the recent inflection in RNG growth. In our view, producers are not in the business of producing RNG; they are in the business of monetizing RNG's environmental attributes through various federal and state programs.[50]



Subsidies & Other Programs That Enhance Revenue from Biogas Sales

In addition to funding sources intended to help livestock operators cover the fixed costs of biogas system construction, state and federal programs subsidize the revenue from biogas production on an ongoing basis.

The Federal Renewable Fuel Standard (RFS), which requires transportation fuels sold in the United States to contain a minimum amount of renewable fuel (a "Renewable Volume Obligation"), is a key source of potential revenue for manure biogas operations. The RFS is a market-based program intended to reduce overall emissions from transportation fuels in the United States. It is structured like a cap-and-trade program, but rather than cap net GHG emissions, the RFS mandates a quota for the amount of renewable fuel that must be incorporated into conventional transportation fuels.

EPA measures the emissions impact of each eligible renewable fuel through the evaluation of fuel "pathways."[51] The pathway for each renewable fuel describes the inputs and processes required, as well as the life cycle GHGs.[52] Renewable fuel producers then apply to EPA for the specific pathways to which their fuel product corresponds. Once approved, these fuel producers can generate renewable identification numbers (RINs), which allow EPA to track and monitor these fuels.[53] Renewable fuels and their corresponding RINs can be sold to producers of conventional fuels so they can meet the quota required by the RFS. Biogas from manure digesters can be used to generate advanced biofuel RINs, coded D5 in the RFS regulation.[54] (77,000 British thermal units are equal to one gallon equivalent or one RIN.[55]) RINs are explicitly allowed to be layered on top of other analogous credits, such as those from California's Low Carbon Fuel Standard.[56]

Meeting the Federal Renewable Fuel Standard (RFS)

EPA measures the emissions impact of renewable fuels by evaluating their fuel "pathway," or the processes required to produce them. Biogas from manure digesters can be used to generate advanced biofuel renewable identification numbers (RINs).



Renewable fuel producers apply to EPA for their product's specific pathway.



Approved fuel producers generate RINs so EPA can track and monitor their fuels.

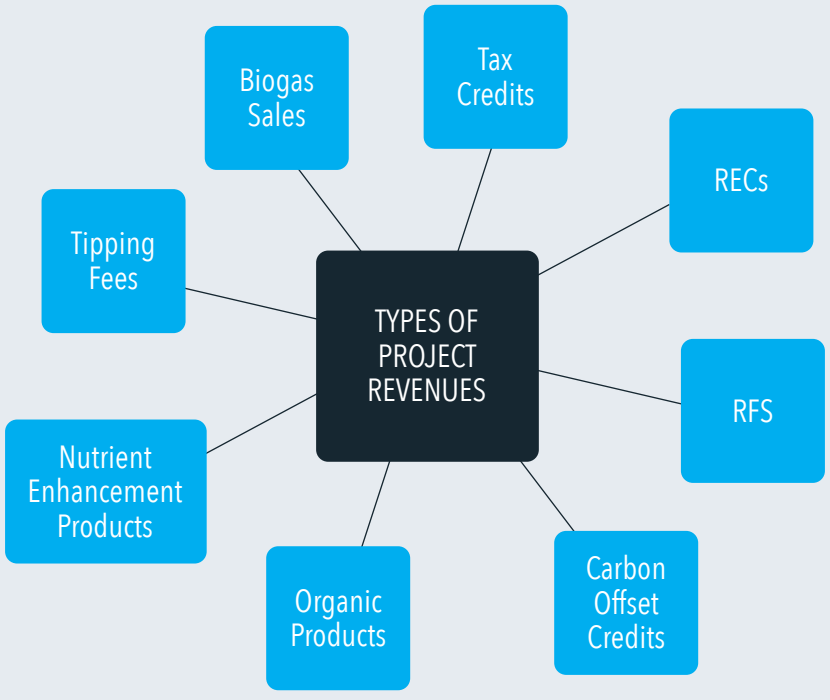


RINs can be sold to conventional fuel producers, allowing them to meet the Renewable Fuel Standard.

The federal Advanced Biofuel Payment Program also subsidizes biogas revenue. The program provides quarterly payments "for the actual quantity of eligible advanced biofuel produced during that quarter" to biofuel producers, including refined biogas from farms.[57] Entities that produce and sell biofuels, as defined in 7 CFR § 4288.102, can apply to participate in the program.[58] This program was granted $322,000,000 in mandatory funding between 2009 and 2023, in addition to $80,000,000 of discretionary funding authorized to be appropriated for the program between 2019 and 2023.[59]

In addition to direct payments, the federal government provides tax credits through the Electricity Production Credit and the Investment Tax Credit. Both corporate tax credits reduce energy producers' tax burdens, but while the Electricity Production Credit compensates producers on a per kilowatt-hour basis for renewable energy (including "open-loop biomass"), the Investment Tax Credit reimburses a set percentage of installation costs.[60] Importantly, taxpayers must choose either the Electricity Production Credit or the Investment Tax Credit—they cannot apply for both.

TYPES OF PROJECT REVENUES



Source: AgSTAR Project Development Handbook, Environmental Protection Agency

[61]

At the state level, the Biofuels Investment Tax Credit also allowed companies in Florida to recoup "75% of all capital, operation, maintenance, and research and development costs incurred in connection with an investment in the production, storage, and distribution of biodiesel (B10-B100), ethanol (E10-E100), or other renewable fuel" through 2016.[62] Additionally, industry groups tout California's Low Carbon Fuel Standard (LCFS) as a boon to the biogas industry's profitability.[63] The program creates a tradeable market for credits and deficits, which are allocated to transportation fuel producers based on the carbon intensity of the fuels they produce. Low carbon intensity fuels receive credits, while high carbon intensity fuels receive deficits. Like the federal RFS, California's LCFS program currently designates manure biogas as a negative emissions fuel and, consequently, awards profitable credits for its production.[64] This revenue is allocated to producers on an ongoing basis in proportion to the quantity of fuel they produce. Biogas producers that participate in the LCFS are also explicitly allowed to participate in California's cap-and-trade program, as well as the federal RFS. Like the stacking of USDA and DOE funds described above, layering multiple credits is explicitly described as a benefit.

Ultimately, however, the layering of credits from multiple market-based programs can undermine the additionality of emissions reductions claimed by those programs. Additionality is a term of art used to evaluate whether the policy intervention in question is in fact the cause of a given real-world behavior change. A behavior is not additional if it would have happened with or without the policy intervention. Compensating or crediting nonadditional behaviors, like the production of manure biogas, risks over-incentivizing them and even increasing rather than decreasing overall emissions. While California's LCFS is the most well-developed credit trading program for transportation fuels, other states are developing similarly structured programs, including Oregon's Clean Fuels Initiative program.

Finally, some states are creating reliable markets for these fuels as a source of "renewable energy" through utilities. Where renewable fuels standards like the programs described above focus on transportation fuels, renewable portfolio standards or renewable electricity standards focus on the use of renewable energy sources for electricity generation. These programs typically mandate that a certain amount of energy be derived from renewable sources and define what constitutes renewable sources for the purposes of the program. Much like the RINs in the federal renewable fuel standard, many renewable portfolio standards at the state level implement trading programs using renewable electricity certificates (RECs). State programs vary, but they usually include manure biogas as a renewable energy source.[65]

Considered collectively, these funds represent potential windfalls for operations well suited to the installation of manure biogas systems. But, smaller, less established operations, or operations that use dry manure management systems or grazing systems are unlikely to benefit from these funds, even though their models may be more climate smart overall in accord with the Biden Administration's stated goals and objectives.

More Information on Funding for Manure Biogas

- *Federal and State Laws and Incentives*, Alternative Fuels Data Center, https://afdc.energy.gov/laws/search
- U.S. Env't Protection Agency, AgStar Handbook, https://www.epa.gov/sites/default/files/2014-12/documents/agstar-handbook.pdf#page=81
- Cal. Dep't of Food and Agriculture, *Dairy Digester Research and Development Program Report of Funded Projects (2015-2019)* (April 2020), https://www.cdfa.ca.gov/oefi/ddrdp/docs/DDRDP_Report_April2020.pdf
- Cal. Public Utilities Comm'n., *Bioenergy Feed-In Tariff Program* (SB 1122), https://www.cpuc.ca.gov/SB_1122/





ANAEROBIC DIGESTERS CAN IMPOSE NEW ENVIRONMENTAL HARMS

TO PRODUCE BIOGAS FROM MANURE, farming operations must install an anaerobic digester, typically by capping or covering an existing manure lagoon to create an oxygen-free environment in which bacteria can break down organic matter. Biogas is a byproduct of this process. These systems offer some climate benefits (namely capturing methane and converting it to carbon dioxide during combustion) but their installation and use can also add new environmental harms. Such harms depend on a range of factors, including:

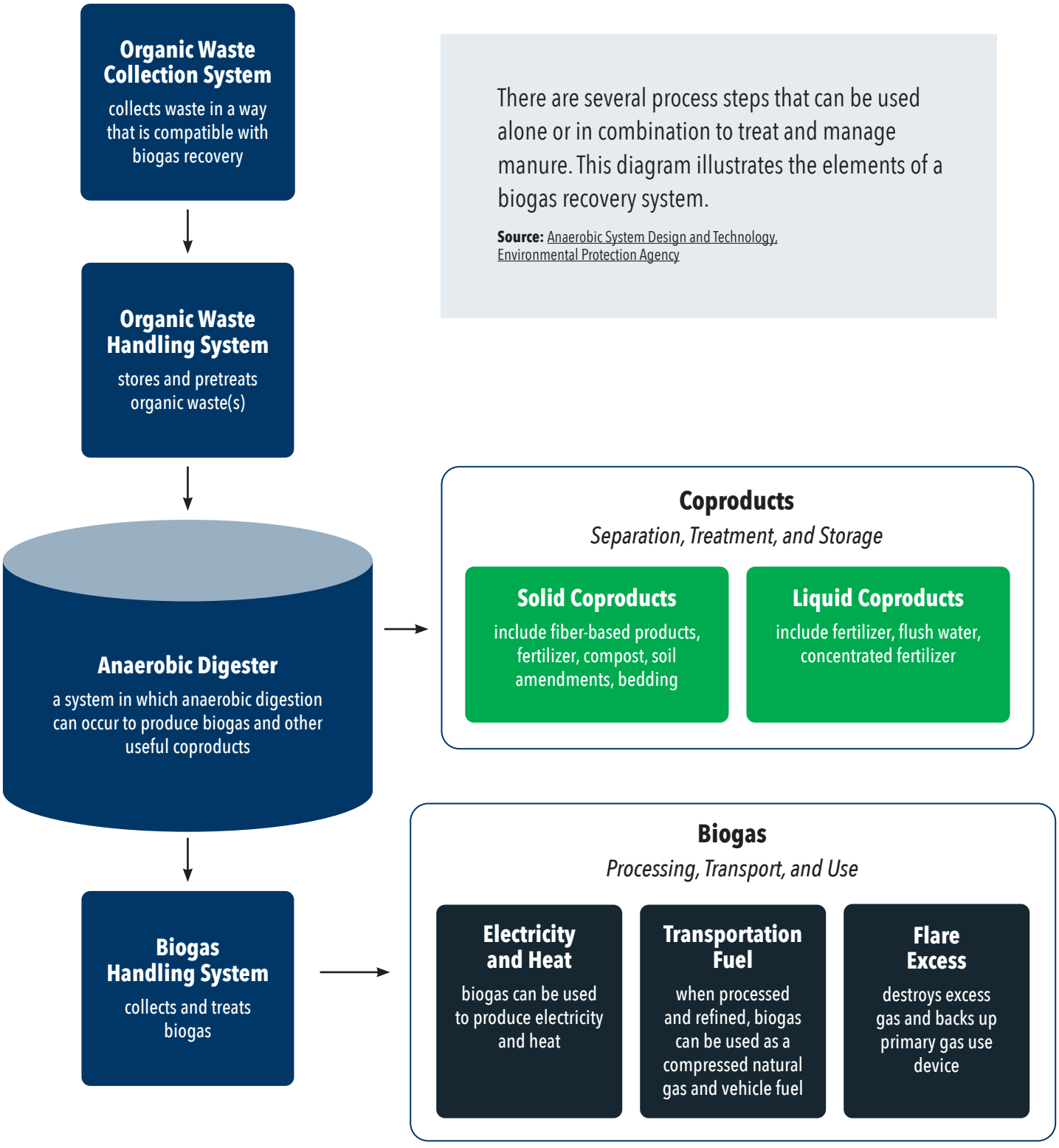
- the scale of the operations;
- the geography of the site;
- existing cumulative impacts to air and water;
- the end use of the biomethane; and
- the management of digestate (a byproduct of anaerobic digestion).

Through the process of anaerobic digestion, animal manure undergoes chemical changes that result in the production of a mix of gases, solid digestate, and liquid effluent. Biogas can be combusted to generate electricity on-site or exported as electricity and sold to the grid or at wholesale rates. The gases can be further "upgraded" to biomethane, which has a range of potential uses. Biomethane can be used on-site, injected into a pipeline, or used as a transportation fuel (when compressed to produce compressed natural gas).[66]

Through the process of anaerobic digestion, animal manure undergoes chemical changes that result in the production of a mix of gases, solid digestate, and liquid effluent.

Photo source: 20120717-OSEC-RBN-8338 by US Department of Agriculture is licensed under CC BY 2.0.

Anaerobic System Design & Technology



There are several process steps that can be used alone or in combination to treat and manage manure. This diagram illustrates the elements of a biogas recovery system.

Source: Anaerobic System Design and Technology, Environmental Protection Agency

Biogas Systems Primarily Benefit Large Operations Using Liquid Manure Management Systems

Two of EPA's screening questions to evaluate a livestock facility's potential for anaerobic digester systems ask whether the operation is "large" and whether it uses a liquid manure management system.[67] To be financially viable, biogas recovery systems typically require manure from at least 2,000 hogs or at least 500 cows.[68] According to EPA, manure biogas projects are "most likely to succeed where manure is collected as a liquid, slurry, or semi-solid and stored in open pits, ponds, or lagoons" because liquid manure can be easily flushed into lagoons.[69] Dry manure management is more common on pasture-based operations, where there is no easy manure collection system. Industrial scale operations and liquid manure management tend to go hand-in-hand because very large facilities often cannot dispose of all of their manure safely through land application without exceeding the amount of nutrients the land can take up. Additionally, liquefaction makes manure management less costly where livestock is confined.[70] A major downside to the liquefaction of manure, however, is that it generates more GHG emissions, since the anaerobic conditions in manure lagoons produce additional methane.[71] A 2022 EPA report explains:

To be financially viable, biogas recovery systems typically require manure from at least 2,000 hogs or at least 500 cows.

> When livestock manure is stored or treated in systems that promote anaerobic conditions (e.g., as a liquid/slurry in lagoons, ponds, tanks, or pits), the decomposition of the volatile solids component in the manure tends to produce CH4 (methane). When manure is handled as a solid (e.g., in stacks or drylots) or deposited on pasture, range, or paddock lands, it tends to decompose aerobically and produce CO2 and little or no CH4.[72]

The same report tied growth in industrial animal agriculture operations that liquefy manure to the broader increase in manure-related methane and nitrous oxide emissions since 1990.[73] EPA concluded:

> In many cases, manure management systems with the most substantial methane emissions are those associated with confined animal management operations where manure is handled in liquid-based systems… The shift toward larger dairy cattle and swine facilities since 1990 has translated into an increasing use of liquid manure management systems, which have higher potential CH4 emissions than dry systems.[74]

Biogas Systems Require New Infrastructure

Depending on the desired end use of the refined biomethane produced by anaerobic digestion and subsequent refining, operations require a range of additional infrastructure. New infrastructure can introduce additional truck traffic or pipeline interconnections and result in significant wear to common infrastructure such as roads. Depending on how the biogas is to be used, on-site gas treatment systems may be necessary to process the gas accordingly. Temporary storage systems for biogas may also be required and excess biogas may need to be flared, or burned off, in some cases.

Biogas Systems Produce New Co-Pollutants & Exacerbate Existing Co-Pollutants

Anaerobic digestion creates a byproduct called digestate, which can be used as animal bedding or as fertilizer. Digestate is chemically different from the original manure. Digestate contains "more soluble plant nutrients due to mineralization and has less degradable biomass than the original substrate resulting in changes in GHG and NH3 emissions."[75] The method of storage and treatment of digestate can significantly impact the total GHG emissions from the biogas system, as well as co-pollutants like volatile organic compounds (VOCs) and hydrogen sulfide.

A 2017 study seeking to provide clarity on the emissions impact of anaerobic digestion (versus solid-liquid separation versus a combination of the two methods) found that anaerobic digestion alone resulted in an 81 percent increase in ammonia emissions during storage.[76] The authors concluded that anaerobic digestion could "significantly increase NH3 emissions from manure storage if manure covers are not implemented."[77] While ammonia is not a greenhouse gas, it



creates serious public health harms and degrades air quality.[78] The study also found that the nitrous oxide from digested separated solids "was much higher than separated solids without digestion," canceling out net GHG reductions.[79] This indicates that the simple adoption of manure biogas systems is not enough to ensure a net reduction in emissions from a given operation.

One study at a swine biogas facility in China took digestate to a research facility, stored it under controlled conditions, and then measured resulting emissions. The study identified 49 VOCs, 22 of which have been described as hazardous air pollutants by EPA. Of these 22 hazardous VOCs, "11 of these had relatively high concentrations . . . 8 were identified to be or likely to be carcinogenic, and 14 were identified to be harmful to other human organs or systems."[80] While most studies on VOCs from manure focus on the odor-causing compounds, the "proportion of hazardous air pollutants (32.77 percent) was shown to be considerably higher than that of odorous pollutants (5.15 percent)."[81]

Another study looked at manure under anaerobic conditions from two different dairy farms in Japan and found that hydrogen sulfide emissions vary considerably based on the mixing speed and frequency of disturbance of the stored manure as well as the manure's total solid content, temperature, and pH. For example, when stored at 18 degrees Celsius (64 degrees Fahrenheit), there was a sudden increase in the concentration of hydrogen sulfide (H_2S).[82] Additionally, "[the highest H_2S emissions were achieved at the fastest speed and longest duration of manure mixing."[83] Given that exposure to hydrogen sulfide is extremely dangerous and has been linked to death, the storage and treatment of manure and digestate is critical.[84]

New Impacts Must Be Evaluated in Analyses of Biogas Systems

These new impacts must be incorporated into analyses intended to evaluate the potential benefits of manure biogas systems. Unfortunately, such analyses often omit key considerations regarding co-pollutants, new infrastructure, and the environmental justice and equity implications associated with manure biogas systems. As stated above, the conventionally cited environmental benefit of manure biogas systems is a net reduction in atmospheric GHG emissions. Policy support for biogas systems rests on this reduction and as a result, life cycle analyses of manure biogas systems typically focus their impact evaluation on GHG emissions specifically and do not always address harms from co-pollutants or new infrastructure.

The metric typically used to quantify the environmental sustainability of a product or service is life cycle analysis (LCA). The goal of LCA is to provide a comprehensive view of environmental impacts to help decision-makers identify the effect of a given good or service. LCAs estimate

To properly account for the full life cycle emissions, any manure biogas LCA should include the storage and disposal of digestate, as well as the emissions generated in the production of manure, that is, the emissions resulting from raising the livestock in question.



the cumulative environmental impacts resulting from all stages of a product, process, or service through the life cycle, from raw material acquisition, manufacturing, use/reuse/maintenance, to recycling/waste management.[85] Programs like the Federal Renewable Fuel Standard and California's Low Carbon Fuel Standard, described above in part II, rely on life cycle assessments to determine the life cycle GHG emissions of participant fuels, including those derived from manure biogas systems. Both EPA and the California Air Resources Board use versions of the Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) life cycle analysis model which is designed for transportation fuels.[86]

System boundaries mark the beginning and end of the process or life cycle in question. Consequently, the boundaries and assumptions used in the LCA model are critical. For example, an LCA that excluded emissions related to digestate would not fully account for life cycle emissions of manure biogas. To properly account for the full life cycle emissions, any manure biogas LCA should include the storage and disposal of digestate, as well as the emissions generated in the production of manure, that is, the emissions resulting from raising the livestock in question.

When produced at an industrial scale, animal manure can create severe environmental harms and adverse impacts to public health. The impacts of manure include water contamination, air pollution, and foul odor (which can degrade quality of life for neighboring communities and decrease property values), in addition to GHG emissions. Manure biogas systems capture some of the emissions from livestock facilities, but fail to address the co-pollutants associated with manure production while also producing new co-pollutants from the processing and storage of the resulting digestate, as discussed above. Multiple toxic pollutants, including VOCs, ammonia, endotoxins, particulate matter, and bioaerosols are linked to large-scale industrial confined animal feeding operations.[87] To the extent that anaerobic digestion technology maintains or even expands the model of concentrated industrial animal agriculture, it can perpetuate and even increase resulting public health harms.

In many parts of the country, these impacts disproportionately harm Black, Indigenous, and low-income communities. Multiple disparity analyses (and resulting civil rights complaints submitted to regulators) have challenged states' approaches to the regulation of industrial animal agriculture. One recent complaint filed with EPA's External Civil Rights Compliance

"These harms disproportionately affect Black and Latinx people living near the Hog Operations, and it is these communities who will suffer most if pollution from the Hog Operations worsens, as is expected with the Permits. Decades of research–including research reviewed by this office–demonstrate how the lagoon and sprayfield waste management system authorized by the Permits pollute rivers, streams, and air quality throughout eastern North Carolina. Despite this, and despite evidence indicating the increased risk of pollution and adverse health impacts to nearby residents from the increases to harmful hog waste pollutants resulting from biogas production, DEQ issued the Permits without addressing these harms. This is unacceptable and a violation of federal law." – SELC complaint to EPA, 2021

Source: Southern Environmental Law Center

Office under Title VI of the Civil Rights Act alleged that North Carolina's new general permit for manure biogas exacerbated existing discriminatory impacts of the livestock industry in the state.[88] The complaint alleges that the North Carolina Department of Environmental Quality's new general permit for biogas systems on confined animal feeding operations "authorizes not only the continued use of the discriminatory lagoon and sprayfield system, but also the use of anerobic digesters and uncovered 'secondary' lagoons, which will exacerbate the underlying system's impacts on communities of color."[89] This complaint follows another civil rights complaint addressing the discriminatory harms of the hog industry in North Carolina, to which EPA responded with a letter expressing "deep concern."[90]

Typical Pollutants Found in Air Surrounding CAFOs

CAFO EMISSIONS	SOURCE	TRAITS	HEALTH RISKS
Ammonia	Formed when microbes decompose undigested organic nitrogen compounds in manure	Colorless, sharp pungent odor	Respiratory irritant, chemical burns to the respiratory tract, skin, and eyes, severe cough, chronic lung disease
Hydrogen Sulfide	Anaerobic bacterial decomposition of protein and other sulfur containing organic matter	Odor of rotten eggs	Inflammation of the moist membranes of eye and respiratory tract, olfactory neuron loss, death
Methane	Microbial degradation of organic matter under anaerobic conditions	Colorless, odorless, highly flammable	No health risks. Is a greenhouse gas and contributes to climate change
Particulate Matter	Feed, bedding materials, dry manure, unpaved soil surfaces, animal dander, poultry feathers	Comprised of fecal matter, feed materials, pollen, bacteria, fungi, skin cells, silicates	Chronic bronchitis, chronic respiratory symptoms, declines in lung function, organic dust toxic syndrome

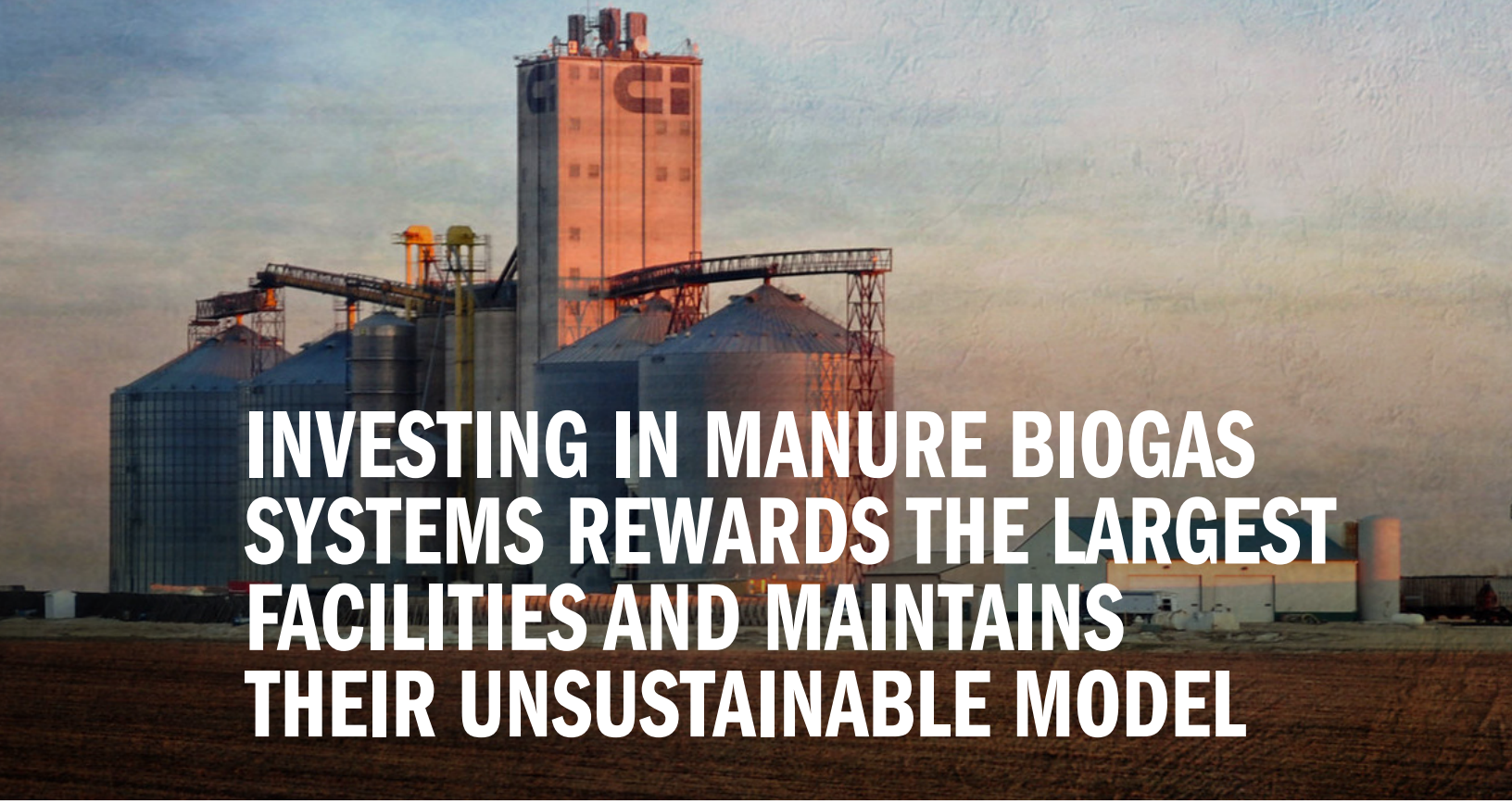
Source: Understanding Concentrated Animal Feeding Operations and Their Impact on Communities

More Information on the Impacts of Manure Biogas

- Michael A. Holly, Rebecca A. Larson, J. Mark Powell, Matthew D. Ruark, & Horacio Aguirre Villegas, *Greenhouse Gas and Ammonia Emissions from Digested and Separated Dairy Manure During Storage and After Land Application*, Agriculture, Ecosystems and Env't 239 410–419 (2017), http://dx.doi.org/10.1016/j.agee.2017.02.007
- Valerio Paolini, Francesco Petracchini, Marco Segreto, Laura Tomasetti, Nour Naja, & Angelo Cecinato, *Environmental Impact of Biogas: A Short Review of Current Knowledge*, 53 J. Env't Sci. Health Pt. A 899-906 (2018), https://doi.org/10.1080/10934529.2018.1459076
- C. Alan Rotz, *Modeling Greenhouse Gas Emissions from Dairy Farms,* 101 J. Dairy Sci. 6675-6690 (2018), https://www.sciencedirect.com/science/article/pii/S002203021731069X
- F. Montes, R. Meinen, C. Dell, A. Rotz, A. N. Hristov, J. Oh, et al., *SPECIAL TOPICS-Mitigation of Methane and Nitrous Oxide Emissions From Animal Operations: II. A Review of Manure Management Mitigation Options*, J. Anim. Sci. 91 5070–5094 (2013), https://doi.org/10.2527/jas.2013-6584
- Emily Grubert, *At Scale, Renewable Natural Gas Systems Could Be Climate Intensive: The Influence of Methane Feedstock and Leakage Rates*, Env't Research Letters 15 084041, 5 (August 2020), https://doi.org/10.1088/1748-9326/ab9335
- Hannah Rigby, *A Critical Review of Nitrogen Mineralization in Biosolids-Amended Soil, the Associated Fertilizer Value for Crop Production and Potential for Emissions to the Environment*, 541 Sci. of the Total Env't 1310, 1310 (Jan. 2016), https://www.sciencedirect.com/science/article/abs/pii/S0048969715305921



Photo source: Anaerobic Digester Fenville, MI by eXtension Farm Energy Community of Practice is licensed under CC BY-NC 2.0.



INVESTING IN MANURE BIOGAS SYSTEMS REWARDS THE LARGEST FACILITIES AND MAINTAINS THEIR UNSUSTAINABLE MODEL

THE SHEER NUMBER OF PROGRAMS designed to support the installation and operation of manure biogas systems on livestock operations presents two important questions. First, are these programs necessary to obtain the intended climate benefits of biogas systems and to what extent do they contribute to an overall emissions reduction? Second, what are the opportunity costs of the intense focus on this one method of reducing livestock emissions, given the range of alternatives? The fact that alternatives exist, coupled with the requirement that manure production continue at staggering rates to ensure the productivity of manure biogas systems calls into question whether it is prudent to focus policy efforts on a single solution.

Biogas Systems May Not Reduce Overall Emissions

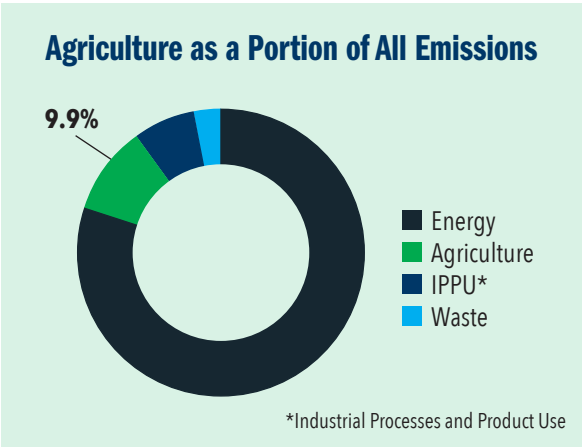
Anaerobic digesters are designed to capture (and monetize) methane and other gases that would otherwise be emitted into the air from manure lagoons. However, *capturing* emissions does not avoid or reduce emissions at the source. Reducing emissions at the source would entail significant changes in livestock production systems. Digester systems are sometimes described as stopgap measures—a means to reduce emissions quickly in the absence of developing or implementing alternative measures. However, climate science demonstrates that significant reductions at the source are required in the next decade. Investing in expensive durable infrastructure that requires ongoing manure production at current rates without emissions reductions fails to meet this imperative.

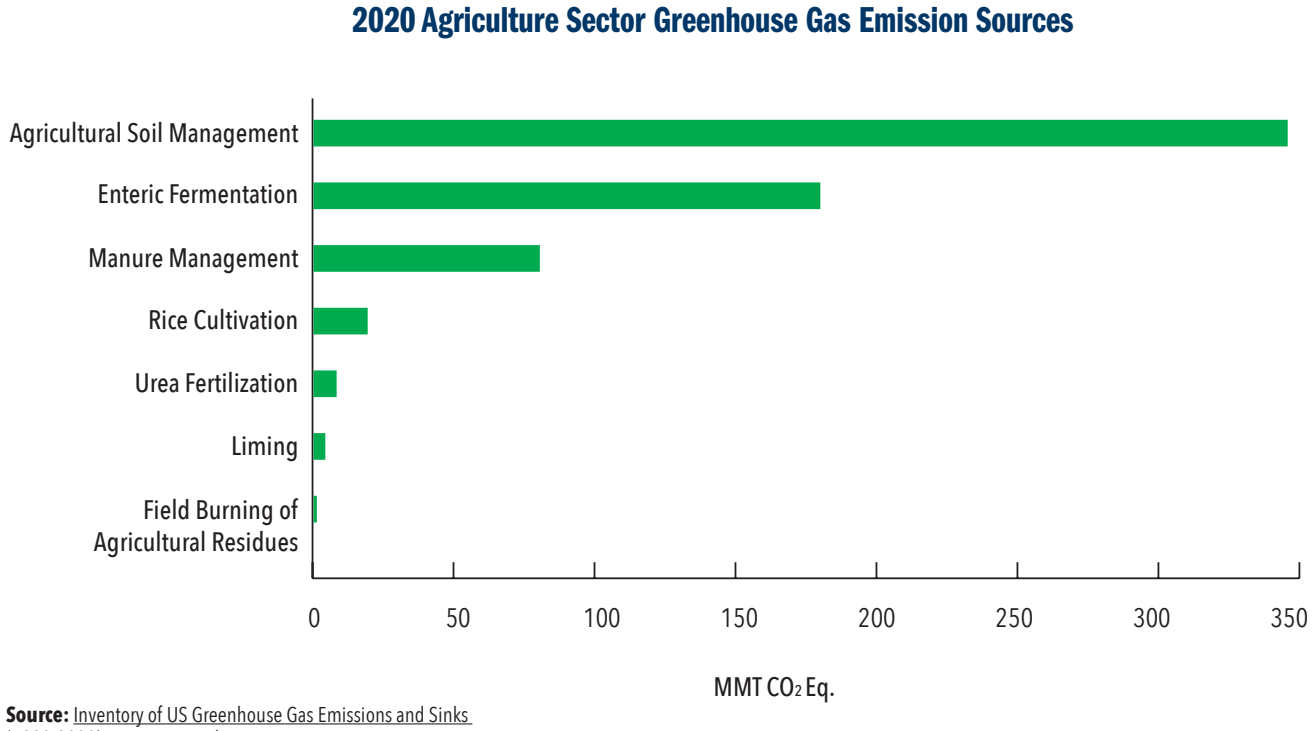
Because manure biogas systems capture rather than reduce emissions, these systems **require the ongoing generation of GHG emissions** to be financially viable. The digester's function is to capture the emissions, so the system breaks down if emissions are reduced at the source. Producers must continue to generate manure at scale for the facilities to remain financially sustainable. The large upfront investment in these systems then fixes the current numbers and concentration of livestock at facilities where they are installed, despite the range of harms

Photo source: Ag Partners, Hartley, Iowa by TumblingRun is licensed under CC BY-NC-ND 2.0.

generated by such concentrated operations. Simultaneously, the new subsidized revenue streams support the ongoing generation of manure at scale. This outcome is sharply at odds with the prescriptions of climate scientists and the Biden Administration's stated climate goals.

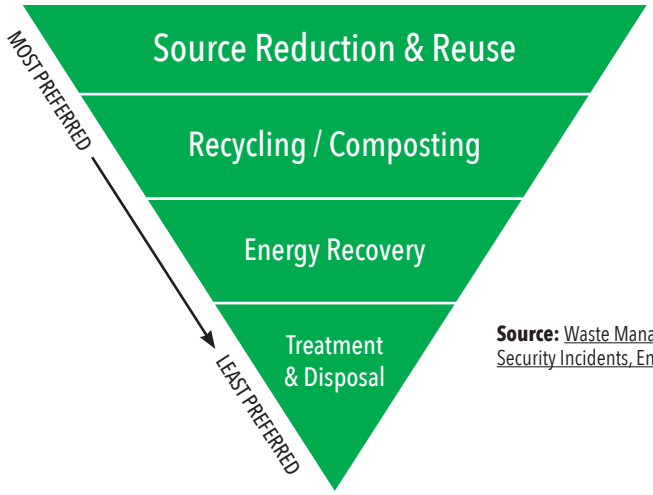
Additionally, while anaerobic digesters capture manure methane from lagoons, they do not capture greenhouse gas emissions before or after this point. The emissions from manure management that can be targeted by digesters make up 9.2 percent of total methane emissions from anthropogenic activities, while emissions from enteric fermentation, which remain untouched by digester systems, make up 26.9 percent.[91] In contrast, other interventions in the industrial animal agriculture system, including alternative methods of manure management and changes to animals' diet, address emissions throughout or at various points in the process of raising livestock. Importantly, a significant portion of livestock GHG emissions result from the decision to liquefy manure.[92] Some manure management emissions can be avoided by using dry manure management systems, as many farmers do. Capturing GHG emissions should be a last resort option after other alternatives have been pursued to avoid





Source: Inventory of US Greenhouse Gas Emissions and Sinks (1990-2020), Environmental Protection Agency

Waste Management Hierarchy



Source: Waste Management Hierarchy and Homeland Security Incidents, Environmental Protection Agency

or reduce emissions. This tracks with other federal policy efforts and priorities, as reduction is the management method at the top of EPA's waste management hierarchy for decision-making (organized from least to most detrimental to human and animal health and the environment).[93]

Alternative measures to reduce methane emissions from animal agriculture are available and feasible. Manure management systems generally include processes for the collection, transfer, storage, and sometimes treatment and end-use of manure.[94] Alternatives are available at each point along the way. At the initial collection stage, operations can opt for dry-scrape systems, rather than the flush systems typically used for lagoons. Dry scrape systems use mechanical scrapers to move manure into holding pits.

Livestock operations can also be designed as pasture-based, rather than confinement. On pasture-based operations, manure is typically left on pasture and produces minimal methane.[95] Pasture-based operations that rely primarily on grazing for animals' nutrition can also avoid emissions associated with the production and transportation of the feed used on confinement operations[96] and can potentially provide carbon sequestration benefits if grasslands and grazing are properly managed.[97] At the storage stage, operations can employ solid-liquid separation rather than flushing all liquefied manure directly into a lagoon. Once liquids have been separated out, manure solids can be composted.[98] A technical report prepared for the California Air Resources Board concluded that, in addition to manure biogas system installation:

> Methane emissions from lagoon storage systems can be decreased by reducing the amount or modifying anaerobic storage (i.e. solids separation and diversion from lagoon, modifying dominant flush collection to manure scraping with drying/composting or other lagoon diversion, etc.), aerating the lagoon (to reduce or eliminate anaerobic conditions).[99]

These are viable methods of manure management that would avoid, rather than simply capture, at least some emissions associated with open-air lagoons of liquid manure.[100] Many livestock operations already employ these lower-emissions practices. Unfortunately for them, however, smaller operations, pasture-based operations, or operations that have a more sustainable business model of dry manure management will not benefit from the significant public funds currently being channeled to biogas-eligible facilities. This sets a perverse precedent of neglecting historically good actors while rewarding the worst polluters in the livestock industry with new revenue and fodder for positive public relations.

Tied to the claim that biogas systems reduce emissions is the argument that the use of manure systems displaces the use of fossil fuels. An empirical analysis of this claim is beyond the scope of this report. However, regulators and policymakers should carefully consider the climate value of replacing fossil fuels with the combustion of biomethane, especially for the magnitude of public funds invested in this displacement. Renewability does not necessarily mean that a fuel is sustainable or climate friendly.[101]

Biogas Systems May Not Generate Revenue & "Design Out Waste"

Another important consideration is whether manure biogas systems really generate revenue and "design out" waste. This reflects a broader trend in policy prescriptions, sometimes referred to as the "circular economy," that seeks to "design out" waste from various industrial life cycles.[102] Proponents of the circular economy use the phrase "designing out" manure or any other waste product to mean that the waste is made profitable through other industrial processes. Unlocking new profits from waste,[103] however, does not necessarily entail any changes to the processes of waste generation or to any environmental or public health harms that arise from these processes.

In the case of manure biogas systems, manure is still produced, liquefied, and transported to manure lagoons—it must be for the biogas system to function. Anaerobic digestion does not make the manure vanish, it produces digestate. As discussed above, digestate has industrial uses, as fertilizer, for example, but also carries many of the same potential environmental harms as manure. Therefore, while it is correct to say that manure biogas systems access the potential economic value of manure as a fuel source, the waste does not disappear and can continue to cause environmental and public health harms, before, during, and after (as digestate) the process of anaerobic digestion.

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The massive quantities of manure produced at industrial scale livestock facilities can and do cause serious environmental, quality of life, and public health harms to neighboring communities. These harms do not cease to exist upon the addition of an anaerobic digester. In fact, while proponents of biogas systems sometimes argue that capping lagoons can address these issues, impacted environmental justice communities around the country have organized against the proliferation of biogas because it is viewed as maintaining and supporting a harmful system.[104]

Beyond the Baseline: Evaluating Mitigation Measures Against Policy Alternatives

The climate benefits associated with greater public resources devoted to expanding manure biogas production can only be evaluated relative to other available policy options. Such policy options cannot be limited to a business-as-usual scenario, which the scientific community has made clear is untenable. Regulators currently consider the displacement of fossil fuels when evaluating the benefits associated with these systems, but they must also consider the alternative emissions reduction strategies that are displaced now and into the future upon investment in large-scale manure biogas systems.

Unfortunately, conventional win-win claims break down when framed in the broader context of policy mechanisms available to address emissions from livestock. This is attributable to the many alternative approaches to reducing emissions from livestock facilities, some of which could reduce emissions throughout the life cycle, instead of those emitted only from



manure lagoons. The Biden Administration's plan to reduce methane names several of these alternatives, including installing "solid separators that reduce methane-producing slurries; providing conservation assistance for transitions to alternative manure management systems, such as deep pits, composting, transitions to pasture, or other practices that have a lower greenhouse gas profile."[105] Despite the administration's support of reducing methane-producing slurries on paper, funding for manure biogas systems that require methane-producing slurries to function continues to dwarf alternatives.

While it is unreasonable to expect a single policy mechanism or technology to solve all problems, there are viable alternative manure management practices and policy mechanisms to decrease emissions as well as co-pollutants in a more equitable manner. Currently, however, these programs are not being funded at nearly the same rate as manure biogas. In California, for example, the Alternative Manure Management Program (AAMP) has been funded at roughly half the rate of the Dairy Digester Research & Development Program (DDRDP) in recent years.[106]

In addition to a broad evaluation of each of these alternative mechanisms and potential policy mechanisms to promote them, it is essential to note the reason policy incentives are strictly necessary in this case—industrial livestock operations have historically been essentially exempt from any regulation of GHG emissions. It is, in fact, only this absence of regulation that makes the calculation of emissions reductions from the addition of digesters so high. The primary alternative policy mechanism should be to treat industrial livestock operations like every other industry in the country and regulate the emissions they externalize to the detriment of the public—the primary funders of manure biogas systems. Regulators should actively support farmers that engage in climate-friendly practices less likely to harm neighboring communities.

In the United States, livestock agriculture has dramatically shifted toward "large scale industrialized production systems."[107] As a result, livestock operations are producing more manure in centralized regions.[108] The storage, transportation, and land application[109] of this waste poses serious environmental risks, in addition to the GHG emissions from other parts of the livestock life cycle. Methane emissions from livestock manure are significant, but experts note that the trade-offs associated with manure management options, including the use of biodigesters, are not well studied and have not been proven to be "climate smarter."[110]

While it is unreasonable to expect a single policy mechanism or technology to solve all problems, there are viable alternative manure management practices and policy mechanisms to decrease emissions and co-pollutants in a more equitable manner.



POLICY RECOMMENDATIONS AND CONCLUSION

LIVESTOCK OPERATIONS' IMPACT ON CLIMATE CHANGE presents an opportunity for a real win-win: the US can develop policies that reduce GHG emissions from these facilities—as is required in order to mitigate the substantial impact of livestock agriculture on the climate—while simultaneously reducing the additional environmental harms many such facilities externalize into local communities. In many cases, have a discriminatory impact on the basis of race. These prerogatives are well aligned with the Biden Administration's Climate Smart Agriculture policy, Executive Order 14008, and Executive Order 13985.[111] Specifically, policymakers should consider the following:

USDA must ensure that recipients of its funding are in compliance with Title VI of the Civil Rights Act of 1964. This includes ensuring that state agencies that receive USDA funding and implement programs supporting manure biogas are developing such policies in a manner that does not disproportionately benefit white operators or disproportionately harm nearby communities on the basis of race, national origin, or color.

Evaluate USDA's programs to ensure that they do not have a disproportionate impact on the basis of race, national origin, or other protected class.

Properly account for the full climate impacts of manure biogas and ensure that emissions life cycle analyses consider the full range of upstream and downstream emissions in the manure biogas life cycle.

Move beyond business-as-usual as a point of comparison for manure biogas, which does not ensure a viable climate-smart future. The point of comparison should be the range of policy alternatives to biogas promotion, including the regulation of methane from agricultural operations.

Properly account for the full impacts of policies supporting manure biogas, including environmental, public health, and quality of life impacts from co-pollutants caused by manure.

Ensure a just transition for all, including for livestock farmers. Policy should ensure that farmers and farmworkers can make viable livelihoods while transitioning to more sustainable models.

Evaluate the efficacy of overlapping programs to ensure that public funds for manure biogas are effectively promoting new emissions reductions.

Endnotes

1 *Why Did the IPCC Choose 2° C As the Goal for Limiting Global Warming*, MIT Climate Portal (June 22, 2021), https://climate.mit.edu/ask-mit/why-did-ipcc-choose-2deg-c-goal-limiting-global-warming/.

2 *See generally* U.S. Climate Change Science Program, The Effects of Climate Change on Agriculture, Land Resources, Water Resources, and Biodiversity in the United States (May 2008), https://www.usda.gov/sites/default/files/documents/CCSPFinalReport.pdf.

3 IPCC, *Sixth Assessment Report Headline Statement from the Summary for Policymakers* at A.3 (August 9, 2021).

4 *Id.* at B.3.

5 Jennifer Shike, *Residents in Top Pork-Producing Counties Reveal Their Perspective on Ag*, Farm Journal's Pork (January 12, 2022), https://www.porkbusiness.com/news/industry/nc-residents-top-pork-producing-counties-reveal-their-perspective-ag.

6 Kendra Pierre-Louis, *Lagoons of Pig Waste Are Overflowing After Florence. Yes, That's as Nasty as It Sounds*, N.Y. Times (September 19, 2018), https://www.nytimes.com/2018/09/19/climate/florence-hog-farms.html; James Bruggers, *After Back-to-Back Hurricanes, North Carolina Reconsiders Climate Change*, Inside Climate News (December 27, 2018), https://insideclimatenews.org/news/27122018/hurricane-damage-north-carolina-climate-change-2018-year-review-florence-michael-matthew/.

7 *California's Central Valley*, U.S. Geol. Survey, https://ca.water.usgs.gov/projects/central-valley/about-central-valley.html.

8 *California is the Leading Farm State*, Cal. Legislative Analyst's Office (December 4, 2014), https://lao.ca.gov/LAOEconTax/Article/Detail/13#:~:text=Over%2080%20percent%20of%20California's,surpassed%20Wisconsin%20in%20milk%20production.

9 The Central Valley is predicted to be "substantially drier (10 to 15 percent) during the mid-late 21st century." *Conjunctive Use in Response to Potential Climate Changes in the Central Valley, California*, USGS, https://ca.water.usgs.gov/projects/central-valley/climate.html; Bettina Boxall, *Overpumping of Central Valley Groundwater Creating a Crisis, Experts Say*, L.A. Times (March 18, 2015), https://www.latimes.com/local/california/la-me-groundwater-20150318-story.html.

10 *See generally* U.S. EPA, Climate Change and Social Vulnerability in the United States, https://www.epa.gov/system/files/documents/2021-09/climate-vulnerability_september-2021_508.pdf. Leah Campbell, *North Carolina Hurricanes Linked to Increases in Gastrointestinal Illnesses in Marginalized Communities*, Inside Climate News (March 7, 2022), https://insideclimatenews.org/news/07032022/north-carolina-hurricanes-gastrointestinal-illnesses/.

11 Huanjia Zhang, *For Black Farmers, Climate Change Magnifies Existing Inequality*, ScienceLine (January 19, 2021), https://scienceline.org/2021/01/for-black-farmers-climate-change-magnifies-existing-inequality/. Internationally, "the negative impacts [of climate change] on [farmer] income are hitting the poorest countries and farmers most due to both higher exposure to climate risks as well as lower adaptation capacity." Food and Agriculture Organization of the United Nationals, Climate Change and Food Security: Risks and Responses (2015) at 21, https://www.fao.org/3/i5188e/I5188E.pdf.

12 Sabri Ben-Achour, *Farmers Need to Adapt Crops to Climate Change to Stay Profitable, Experts Say*, Marketplace (October 20, 2020), https://www.marketplace.org/2020/10/20/many-farmers-need-swap-crops-stay-profitable-climate-change-continues/.

13 Walter Willett, MD *et al.*, *Food in the Anthropocene: the EAT-Lancet Commission on Healthy Diets from Sustainable Food Systems,* The Lancet (January 16, 2019), https://doi.org/10.1016/S0140-6736(18)31788-4; Gidon Eshel *et al.*, *Land, Irrigation Water, Greenhouse Gas, and Reactive Nitrogen Burdens of Meat, Eggs, and Dairy Production in the United States*, PNAS (July 21, 2014), https://www.pnas.org/doi/10.1073/pnas.1402183111; Henry Fountain, *Cutting Greenhouse Gases From Food Production Is Urgent, Scientists Say*, N.Y. Times (October 26, 2021), https://www.nytimes.com/2020/11/05/climate/climate-change-food-production.html; Andrea Thompson, *Here's How Much Food Contributes to Climate Change*, Scientific American (September 13, 2021), https://www.scientificamerican.com/article/heres-how-much-food-contributes-to-climate-change/. It has recently been argued that estimates of methane emissions from U.S. livestock operations have routinely been underestimated. *See* Matthew N. Hayek and Scot M. Miller, *Underestimates of Methane from Intensively Raised Animals Could Undermine Goals of Sustainable Development*, Env't Res. Lett. *16 (June 4, 2021),* https://iopscience.iop.org/article/10.1088/1748-9326/ac02ef.

14 Understanding Global Warming Potential, U.S. Env't Protection Agency, https://www.epa.gov/ghgemissions/understanding-global-warming-potentials.

15 *Burps in Merps: Addressing Agricultural Methane Emissions in the U.S. Methane Emission Reduction Plan (MERAP),* https://storymaps.arcgis.com/stories/be03fd94bbfb4586bf7ccf5627aa4afb. Not only are overall emissions from agriculture increasing, but per head emissions from enteric fermentation are also increasing. U.S. Greenhouse Gas Inventory Agriculture at 5-5, U.S. Env't Protection Agency, https://www.epa.gov/system/files/documents/2022-04/us-ghg-inventory-2022-chapter-5-agriculture.pdf. .

16 *See, e.g.,* Sustainia, *Win-Win Scheme Turns Pig Waste into Power*, Global Opportunity Explore (March 14, 2019), https://goexplorer.org/win-win-scheme-turns-pig-waste-into-power/; *Using Methane from Waste Streams for Energy: A Win-Win Solution*, Environmental and Energy Study Institute (March 9, 2010), https://www.eesi.org/articles/view/using-methane-from-waste-streams-for-energy-a-win-win-solution.

17 Laura Melling, *USDA Offers Funding to Help Farmers Turn Manure into Energy*, U.S. Dep't of Ag. (February 21, 2017), https://www.usda.gov/media/blog/2010/11/18/usda-offers-funding-help-farmers-turn-manure-energy.

18 American Biogas Council, *How to Maximize USDA Funds Webinar* (January 30, 2020), *available at* https://www.google.com/url?sa=t&rct=j&q=&esrc=s&source=web&cd=&cad=rja&uact=8&ved=2ahUKEwiG3YaUrtz1AhXmIEQIHbk7B0cQFnoECAMQAQ&url=https%3A%2F%2Famericanbiogascouncil.org%2Fwp-content%2Fuploads%2F2020%2F01%2FHow-to-Maximize-USDA-Grant-Dollars-from-REAP.pdf&usg=AOvVaw3u_9Ola0x9SiHDF3spSqC1.

19 Michael Clark *et al., Global Food System Emissions Could Preclude Achieving the 1.5 and 2 C Climate Change Targets,* 370 Science 6517 (November 6, 2020), https://www.science.org/doi/10.1126/science.aba7357.

20 Ximena Bustillo, *'Rampant Issues': Black Farmers Are Still Left Out at USDA*, Politico (July 5, 2021), https://www.politico.com/news/2021/07/05/black-farmers-left-out-usda-497876; Nathan Rosenberg and Bryce Wilson Stucki, *How USDA Distorted Data to Conceal Decades of Discrimination Against Black Farmers*, The Counter (June 26, 2019), https://thecounter.org/usda-black-farmers-discrimination-tom-vilsack-reparations-civil-rights/.

21 *Who Is the American Farmer?,* USA Facts, https://usafacts.org/articles/farmer-demographics/ (95.4% of American farmers are white).

22 Dania Francis, Darrick Hamilton, Thomas Mitchell, Nathan Rosenberg, and Bryce Wilson Stucki, *How the Government Helped White Farmers Steal Black Farmland*, The New Republic (May 5, 2020), https://newrepublic.com/article/166276/black-farm-land-lost-20th-century-billions.

23 Today the average size of farms owned by Black farmers is 132 acres, as compared to 441 acres for white farmers. 15% of Black farmers own farms larger than 180 acres, as compared to 32% of white farmers. *2017 Agricultural Census,* U.S. Dep't. of Ag., https://www.nass.usda.gov/Publications/AgCensus/2017/Online_Resources/Race,_Ethnicity_and_Gender_Profiles/cpd99000.pdf.

24 *See, e.g.* Ji-Young Son *et al.*, *Distribution of Environmental Justice Metric for Exposure to CAFOs in North Carolina*, USA, Env't Research 195 (April 2021), https://doi.org/10.1016/j.envres.2021.110862.

25 For example, heat stress due to climate change has already significantly impacted dairy production in the United States and is expected to further contribute to economic losses for that sector. More broadly, the "U.S. Global Change Research Program (USGCRP) recognizes that increased heat stress will increase livestock production costs, lower feed efficiency, and compromise livestock health." *Climate Change, Heat Stress, and US Dairy Production,* U.S. Dep't. of Ag. Econ. Research Serv. at 1-2 (2014), https://www.ers.usda.gov/webdocs/publications/45279/49164_err175.pdf?v=2463.8.

26 Exec. Order No. 14008, Tackling the Climate Crisis at Home and Abroad, 86 Fed. Reg. 7619 (2021).

27 Exec. Order 13985, Advancing Racial Equity and Support for Underserved Communities Through the Federal Government, 86 Fed. Reg. 7009 (2021).

28 *See generally* Exec. Order No. 14008, Tackling the Climate Crisis at Home and Abroad, 86 Fed. Reg. 7619 (2021).

29 *See generally* Exec. Order No. 14008, Tackling the Climate Crisis at Home and Abroad, 86 Fed. Reg. 7619 (2021).

30 U.S. Dep't of Ag., Climate-Smart Agriculture and Forestry St5rategy: 90-Day Progress Report (May 2021), https://www.agri-pulse.com/ext/resources/pdfs/Embargoed-climate-smart-ag-forestry-strategy-90-day-progress-report.pdf.

31 Lisa Friedman, *Biden Administration Moves to Limit Methane, a Potent Greenhouse Gas*, N.Y. Times (November 2, 2021), https://www.nytimes.com/2021/11/02/climate/biden-methane-climate.html.

32 Jared Strong, *USDA Pledges $1B for 'Climate Smart' Ag Products*, Missouri Independent (February 7, 2022), https://missouriindependent.com/briefs/usda-pledges-1b-for-climate-smart-ag-products/.

33 *Rural Energy for America Program Renewable Energy Systems & Energy Efficiency Improvement Guaranteed Loans & Grants*, U.S. Dep't of Ag. Rural Development, https://www.rd.usda.gov/programs-services/energy-programs/rural-energy-america-program-renewable-energy-systems-energy-efficiency-improvement-guaranteed-loans.

34 *Conservation Programs*, U.S. Dep't of Ag. Rural Development, https://www.fsa.usda.gov/programs-and-services/conservation-programs/index.

35 7 U.S.C.A. § 8103 ("The purpose of this section is to assist in the development of new and emerging technologies for the development of advanced biofuels, renewable chemicals, and biobased product manufacturing…")

36 7 U.S.C.A. § 8105 ("The Secretary shall make payments to eligible producers to support and ensure an expanding production of advanced biofuel.")

37 7 U.S.C.A. § 8108.

38 7 U.S.C.A. § 8106 "…make competitive grants to eligible entities to educate governmental and private entities that operate vehicle fleets, other interested entities (as determined by the Secretary), and the public about the benefits of biodiesel fuel use.")

39 7 U.S.C.A. § 8115. This program provides grants to educate agricultural producers and other stakeholders about the collection of organic waste from multiple sources to be used in a single biogas system.

40 *Biogas Opportunities Roadmap Progress Report*, U.S. Dep't of Ag., Env't Protection Agency & Dep't of Energy (December 2015) at 2, https://www.energy.gov/sites/prod/files/2015/12/f27/biogas_opportunites_roadmap_progress_report_0.pdf.

41 *Dairy Digester Research & Development Program*, Cal.

Dep't Food & Ag., https://www.cdfa.ca.gov/oefi/ddrdp/.

42 *Methane Digester Loan Program*, Minn. Dep't of Ag., https://www.mda.state.mn.us/methane-digester-loan-program.

43 Referring to Section 1603 of the 2009 American Recovery and Reinvestment Act (ARRA).

44 *1603 Program: Payments for Specified Energy Property in Lieu of Tax Credits*, U.S. Dep't of the Treasury, https://home.treasury.gov/policy-issues/financial-markets-financial-institutions-and-fiscal-service/1603-program-payments-for-specified-energy-property-in-lieu-of-tax-credits.

45 *ARRA Section 1603 Grants in Lieu of Tax Credits for Renewable Energy: Overview, Analysis, and Policy Options*, Congressional Research Service (November 9, 2011), https://www.everycrsreport.com/files/20111109_R41635_f042092b5c65021d792f0ccb79634694bd9aeea8.pdf.

46 *Id.* at 5, Figure 1.

47 *1603 Program List of Awards*, U.S. Dep't of the Treasury, *available at* https://home.treasury.gov/policy-issues/financial-markets-financial-institutions-and-fiscal-service/1603-program-payments-for-specified-energy-property-in-lieu-of-tax-credits.

48 Stifel Equity Research, Energy & Power – Biofuels: Renewable Natural Gas (March 8, 2021) at 4.

49 *See also*, *Chevron's Energy Transition Spotlight Edited Transcript,* Chevron Corp. (September 14, 2021), *available at* https://chevroncorp.gcs-web.com/static-files/f9d402c6-22e2-4c00-ad45-3a61fde9ff73 ("For roughly half a billion dollars committed to date, we're building an RNG business expected to produce about 10,000 million BTUs per day in less than five years, with expected double-digit returns and an average carbon intensity feedstock score of around negative 250 under California's Low Carbon Fuel Standard.")

50 Stifel Equity Research, Energy & Power – Biofuels: Renewable Natural Gas (March 8, 2021) at 5.

51 For general information on fuel pathways, *see What is a Fuel Pathway?,* U.S. Env't Protection Agency, https://www.epa.gov/renewable-fuel-standard-program/what-fuel-pathway.

52 40 C.F.R. § 80 subpart M. EPA also provides a list of fuel pathways online at *Approved Pathways for Renewable Fuel*, U.S. Env't Prot. Agency, https://www.epa.gov/renewable-fuel-standard-program/approved-pathways-renewable-fuel.

53 *Renewable Identification Numbers*, Alternative Fuels Data Center, U.S. Dep't of Energy, https://afdc.energy.gov/laws/RIN.html.

54 40 C.F.R. § 80.1426; *Renewable Fuel Standard*, Alternative Fuels Data Center, U.S. Dep't of Energy, https://afdc.energy.gov/laws/RFS; *Approved Pathways for Renewable Fuel*, U.S. Env't Protection Agency, https://www.epa.gov/renewable-fuel-standard-program/approved-pathways-renewable-fuel.

55 U.S. Env't Protection Agency, *Information About Renewable Fuel Standard for Landfill Gas Energy Project,* https://www.epa.gov/lmop/information-about-renewable-fuel-standard-landfill-gas-energy-projects.

56 "The federal RFS and state LCFS incentives are additive, meaning both incentives can be earned for a specific project." *Renewable Natural Gas from Agricultural-Based AD/Biogas Systems*, U.S. Env't Protection Agency, https://www.epa.gov/agstar/renewable-natural-gas-agricultural-based-adbiogas-systems.

57 *Advanced Biofuel Payment Program*, U.S. Dep't of Ag. Rural Development, https://www.rd.usda.gov/programs-services/energy-programs/advanced-biofuel-payment-program.

58 7 C.F.R Part 4288, Advanced Biofuel Payment Program Final Rule, *available at* https://www.rd.usda.gov/sites/default/files/AdvancedBiofuel_9005_FinalRule122719.pdf; *Advanced Biofuel Payment Program in California,* U.S. Dep't of Ag. Rural Development, https://www.rd.usda.gov/programs-services/energy-programs/advanced-biofuel-payment-program/ca.

59 7 U.S.C. § 8105(g).

60 *Renewable Electricity Production Tax Credit Information*, U.S. Env't Protection Agency, https://www.epa.gov/lmop/renewable-electricity-production-tax-credit-information; *Form 8835*, Dep't of the Treasury Internal Revenue Service, *available at* https://www.irs.gov/pub/irs-pdf/f8835.pdf.

61 U.S. Env't Protection Agency, AgStar, Project Development Handbook: A Handbook for Developing Anaerobic Digestion/Biogas Systems on Farms in the United States 3rd Edition, *available at* https://www.epa.gov/sites/default/files/2014-12/documents/agstar-handbook.pdf#page=81.

62 *Biofuels Investment Tax*, Alternative Fuels Data Center, U.S. Dep't. of Energy, https://afdc.energy.gov/laws/6074.

63 Cal. Code of Regs Tit. 17 § 95480.

64 *See* Jessica Fu, *Is California Giving Its Methane Digesters Too Much Credit?,* Grist (May 19, 2022), https://grist.org/accountability/california-methane-digesters-low-carbon-fuel-standard/; Evan Halper, *California Set Off a Biofuel Boom–But Can It Manage the Fallout?,* L.A. Times (March 24, 2022), https://www.latimes.com/politics/story/2022-03-24/california-set-off-a-biofuel-boom-but-can-it-manage-the-fallout.

65 *State Renewable Portfolio Standards and Goals*, National Conference of State Legislatures, https://www.ncsl.org/research/energy/renewable-portfolio-standards.aspx.

66 U.S. Env't Protection Agency, AgStar, Project Development Handbook: A Handbook for Developing Anaerobic Digestion/Biogas Systems on Farms in the United States 3rd Edition at 6.3.2., *available at* https://www.epa.gov/sites/default/files/2014-12/documents/agstar-handbook.pdf#page=81.

67 *Is Anaerobic Digestion Right for Your Farm*, U.S. Env't Protection Agency, Ag Star, https://www.epa.gov/agstar/anaerobic-digestion-right-your-farm#q2.

68 *Id.*

69 U.S. Env't Protection Agency, AgStar, Market Opportunities for Biogas Recovery Systems at US Livestock Facilities (June 2018), *available at* https://www.epa.gov/sites/default/files/2018-06/documents/epa430r18006agstar-marketreport2018.pdf.

70 Horacio A. Aguirre-Villegas, Rebecca A. Larson, and Mahmoud A. Sharara, *Anaerobic Digestion, Solid-Liquid Separation, and Drying of Dairy Manure: Measuring Constituents and Modeling Emission*, Sci. of the Total Env't 696 (December 2019), https://www.sciencedirect.com/science/article/pii/S0048969719340367.

71 S.O. Peterson et al., *Manure Management for Greenhouse Gas Mitigation*, Animal 7 at 2 (2013), https://doi.org/10.1017/S1751731113000736 ("CH4 emissions may occur from all manure environments, but is mainly associated with liquid or compacted manure.")

72 U.S. Env't Protection Agency, U.S. Greenhouse Gas Inventory Agriculture at 5-11, https://www.epa.gov/system/files/documents/2022-04/us-ghg-inventory-2022-chapter-5-agriculture.pdf.

73 Ben Lilliston, *EPA Data Confirms Role of Factory Farms in Rising Agriculture Emissions*, Inst. for Ag. and Trade Policy, https://www.iatp.org/new-epa-data-confirms-role-factory-farms-rising-agriculture-emissions.

74 U.S. Env't Protection Agency, U.S. Greenhouse Gas Inventory Agriculture at 5-12, https://www.epa.gov/system/files/documents/2022-04/us-ghg-inventory-2022-chapter-5-agriculture.pdf.

75 Holly, et al., *Greenhouse gas and ammonia emissions from digested and separated dairy manure during storage and after land disposal*, AG., Ecosystems and Env't 239 at 411 (2017), https://doi.org/10.1016/j.agee.2017.02.007.

76 *Id.* at 413. This increase was attributed to the "mineralization of organic N through the digestion process which increased NH4 + NH3 concentrations in manure."

77 *Id.* at 418.

78 *See* Ma, R., Li, K., Guo, Y. *et al. Mitigation potential of global ammonia emissions and related health impacts in the trade network*, Nat Commun 12 at 6308 (2021), https://doi.org/10.1038/s41467-021-25854-3 (""NH_3 emissions contribute to $PM_{2.5}$ pollution through the chemical formation of particulate ammonium sulfate and ammonium nitrate, and lead to tens of thousands of deaths annually.")

79 Holly, et al. at 418 ("…anaerobically stacking digested solids increase emissions of N20 negating abatement of total GHG.")

80 Y. Zhang et al., *Characterization of Volatile Organic Compound (VOC) Emissions from Swine Manure Biogas Digestate Storage*, Atmosphere 10(7):411 at 8 (2019). https://doi.org/10.3390/atmos10070411.

81 *Id.* at 9.

82 Fetra J. Andriamanohiarisoamanana, et al., *Effects of handling parameters on hydrogen sulfide emission from stored dairy manure*, J. of Env't Management, Vol. 154 at 112 (2015), https://doi.org/10.1016/j.jenvman.2015.02.003.

83 *Id.* at 115.

84 Wendee Nicole, *CAFOs and Environmental Justice*, Env't Health Perspectives (June 2013), https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3672924/A ("As one pair of investigators explained, '[P]eople of color and the poor living in rural communities lacking the political capacity to resist are said to shoulder the adverse socio-economic, environmental, or health related effects of swine waste externalities without sharing in the economic benefits brought by industrialized pork production.'")

85 Scientific Applications International Corp., *Life Cycle Assessment: Principles and Practice*, prepared for U.S. Env't Protection Agency, *available at* https://www.epa.gov/nscep. Life cycle studies can be conducted within different scopes, including "cradle to gate" (from raw materials to factory gate), gate to gate (only focusing on the manufacturing processes), cradle to grave (from raw materials until disposal), or cradle to cradle (a specific cradle to grave assessment, in which the disposal process is actually a recycling process). Life cycle assessments which are not conducted for a full life cycle from "cradle to grave" are called partial life cycle assessments.

86 Meltem Urgun-Demirtas, *The Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation Model*, U.S. Dep't of Energy (May 16, 2019), https://www.energy.gov/eere/bioenergy/articles/greet-greenhouse-gases-regulated-emissions-and-energy-use-transportation.

87 Christine Loftus et al., *Estimated time-varying exposures to air emissions from animal feeding operations and childhood asthma*, International J. of Hygiene and Env't Health, Vol. 223: 1 (2020), https://doi.org/10.1016/j.ijheh.2019.09.003; B. Yuan et al., *Emissions of volatile organic compounds (VOCs) from concentrated animal feeding operations (CAFOs): chemical compositions and separation of source*s, Atmos. Chem. Phys. 17 (2017), https://doi.org/10.5194/acp-17-4945-2017.

88 SELC Complaint to EPA, 2021, https://www.southernenvironment.org/wp-content/uploads/2021/09/2021-09-27-Title-VI-Complaint-Index-DEQ-Biogas-Permits.pdf.

89 *Id.* at 3.

90 *Letter to Secretary Ross re: EPA File No. 11R-14-R4* (November 12, 2017), *available at* https://www.epa.gov/sites/default/files/2018-05/documents/letter_of_concern_to_william_g_ross_nc_deq_re_admin_complaint_11r-14-r4_.pdf.

91 U.S. Env't Protection Agency, U.S. Greenhouse Gas Inventory Agriculture , https://www.epa.gov/system/files/documents/2022-04/us-ghg-inventory-2022-chapter-5-agriculture.pdf.

92 U.S. Env't Protection Agency, U.S. Greenhouse Gas Inventory Agriculture , https://www.epa.gov/system/files/documents/2022-04/us-ghg-inventory-2022-chapter-5-agriculture.pdf.

93 *Waste Management Hierarchy and Homeland Security Incidents*, U.S. Env't Protection Agency, https://www.epa.gov/homeland-security-waste/waste-management-hierarchy-and-homeland-security-incidents (last updated May 31, 2018).

94 Randall James et al., *Ohio Livestock Management Guide*, Ohio State Univ. Extension at 18 (2006), *available at* https://agcrops.osu.edu/sites/agcrops/files/imce/fertility/bulletin_604.pdf.

95 U.S. Env't Protection Agency, U.S. Greenhouse Gas Inventory Agriculture , https://www.epa.gov/system/files/documents/2022-04/us-ghg-inventory-2022-chapter-5-agriculture.pdf ("When manure is handled as a solid (e.g., in stacks or drylots) or deposited on pasture, range, or paddock lands, it tends to decompose aerobically and produce CO2 and little or no CH4.")

96 Feed production can generate nitrous oxide emissions from the application of synthetic N or manure to crops, while energy use in field operations, feed transport, fertilizer manufacturing, feed blending, etc. can contribute more nitrous oxide as well as carbon dioxide and methane emissions. Gerber, P.J., Steinfeld, H., Henderson, B., Mottet, A., Opio, C., Dijkman, J., Falcucci, A. & Tempio, G., *Tackling Climate Change Through Livestock – A Global Assessment of Emissions and Mitigation Opportunities*, Food and Agriculture Organization of the United Nations (2013) Table 1 at 7, https://www.fao.org/3/i3437e/i3437e.pdf.

97 *Id.* at 12.

98 Randall James et al., *Ohio Livestock Management Guide*, Ohio State Univ. Extension at 31 (2006), https://agcrops.osu.edu/sites/agcrops/files/imce/fertility/bulletin_604.pdf.

99 Stephen Kaffka, Tyler Barzee, Hamed El-Mashad, Rob Williams, Steve Zicari, and Ruihong Zhang, *Evaluation of Dairy Manure Management Practices for Greenhouse Gas Emissions Mitigation in California, FINAL TECHNICAL REPORT to the State of California Air Resources Board Contract # 14□456 (*February 26, 2016), https://biomass.ucdavis.edu/wp-content/uploads/ARB-Report-Final-Draft-Transmittal-Feb-26-2016.pdf.

100 *See Alternative Manure Management Program*, Cal. Dep't Food and Ag., https://www.cdfa.ca.gov/oefi/AMMP/.

101 Renewability describes an energy source that is replenished over time. However, even renewable sources can contribute to climate change or impose environmental harms. For example, wood pellets used as biomass may technically be renewable but the . Similarly, a solar array may provide renewable energy and climate benefits but cause other environmental harms by destroying habitat. Policymakers evaluating a given energy source should be vigilant to avoid the all-too-common slippage between "renewable" and "climate-friendly" in order to properly identify the costs and benefits of a given intervention.

102 *The Circular Economy in Detail*, Ellen Macarthur Foundation, https://archive.ellenmacarthurfoundation.org/explore/the-circular-economy-in-detail.

103 An Ellen Macarthur Foundation report doesn't mince words: "The circular economy presents a multi-trillion-dollar economic opportunity… More and more companies across industries are adopting circular principles to reduce costs, increase revenues, and manage risks." Ellen MacArthur Foundation, Financing the Circular Economy, Executive Summary, *available at* https://ellenmacarthurfoundation.org/financing-the-circular-economy-capturing-the-opportunity.

104 *See, e.g.,* Phoebe Gittelson et al., *The False Promises of Biogas: Why Biogas Is an Environmental Justice Issue*, Mary Ann Liebert, Inc., https://doi.org/10.1089/env.2021.0025.

105 White House Office of Domestic Climate Policy, U.S. Methane Emission Reduction Act Plan at 11 (November 2021), https://www.whitehouse.gov/wp-content/uploads/2021/11/US-Methane-Emissions-Reduction-Action-Plan-1.pdf.

106 *See* Cal. Dep't Food and Ag., AMMP Program-Level Data of Executed and Funded Grant Projects (updated December 23, 2021), https://www.cdfa.ca.gov/oefi/AMMP/docs/AMMP_Program_Level_Data.pdf; and Cal. Dep't Food and Ag., DDRDP Program-Level Data of Executed and Funded Grant Projects (updated December 23, 2021), https://www.cdfa.ca.gov/oefi/DDRDP/docs/DDRDP_Program_Level_Data.pdf.

107 U.S. Dep't of Ag. Econ. Research Service, The Transformation of U.S. Livestock Agriculture: Scale, Efficiency, and Risks (2009), https://www.ers.usda.gov/webdocs/publications/44292/10992_eib43.pdf?v=0 (2009).

108 *Id.* at iv ("Livestock wastes are becoming more geographically concentrated in the United States, and excessive applications of the nutrients contained in manure pose risks to air and water resources.")

109 *Id.* at 29 ("Large livestock operations store substantial quantities of manure onsite. The manure is generally applied to cropland much more intensely than on smaller farms, and large volumes of manure must still be removed from the operation. High concentrations of manure–whether stored in lagoons, pits, or ponds prior to transport or application–raise the likelihood of leaching or volatilization, threatening groundwater and air quality. And farms that intensively apply manure to cropland and pasture may apply it at rates that exceed the ability of crops to absorb nutrients, with the excess nutrients transmitted to water and air resources.").

110 Leslie Lipper et al., *Climate Smart Agriculture*, Food and Ag. Org. of the United Nations at 397-398, https://link.springer.com/content/pdf/10.1007/978-3-319-61194-5.pdf.

111 Exec. Order No. 14008, Tackling the Climate Crisis at Home and Abroad, 86 Fed. Reg. 7619; Exec. Order No. 13985, Advancing Racial Equity and Support for Underserved Communities Through the Federal Government, 86 Fed. Reg. 7009.


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CLIMATE BENEFITS OF REDUCING NUTRIENT POLLUTION IN AQUATIC ECOSYSTEMS

Jake Beaulieu[1*], Elizabeth Kopits[2], Chris Moore[2], Bryan Parthum[2]

[1]US EPA, Office of Research and Development, Cincinnati, OH
[2]US EPA, National Center for Environmental Economics, Washington DC
*Presenting author beaulieu.jake@epa.gov



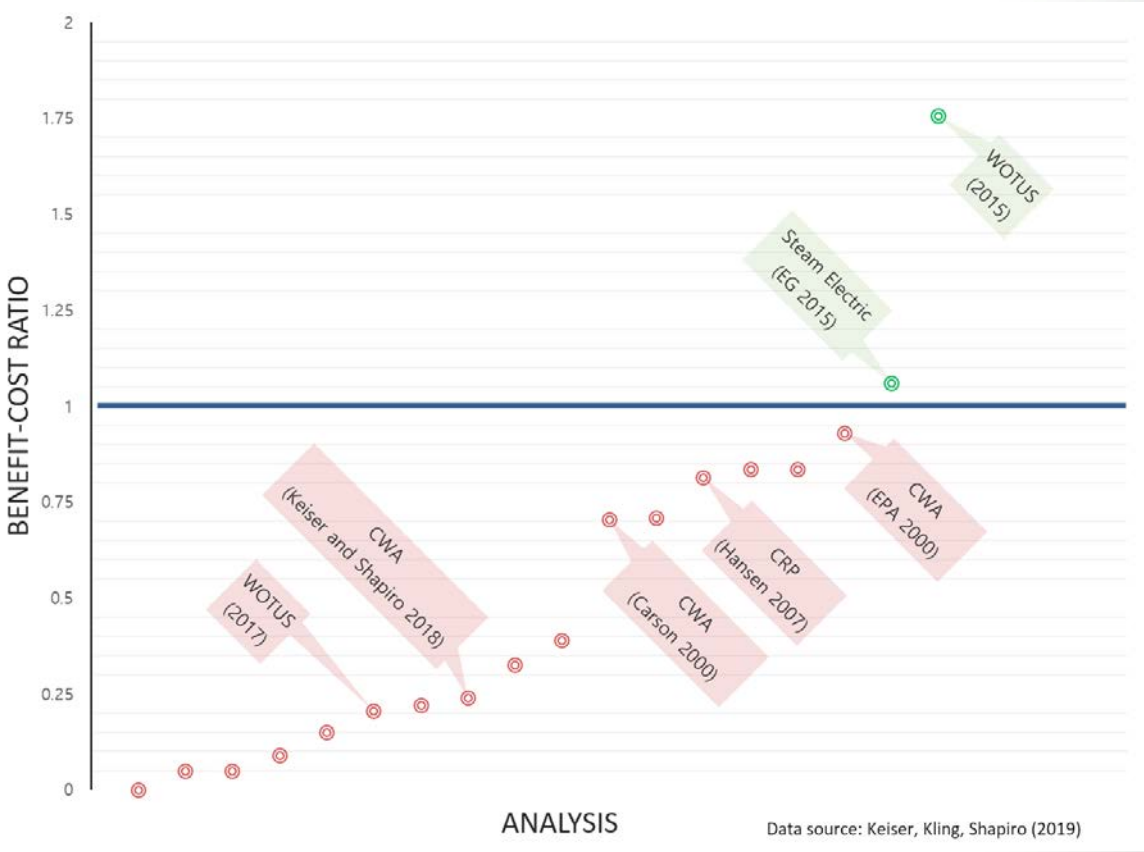
The views expressed during this presentation are those of the presenter and do not necessarily represent those of the U.S. EPA.

Outline

- **Motivation and Background**
  - **Benefit-cost analysis (BCA) of water quality regulations**
  - **GHG emissions and water quality**
- **Case Study: Chesapeake Bay TMDL**
  - **Objective**
  - **Data and methods**
    - ~~**Water quality modeling**~~
    - ~~**GHG models**~~
    - ~~**Brief SCC methods**~~
- **Results**
  - **GHG emissions reductions**
  - **Monetized climate benefits**
- **Discussion**

BCAs of water quality regulations are typically very incomplete

- BCAs of water quality regulations typically show monetized benefits < costs
- Many have pointed out important missing benefit categories
  - Health effects, existence values, non-standard pollutants, benefits to coastal and groundwaters from nutrient management policies (Keiser et al., Griffiths et al.)
- GHG emissions reductions from lakes are another benefit from nutrient management that has been ignored to date

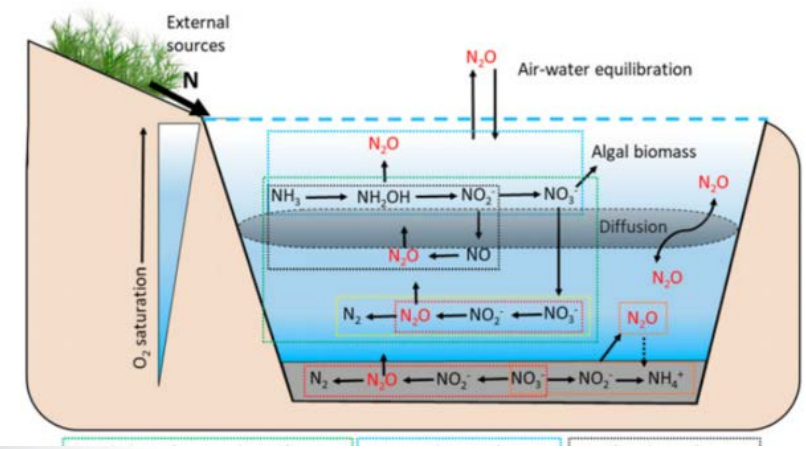


Keiser et al. 2019. The low but uncertain measured benefits of US water quality policy. Proc Natl Acad Sci U S A **116**:5262-5269.

Griffiths et al. 2012 US Environmental Protection Agency valuation of surface water quality improvements. Rev Env Econ and Policy 6.1: 130-146.

GHG Emissions from Lakes

Lakes naturally produce N_2O, CO_2, and CH_4



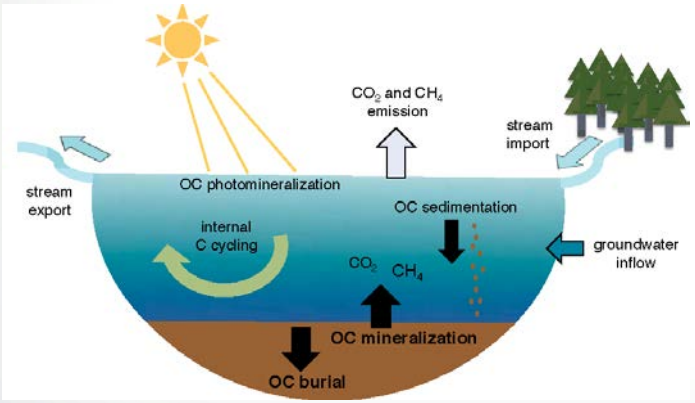
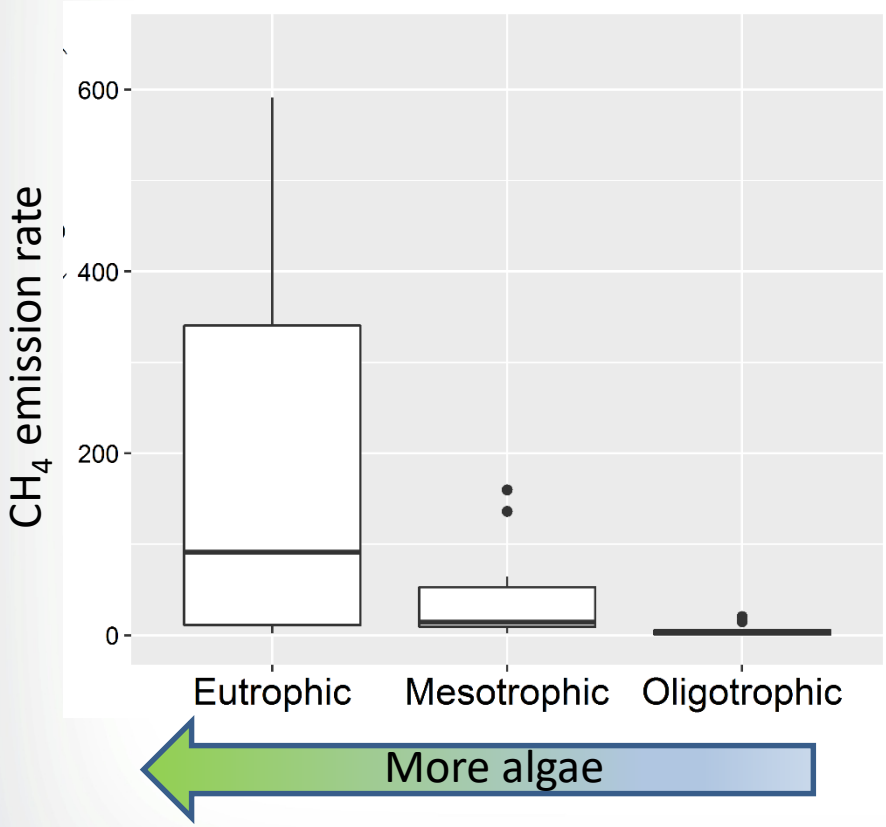


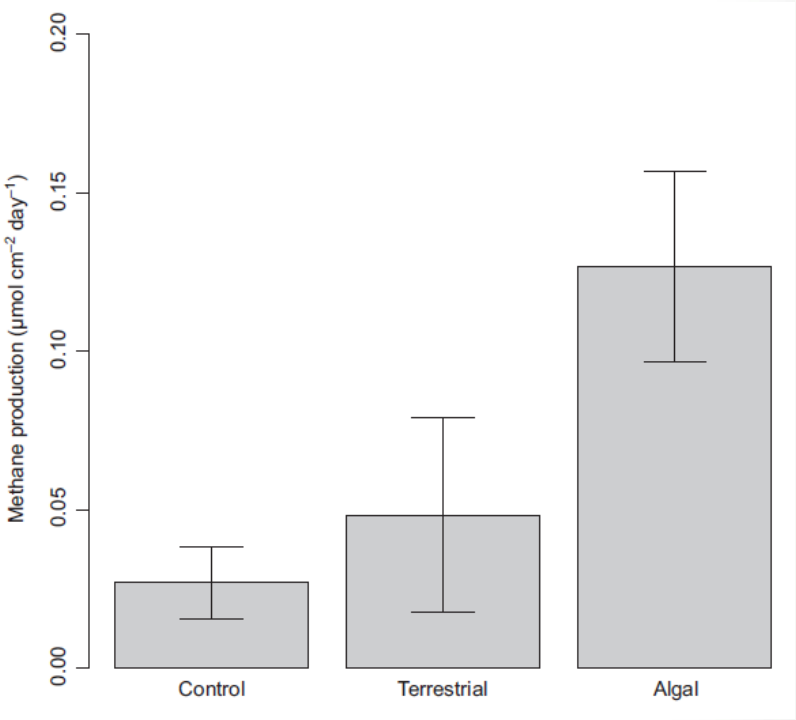

Image credit: National Geographic

Chmiel, H. (2015). "The role of sediments in the carbon cycle of boreal lakes." Environmental Science.

Webb et al. 2019. Widespread nitrous oxide undersaturation in farm waterbodies creates an unexpected greenhouse gas sink. Proc Natl Acad Sci.

Nutrients and algae enhance GHG production





Deemer, et al. 2016. Greenhouse Gas Emissions from Reservoir Water Surfaces: A New Global Synthesis. Bioscience **66**:949-964.

West, et al. 2016. Productivity and depth regulate lake contributions to atmospheric methane. Limnology and Oceanography **61**:S51-S61..

Case study: Chesapeake Bay TMDL

Objective

- **Monetize the climate benefits of a water quality regulation**

Chesapeake Bay Total Maximum Daily Load

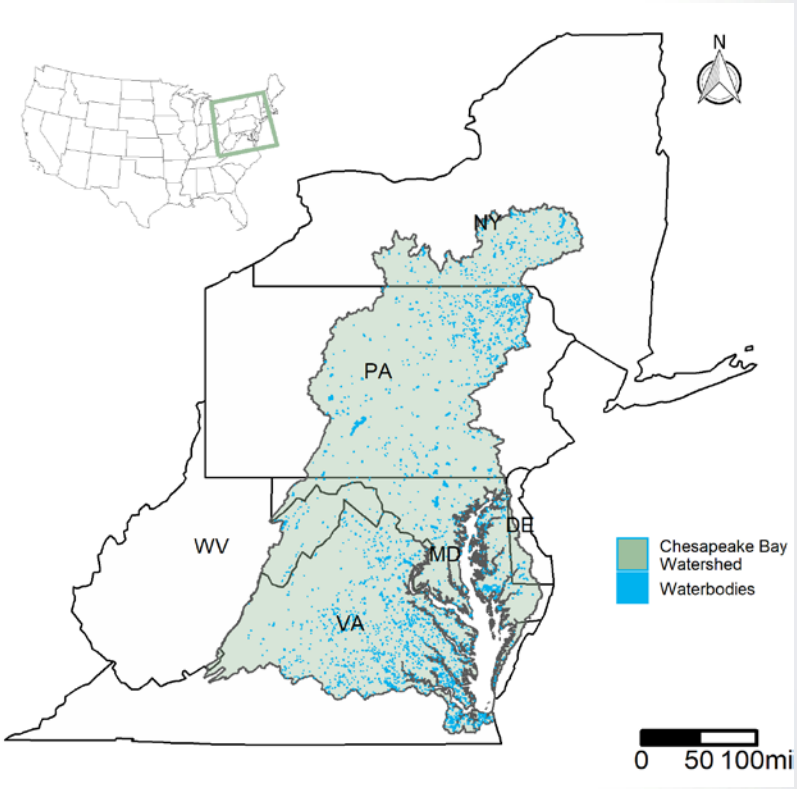
- **Reduce nitrogen loads to Bay by 25%**
- **Reduce phosphorus loads to Bay by 24%**

Watershed Implementation Plans (WIPs)

- **Included management practices for agriculture, urban stormwater, and point sources**

Lake Benefits

- **As part of the stated preference benefits estimation, EPA modeled changes in nutrient loads and trophic status for over 4,200 lakes in the watershed**



Analytical Framework

2010 Baseline input data
Loadings, land use, soil, precipitation

+

Policy Intervention
Watershed implementation plans

Chesapeake Bay Watershed Model
Simulates loading and transport of nitrogen and phosphorus

Northeast Lakes Model
Model nutrient retention and outflows from lakes and reservoirs

Greenhouse Gas Emissions Modeling
Estimates emissions of CO_2, CH_4, N_2O based on lake size, P & chl-a concentration
Adjust for ice cover days and convert rates to metric ton per year per lake

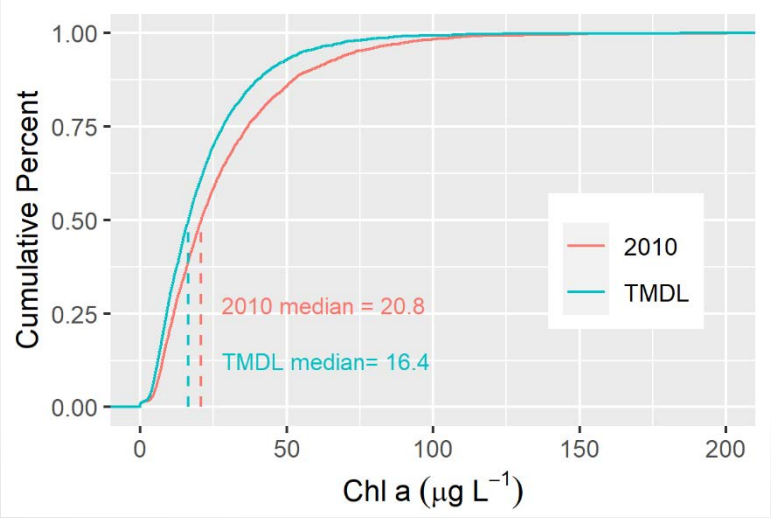
Monetize Climate Benefits
Find incremental emissions from policy in each lake and apply SC-GHGs

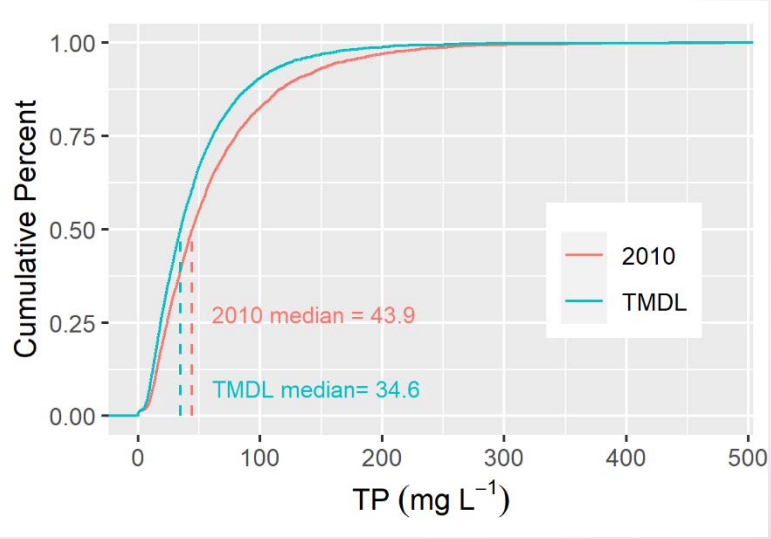
Existing Work

New Work

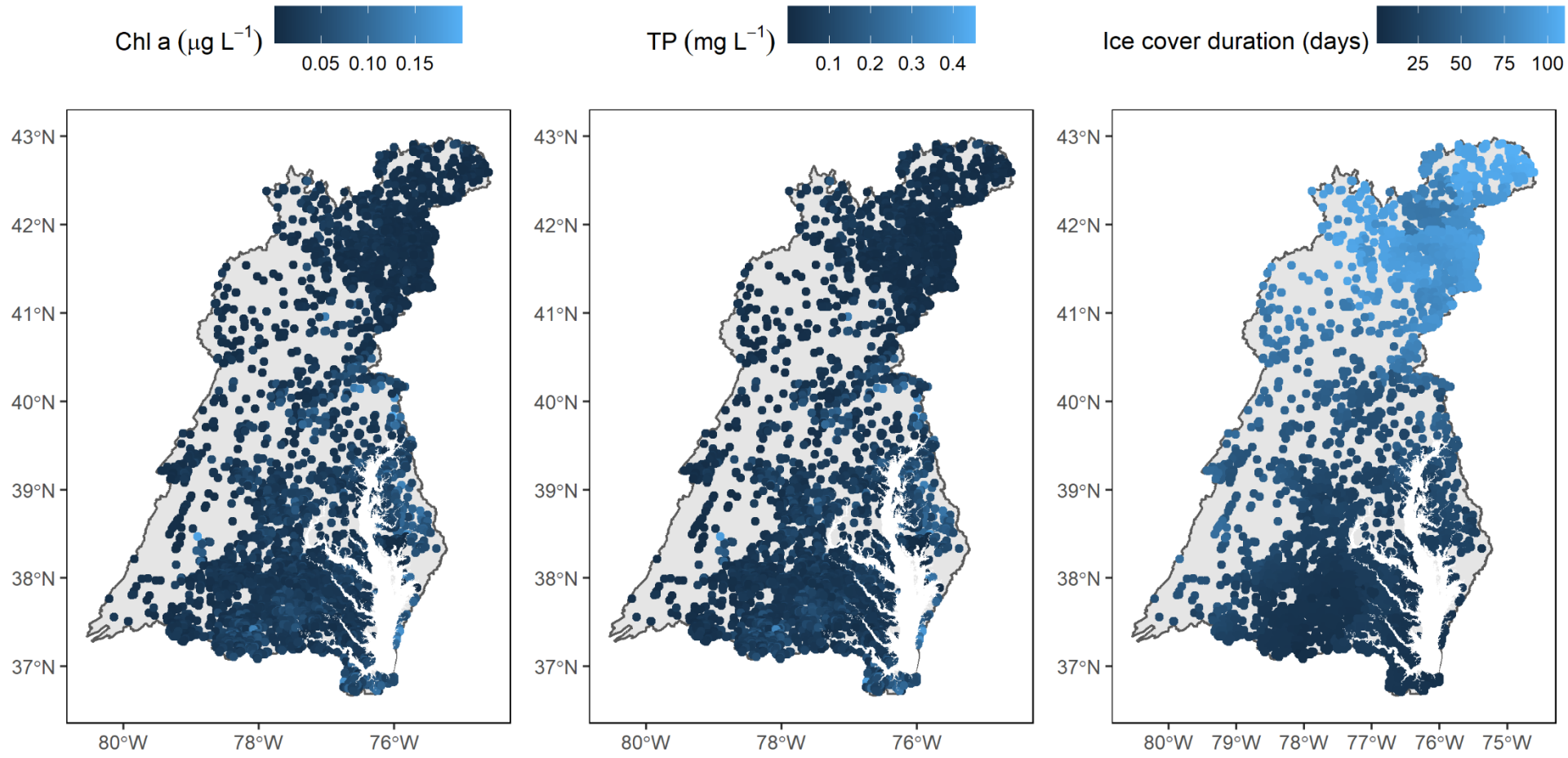
Lakes Data for GHG Model

N = 4,226	Mean	Median	Inner 99th percentile	
Lake surface area (km^2)	0.116	0.031	0.004	2.936
P Conc 2010	60	44	0.019	252
P Conc TMDL	46	34	0.016	189.9
Chl-a 2010	27	21	0.02	106.1
Chl-a TMDL	21	16	0.017	82





Lakes Data for GHG Model



Analytical Framework

2010 Baseline input data
Loadings, land use, soil, precipitation

+

Policy Intervention
Watershed implementation plans

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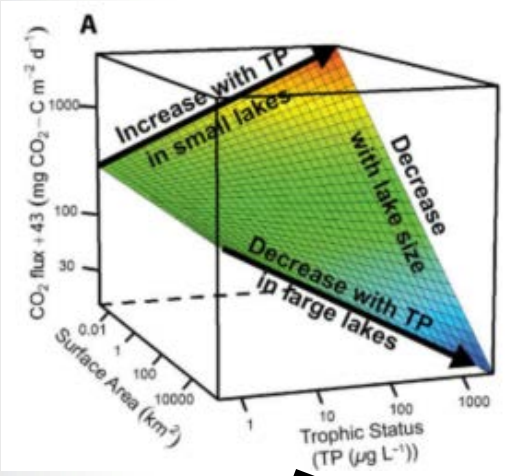
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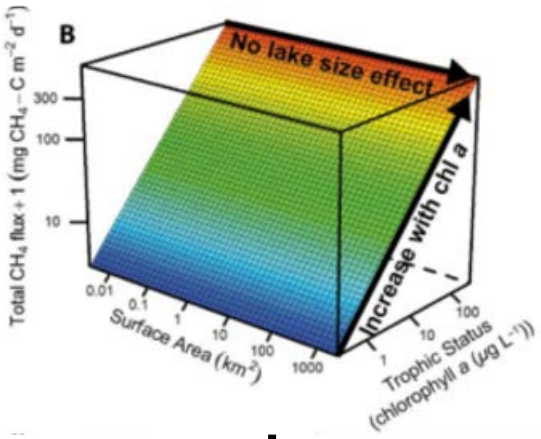
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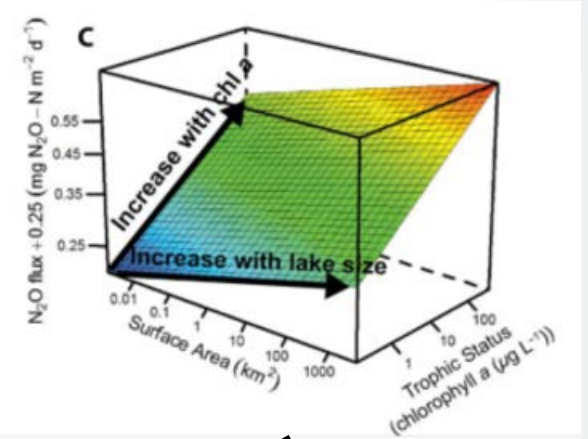
Existing Work

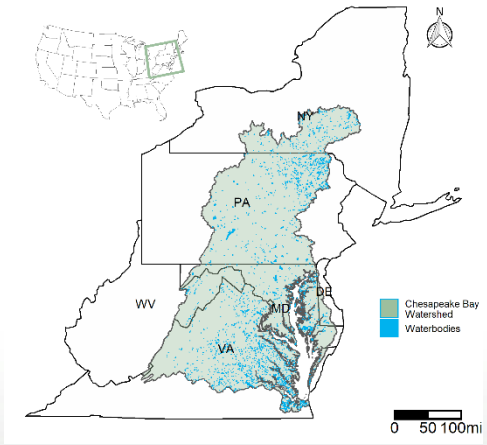
New Work

GHG Model





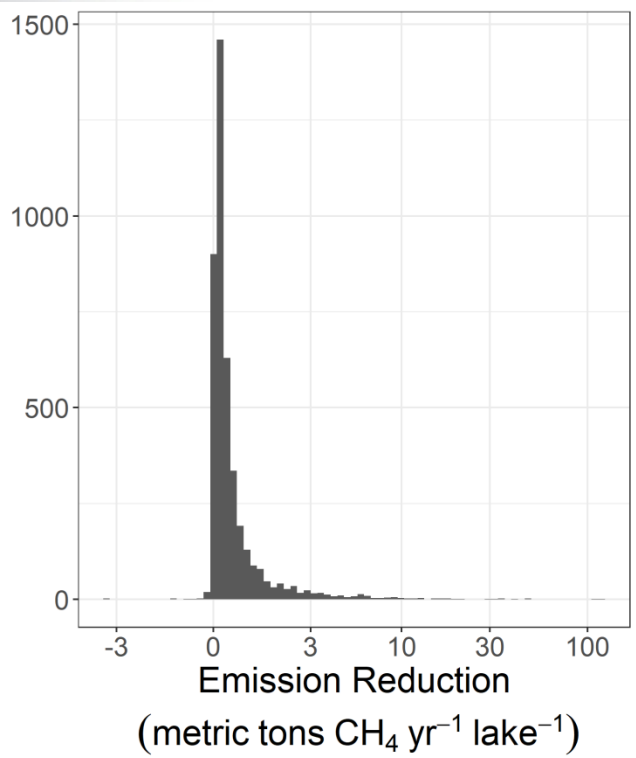


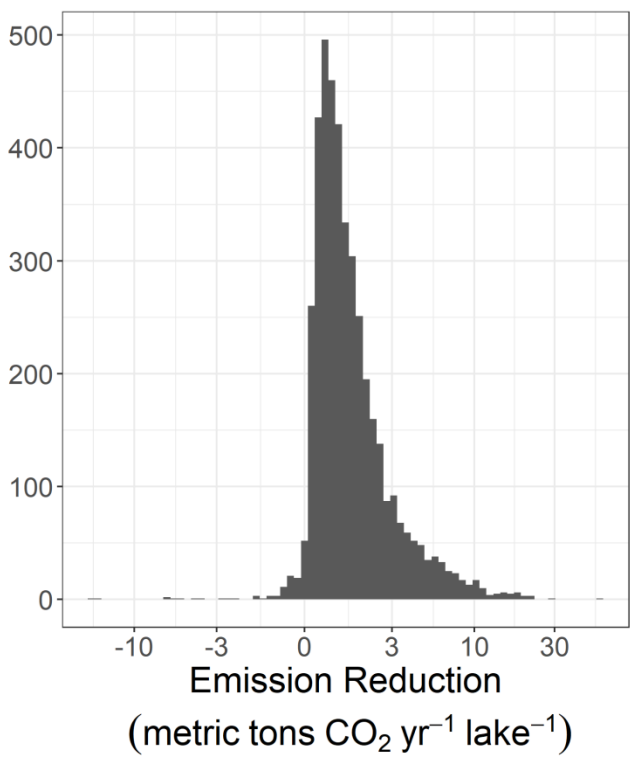


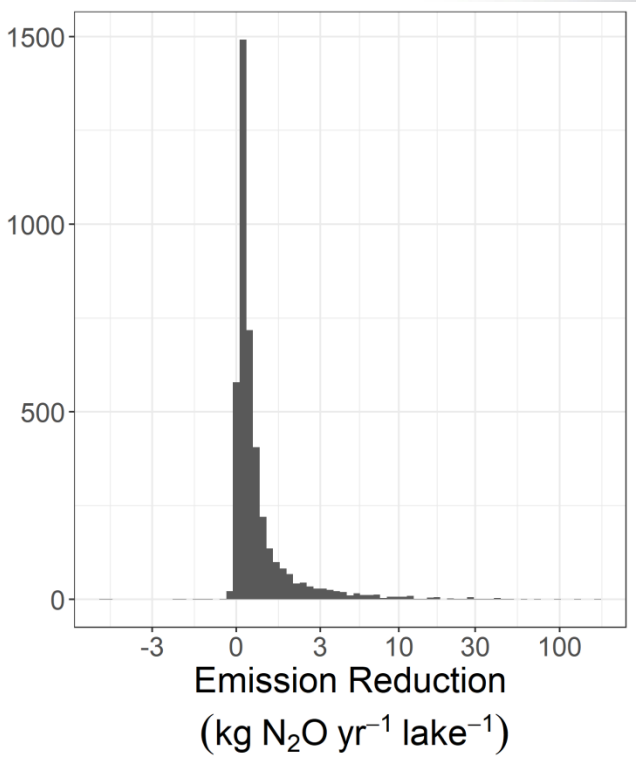
DelSontro, T., Beaulieu, J.J., and Downing, J.A. (2018) "Greenhous gas emissions from lakes and impoundments: Upscaling in the face of global change. Limnology and Oceanography Letters.

GHG Emission Reductions

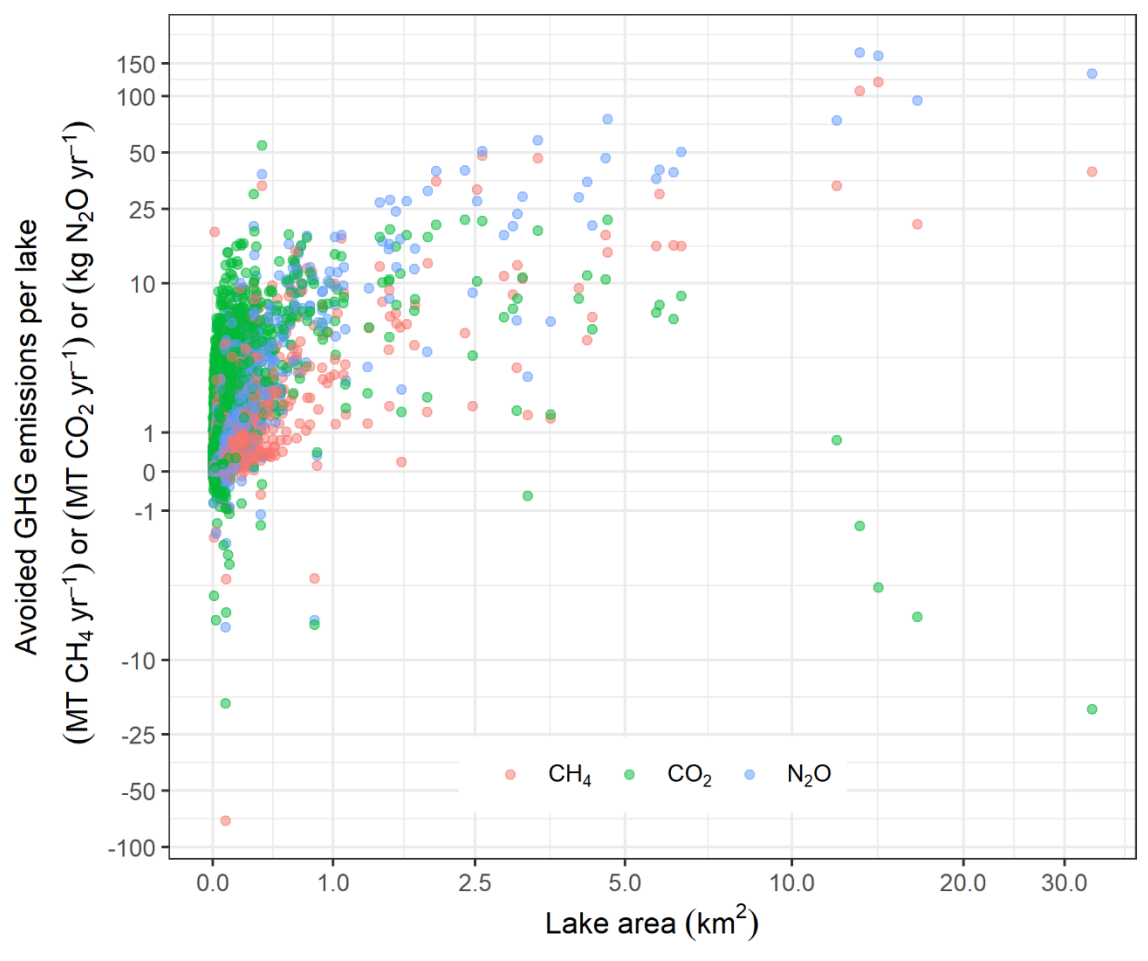
Emission reduction = 2010 emissions – TMDL emissions



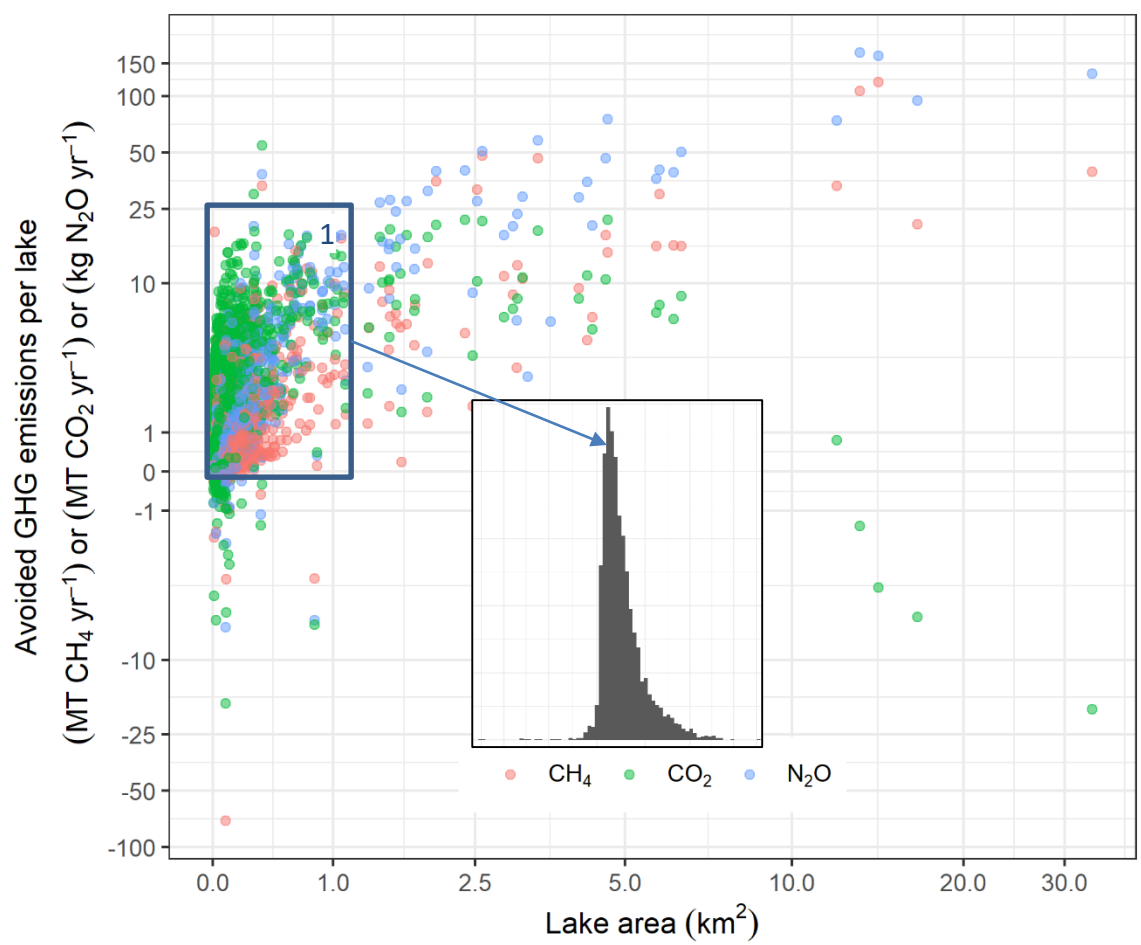




GHG Emission Reductions

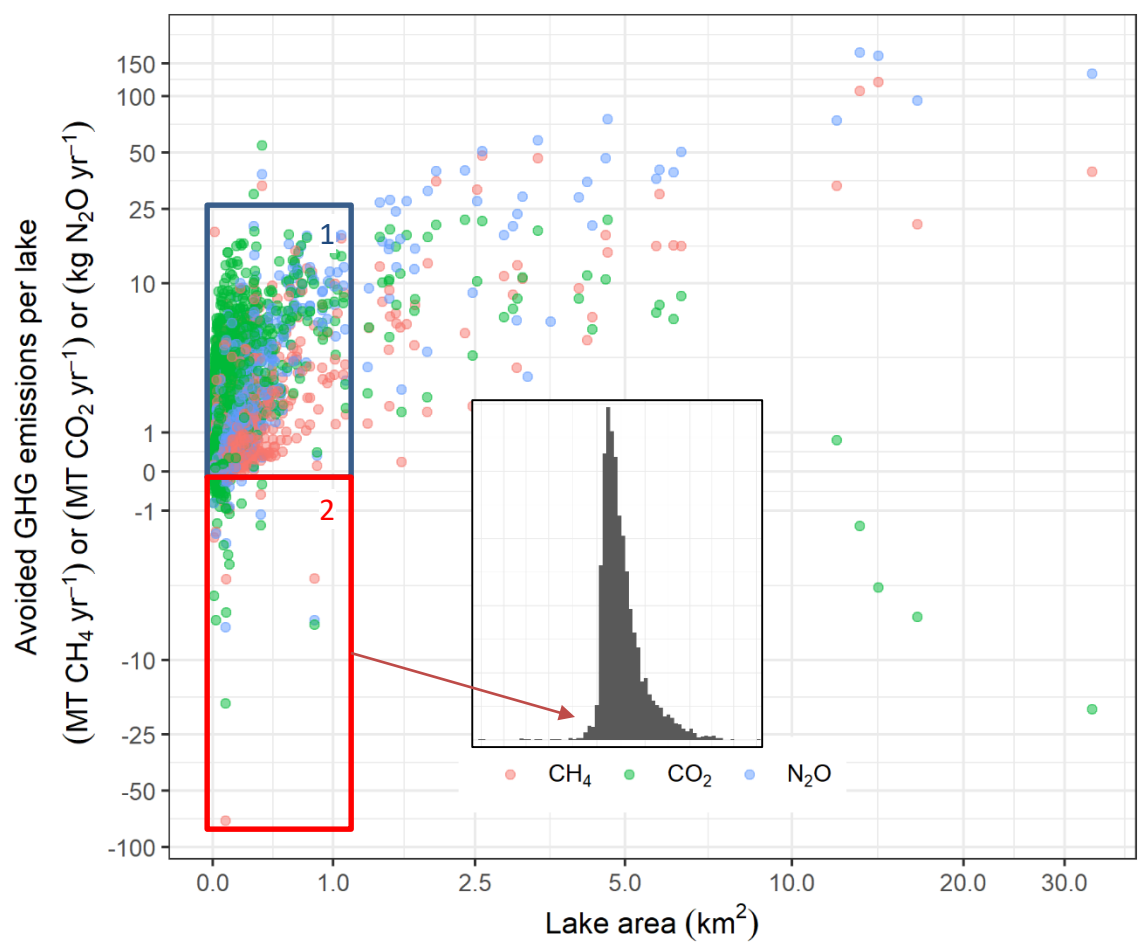


GHG Emission Reductions



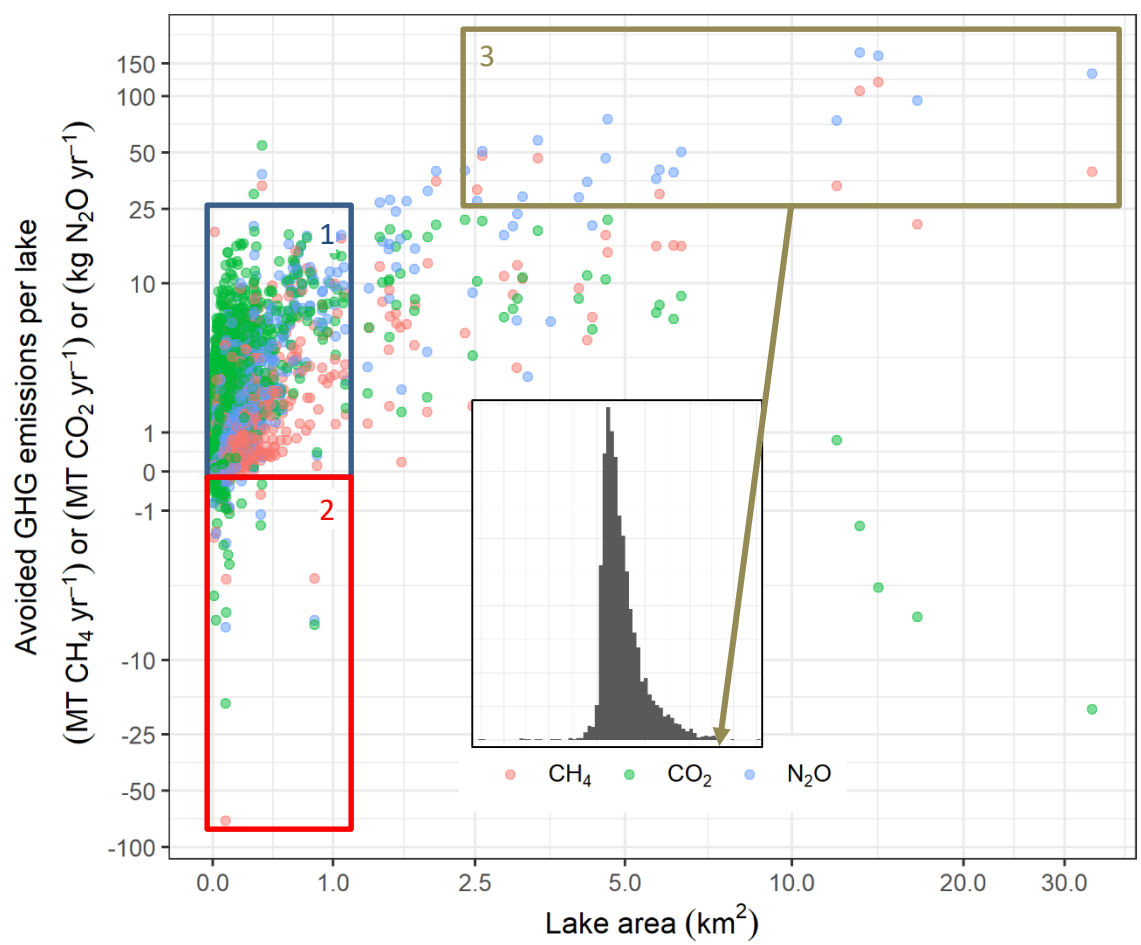
1. Small lakes with decreased nutrients and emissions.

GHG Emission Reductions



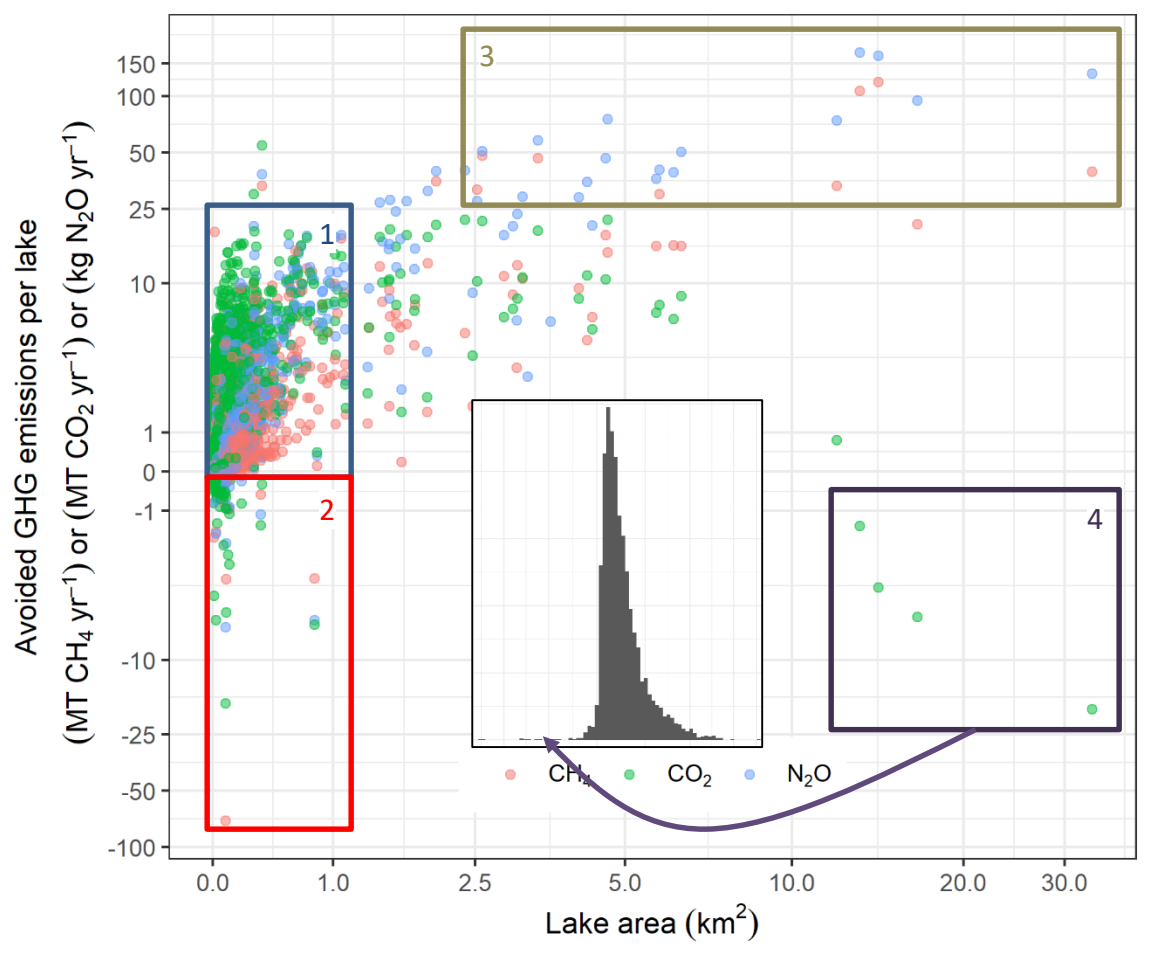
1. Small lakes with decreased nutrients and emissions.
2. Small lakes with increased nutrients, therefore increased GHG emissions

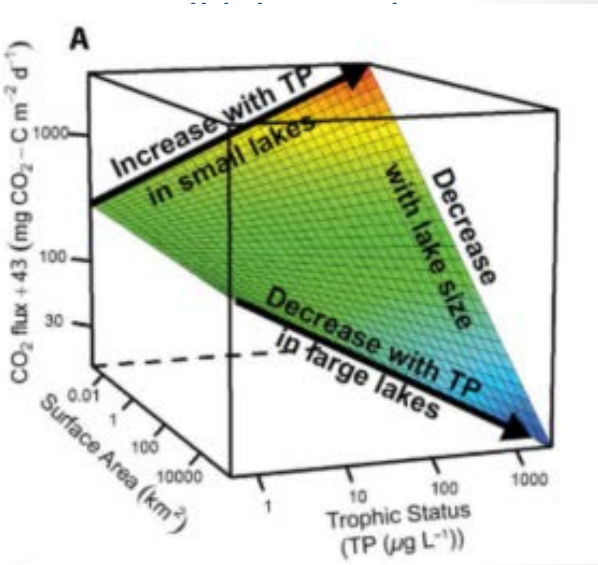
GHG Emission Reductions



1. Small lakes with decreased nutrients and emissions.
2. Small lakes with increased nutrients, therefore increased GHG emissions
3. Larger lakes with decreased nutrients and emissions.

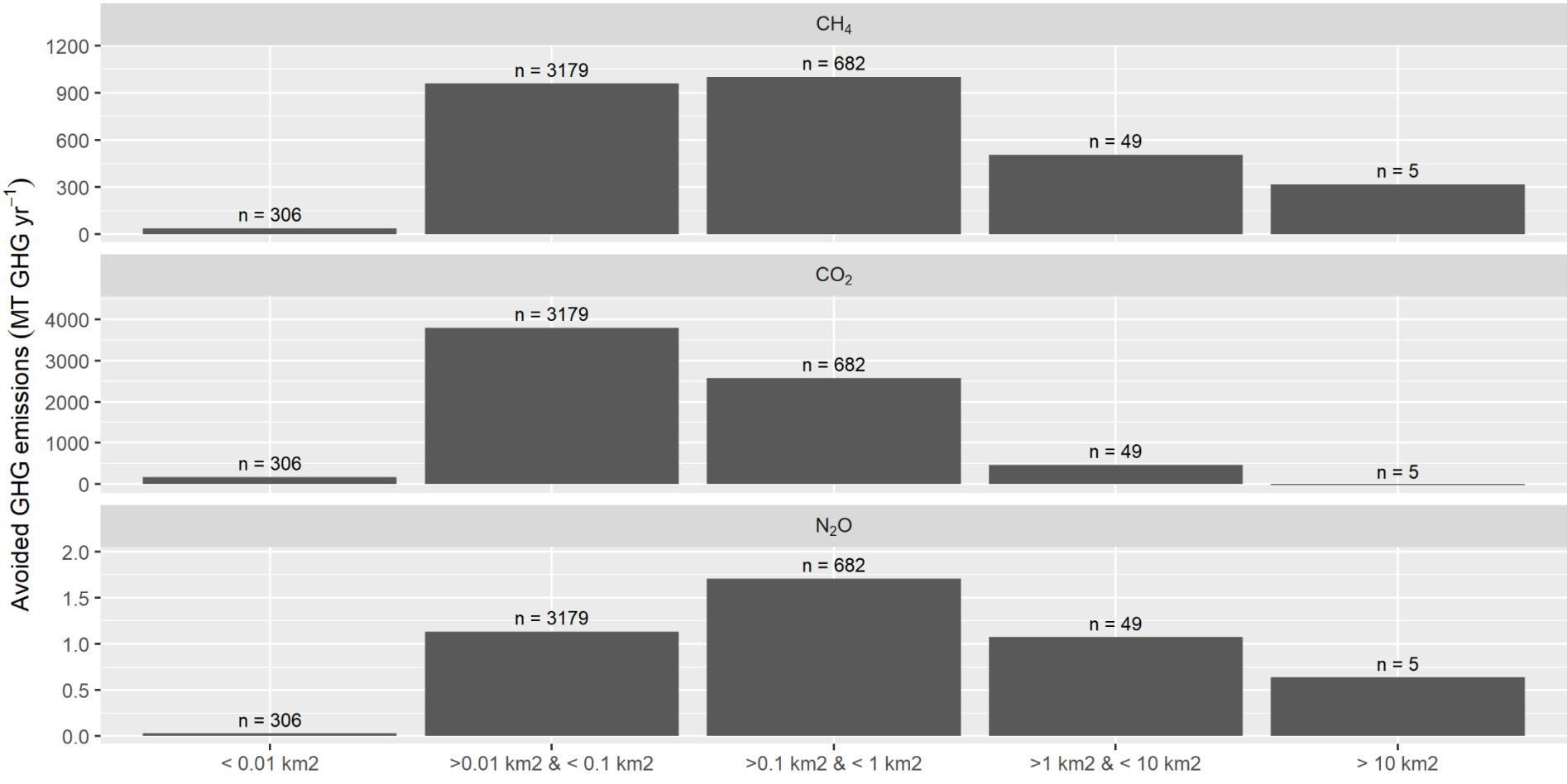
GHG Emission Reductions





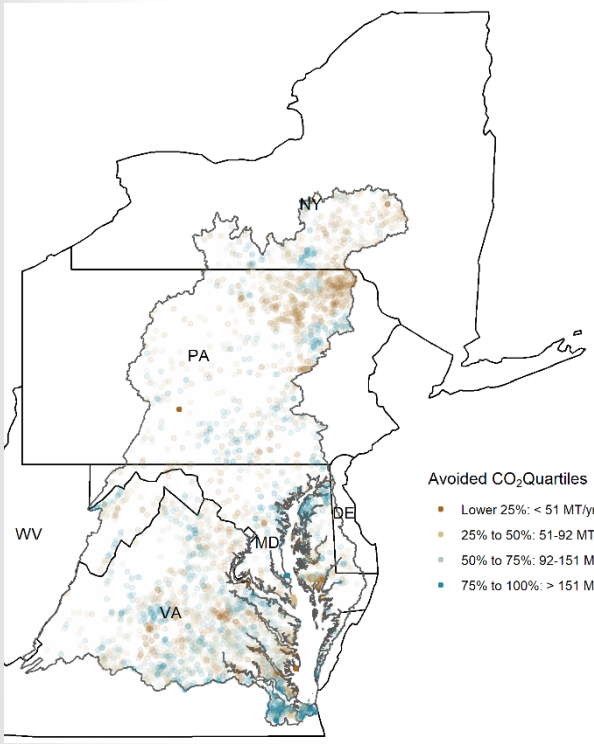
4. Large lakes with decreased nutrients and increased CO_2.

GHG Emission Reductions by Lake Size

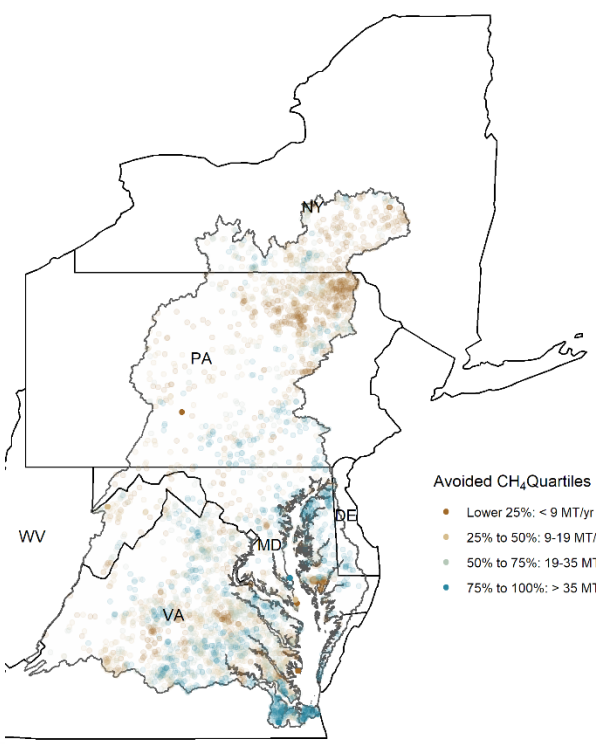


GHG Emission Reductions

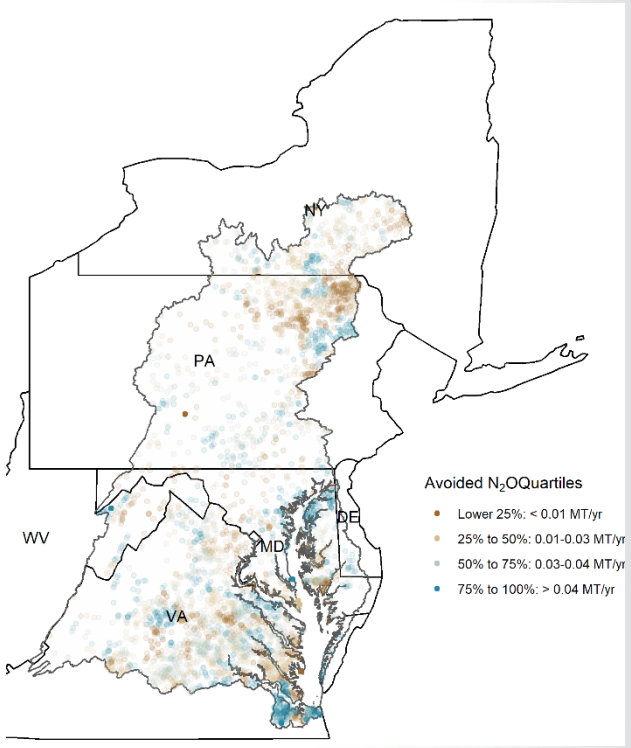
CO_2



CH_4

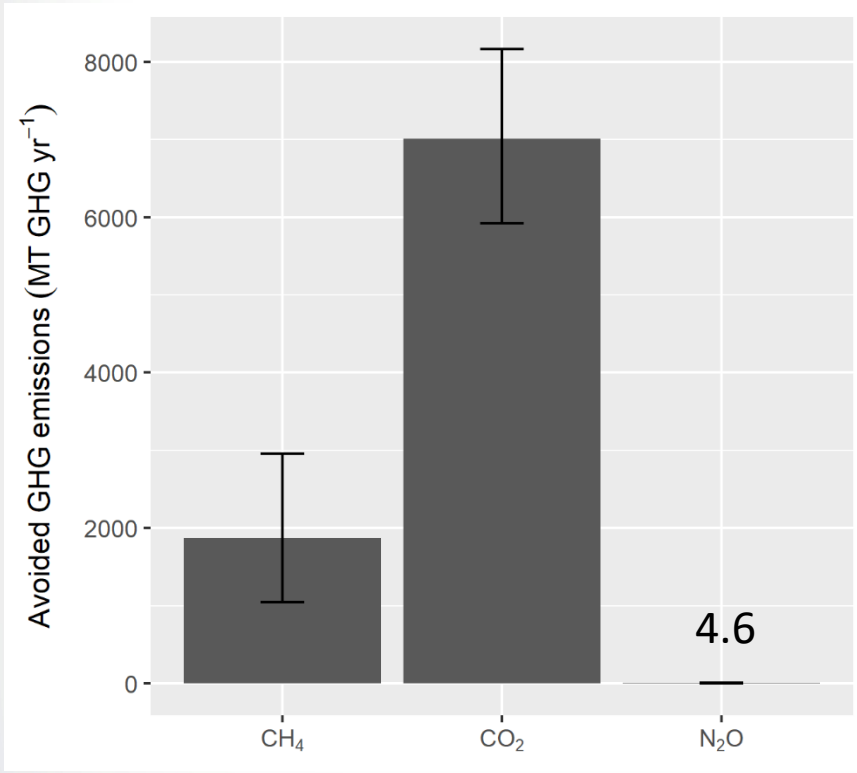


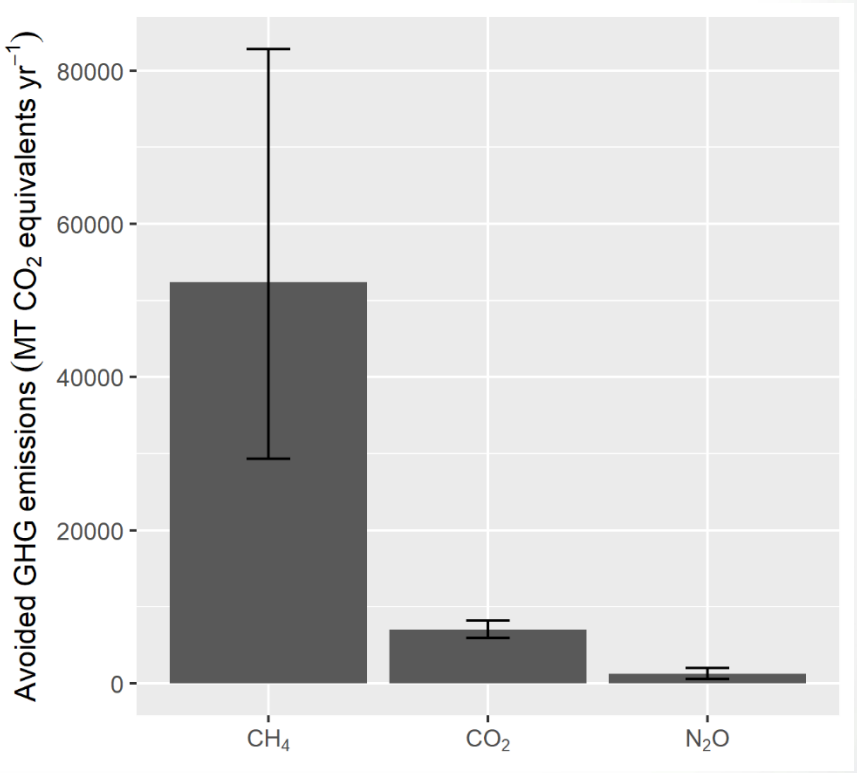
N_2O



GHG Emission Reductions in GWP

CH_4 GWP is 28x that of CO_2
N_2O GWP is 265 times that of CO_2





Climate Benefits of GHG Reductions

- We monetize the social benefits of GHG emissions reductions using estimates of the social cost of carbon (SC-CO_2), social cost of methane (SC-CH_4), and social cost of nitrous oxide (SC-N_2O)
  - Collectively referred to as "social cost of greenhouse gases" (SC-GHG)

- The SC-GHG is the monetary value of the net harm to society associated with an incremental increase in emissions of that GHG in a given year (and conversely, the benefits for an incremental decrease).
  - This is how benefits of GHG reductions are valued in benefit-cost analysis.

- We use SC-GHG estimates based on the same methodology underlying the USG's interim SC-GHGs developed under Executive Order 13990 (issued in February 2021).
  - We use SC-GHG estimates for 2030 based on 2% and 3% discount rates.

2030 Climate Benefits of the Chesapeake Bay TMDL

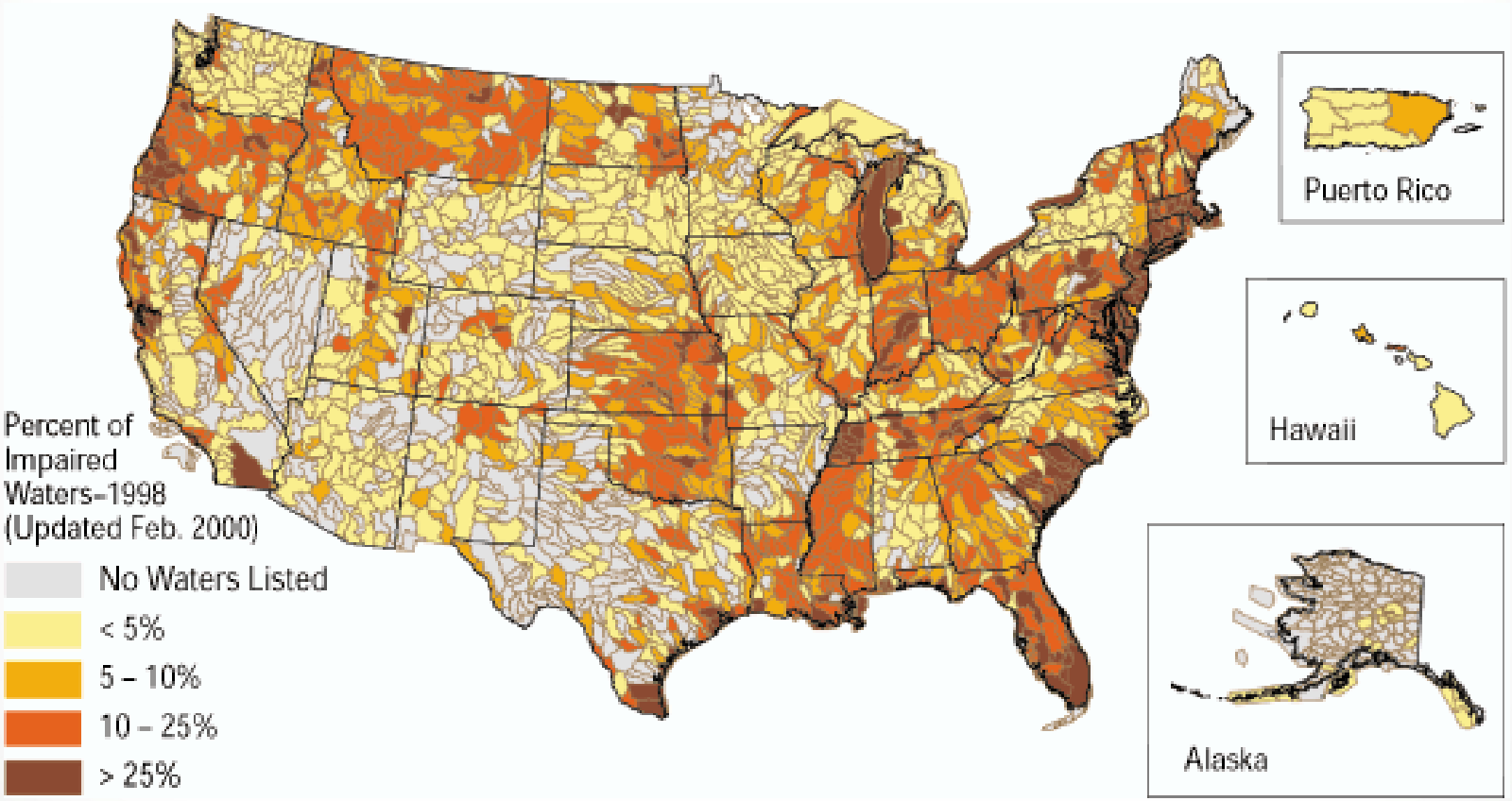
	CO_2	CH_4	N_2O
Annual Emissions Reduction *(metric tons of each gas/yr)*	7008 (5921, 8166)	1870 (1048, 2958)	4.7 (2.1, 7.6)
Social Cost of Greenhouse Gas (SC-GHG) for 2030 Emissions *(2020$ per metric ton of each gas)*			
3% discount rate	$62	$2,000	$23,000
2% discount rate	$140	$3,400	$50,000
Climate Benefits in 2030 (millions 2020$)			
Using SC-GHG at 3% discount rate	$0.40 (0.36, 0.50)	$3.7 (2.10, 5.80)	$0.11 (0.48, 0.17)
Using SC-GHG at 2% discount rate	$0.98 (0.83, 1.10)	$6.3 (3.5, 10.0)	$0.23 (0.10, 0.38)

Discussion

Monetized Benefits of Chesapeake Bay TMDL	Annual Value ($ millions)
Previously Estimated Annual Benefits (<cite bay study>)	
Commercial Fishing	3 -28
Recreational Fishing	5 - 58
Groundwater Contamination	≤6
Dredging of navigational channels and reservoirs	≤12
Reduced cost of drinking water treatment	≤14
Carbon sequestration	≤147
Other Recreation	150 - 300
Particulate formation and health	137 - 347
Climate Benefits from Lake GHG Impacts in 2030	***4.5 - 11.5 (2% discount rate)***

Discussion

- Our study area includes just 0.1% of the lake surface area in the contiguous US.



USGS Fact Sheet FS-130-01

Water Air Soil Pollut (2015) 226: 407
DOI 10.1007/s11270-015-2669-y

Industrial Swine and Poultry Production Causes Chronic Nutrient and Fecal Microbial Stream Pollution

Michael A. Mallin · Matthew R. McIver · Anna R. Robuck · Amanda Kahn Dickens

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Abstract Concentrated animal feeding operations (CAFOs) are the principal means of livestock production in the USA and Europe, and these industrial-scale facilities have a high potential to pollute nearby waterways. Chemical and biological stream water quality of a swine and poultry CAFO-rich watershed was investigated on 10 dates during 2013. Geometric mean fecal coliform counts were in the thousands at five of seven sites, especially in locations near swine waste sprayfields. Nitrate concentrations were very high and widespread throughout the watershed, with some individual samples yielding >10 mg-N/L. Ammonium concentrations were likewise high, but greatest near swine waste sprayfields, ranging up to 38 mg-N/L. Five-day biochemical oxygen demand (BOD5) concentrations exceeded 10 mg/L in 11 of 70 stream samples, reaching as high as 88 mg/L. BOD5 concentrations were significantly correlated with components of animal waste including total organic carbon, ammonium, and phosphorus, as well as the nutrient response variable chlorophyll *a*. The degree of nutrient and fecal contamination did not significantly differ between rainy and dry periods, indicating that surface and groundwater pollution occurs independently of stormwater runoff. This research shows that industrial-scale swine and poultry production leads to chronic pollution that is both a human health and ecosystem hazard. There are approximately 450,000 CAFOs currently operating in the USA, with the majority located in watersheds feeding major riverine and estuarine systems with known water quality problems. Current US waste management protocols for this widespread system of livestock production fail to protect freshwater and estuarine ecosystems along the US Mid-Atlantic, Southeast and Gulf coasts, and expansion into industrializing nations will likely bring severe pollution with it.

Keywords CAFO · Nutrients · Fecal bacteria · BOD · Algal blooms

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1 Introduction

Industrial-scale livestock production is the most common and widespread means of swine and poultry production in the USA and Europe (Thu and Durrenberger 1998; Thorne 2007) and occurs within facilities known as concentrated, or confined, animal feeding operations (CAFOs). The USEPA (2014) defines large CAFOs as containing ≥1000 head of beef cattle, 2500 swine >25 kg, 10,000 swine <25 kg, 125,000 chickens, 82,000 laying hens, or 55,000 turkeys. Large-scale production of livestock in CAFOs involves shipping in vast quantities of feed from elsewhere (often from other states) which results in the deposition of large amounts of excretory nitrogen, phosphorus, organic matter, and fecal microbes in the watershed where the CAFO is located (Cahoon et al. 1999; Mallin and Cahoon 2003). Waste generated by swine in CAFOs is hosed

through slats in the floor of confinement buildings and is drained or pumped outdoors into a cesspit which the industry calls a "lagoon." Periodically, the liquid waste supernatant of lagoons is pumped out and sprayed onto surrounding fields (i.e., sprayfields), which are planted with a cover crop such as Bermuda grass to absorb excess nutrients. Poultry waste is usually collected as dry litter, mixed with straw, and spread on neighboring fields; some CAFOs containing laying hens use the lagoon system. However, the production of vast quantities of animal manure within watersheds can overload the ecosystem's capacity to dilute and process such waste (Carpenter et al. 1998; Weldon and Hornbuckle 2006). According to the USEPA (2014), there are approximately 450,000 CAFOs in the USA, unevenly distributed with the vast majority concentrated in a few states. While inventory and sales vary year to year, the largest swine-producing states include Iowa, North Carolina, Minnesota, Illinois, and Nebraska; the largest broiler chicken producers include Arkansas, Alabama, Mississippi, North Carolina, and Texas; and the largest turkey producers include North Carolina, Arkansas, Minnesota, Missouri, and South Carolina (USDA 2014a). This investigation did not include cattle CAFOs; however, cattle production is especially large in Texas, Nebraska, Kansas, Oklahoma, Iowa, Mississippi, and Wisconsin (USDA 2014a). The CAFO system has currently expanded beyond the USA and northern Europe into Eastern Europe and South America (Thorne 2007).

Serious human health (Cole et al. 2000; Wing and Wolf 2000) and environmental impacts (Campagnolo et al. 2002; Burkholder et al. 2007) of industrial animal production have been documented by researchers, including water quality impacts. The acute polluting impacts of large-scale accidents and hurricanes involving CAFO waste on freshwater streams and estuaries have been well documented (Burkholder et al. 1997; Mallin 2000; Mallin et al. 1999). The location of many CAFOs on river and stream floodplains renders receiving water vulnerable to such accidents, especially during major storms (Wing et al. 2002). CAFOs have been cited as supplying excessive nitrate to Midwestern streams in Ohio and Iowa (Weldon and Hornbuckle 2006; Hoorman et al. 2008). Karr et al. (2001) were able to trace nitrogen that was derived from CAFOs several kilometers downstream using isotopic techniques. A broad-scale study found that streams whose watersheds contained swine and poultry CAFOs had significantly higher concentrations of ammonium, nitrate, and total N than streams whose watersheds lacked CAFOs (Harden 2015). Additionally, the deposition of manure and urine in storage lagoons and on surrounding fields has caused ammonium and/or nitrate pollution of groundwater on or near production facilities (Ritter and Chirnside 1990; Westerman et al. 1995; Liebhardt et al. 1979).

However, chronic pollution of surface waters by a suite of potential pollutants has not been comprehensively assessed for a CAFO-rich watershed. This research investigated physical, chemical, and biological pollution of stream waters in a watershed containing numerous swine and poultry CAFOs while lacking industrial or municipal point sources of pollution and containing little traditional crop agriculture. The degree of pollution was determined from two perspectives: first, since this stream consists of public waters, it was of interest to investigate whether or not these waters were impaired based on state chemical and biological standards. Second, comparative water quality conditions based on parameter concentrations were made using the published literature on coastal plain streams as well as broad-scale literature analyses of streams in general.

Stocking Head Creek (Fig. 1) is a second-order blackwater stream located in the Northeast Cape Fear River basin in eastern North Carolina. Catchment area is 1980 ha (4893 acres), and stream length to where it enters the Northeast Cape Fear River is 22.1 km (13.7 mi). The watershed soils are dominated by Noboco loamy fine sand, Johns fine sandy loam, Autryville loamy fine sand, Pactolus fine sand, Lumbee sandy loam, and Marvyn and Gritney soils (NRCS 2014a). There is some traditional row crop agriculture within this watershed, but aerial photography indicates that coverage by such is small in comparison to CAFO sprayfields and forest cover. The Northeast Cape Fear River is a fifth-order tributary of the sixth-order Cape Fear River, the watershed of which contains approximately half of the 9,000,000 plus swine in North Carolina as well as vast numbers of confined poultry. Cahoon et al. (1999) estimated that the Cape Fear River basin annually received 82,700 metric tons of nitrogen and 26,000 metric tons of phosphorus as animal waste in this watershed from CAFOs alone. Thus, CAFO-rich subwatersheds are likely to be sources of considerable nutrient pollution to larger rivers and estuaries (Mallin and Cahoon 2003; Burkholder et al. 2007). As such, our primary objective was to investigate potential environmental impacts to a stream draining a swine and poultry

CAFO-rich watershed. From July to October 2013, we sampled four main channels and three tributary stations for a broad selection of physical, chemical, and biological water quality parameters.

The location of swine CAFOs and the permitted numbers of swine for each are available from the North Carolina Department of Environment and Natural Resources, and we used these data to map and enumerate swine CAFOs. However, the N.C. Department of Agriculture and Consumer Services (NCDA & CS) does not provide such watershed-specific information on poultry CAFOs to the public or other agencies, although counts of each type of livestock are available on a county-by-county basis from NCDA & CS. Thus, a second objective was to obtain the locations of poultry CAFOs within this basin and estimate poultry numbers confined within them using alternative GIS and aerial photography-based techniques.

2 Methods

2.1 Sample Locations and Frequency

Seven stations were sampled, four on the main stream and two on first-order tributaries (Table 1, Fig. 1). The seventh station (MC-50) was collected on second-order Maxwell Creek, which joins lower Stocking Head Creek before it enters the Northeast Cape Fear River. The Maxwell Creek watershed also contains CAFOs, but they are not as concentrated near stream waters as those in the Stocking Head Creek watershed and they are not quantified in this investigation; MC-50 is used as a comparison site herein. All sites were sampled from bridges on public right-of-ways. The sampling design included five sample trips each taken during two different 30-day periods, one in mid-summer and one in fall. This was planned in accordance with the North Carolina Department of Environment and Natural Resources (NCDENR)'s protocol for fecal coliform sampling for assessment of whether a given stream supported its designated use or if it belongs on the state's 303(d) list for impaired waters. Sampling of Stocking Head Creek occurred during both dry and wet periods. Rainfall data were obtained from the NC CRONOS data set, using Station #319026 Wallace, latitude 34.72, longitude 77.97778, in Duplin County. Rainfall amount was computed for the day of sampling, the day of sampling plus the previous 24-h period, and the day of sampling plus the previous 48-h period.

2.2 Sample Parameters and Methodology

To obtain a full perspective of the stream's physical and chemical qualities, a suite of parameters was sampled. Field measurements were made on-site using YSI field meters calibrated and checked according to standard procedures for water temperature, pH, dissolved oxygen, turbidity, and specific conductance. Samples were collected from surface waters by bucket haul and distributed into pre-cleaned bottles for nutrient (ammonium, nitrate, total nitrogen, orthophosphate, total phosphorus), total suspended solids (TSS), chlorophyll *a*, and 5-day biochemical oxygen demand (BOD5) analyses. Samples were kept on ice and delivered to the laboratory for subsequent analysis within proper holding times. Chain of custody records was maintained.

Analytical methods used (see APHA 1995; USEPA 1983, 1997) were as follows: TSS, SM 2540D; ammonium, EPA 350.1; nitrate+nitrite, EPA 353.2; TKN, EPA 351.2, total nitrogen as calculation of TKN+nitrate; orthophosphate, SM 4500PE; total phosphorous, SM 4500 PE; BOD5, SM 5210B; and fecal coliform bacteria, SM 9222D MF. Total organic carbon concentrations (TOC) were obtained during the fall sampling in an effort to better understand causes of high BOD5 levels that were seen in the summer; the analytical method used for TOC was SM 5310B. Chlorophyll *a* measurements were performed using EPA method 445.0, based on the Welschmeyer (1994) fluorometry method.

2.3 Statistical Analyses

Summary statistics were derived for each parameter (means, standard deviations, medians, minimum, maximum for all data, also geometric means for fecal coliform analysis). Data were tested for normality using the Shapiro-Wilk test, with most chemical and biological parameters requiring log-transformation prior to further statistical analysis. An important consideration was whether or not the pollutant concentrations measured in Stocking Head Creek were the result of acute stormwater-driven surface runoff into the creek or a result of chronic, long-term pollution impacting groundwater as well as surface waters. As such, we analyzed whether or not rainfall produced higher pollutant

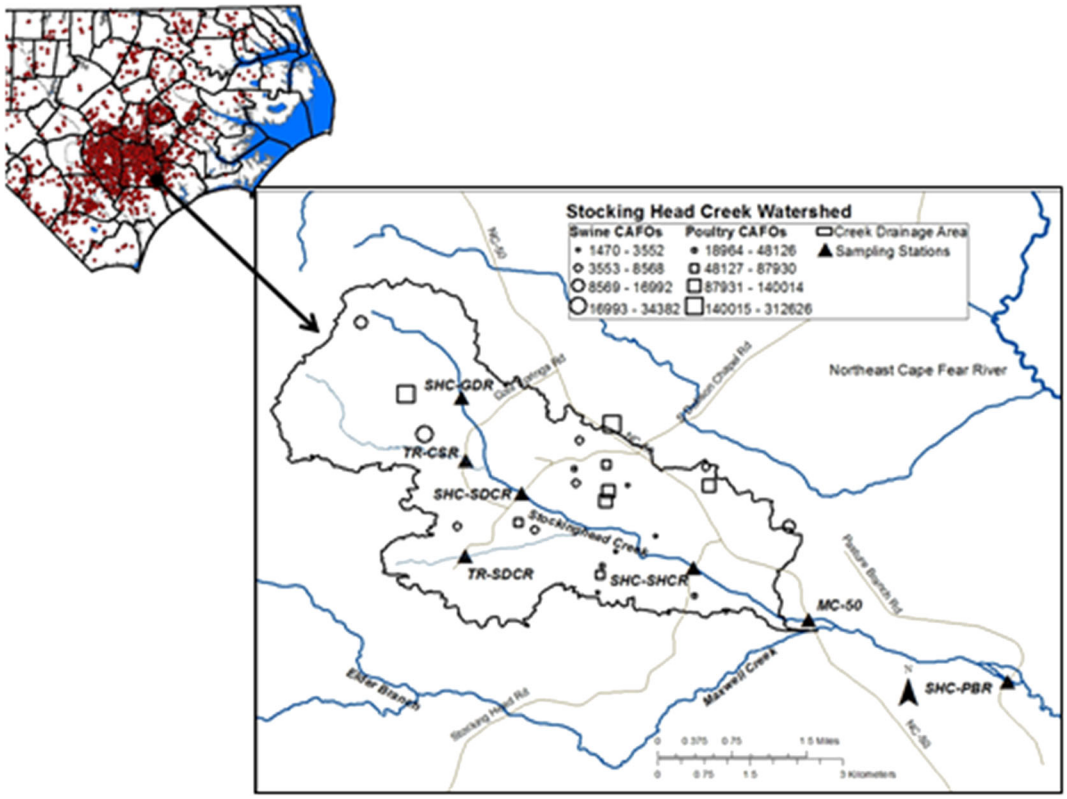


Fig. 1 Map of the Stocking Head Creek watershed, eastern North Carolina, USA, including streams, roads, sampling sites, and swine and poultry CAFOs sorted by size groups. *Inset* is the North Carolina Coastal Plain with *red dots* indicating location of swine CAFOs

parameter concentrations than occurred on non-rain periods. Measurable rainfall occurred either on the day of sampling or within the 48 h preceding the sample day on five of 10 sampling occasions. They were August 1 and 13, September 24, and October 8 and 10. *T* tests were used to test selected parameter concentrations between wet and dry periods (α=0.05). Parameters tested for wet-dry differences included ammonium, nitrate, and fecal coliform bacterial concentrations. To assess potential chemical and biological parameters influencing BOD, correlation and regression analyses were performed using SAS (Schlotzhauer and Littell 1987).

2.4 CAFO Map Construction

A digital elevation model was downloaded from the USGS geospatial portal and used as the data input to delineate the watershed boundaries of Stocking Head Creek. The ArcMap 10.1 Hydrology toolset was utilized, and the catchment area of Stocking Head Creek system was identified. A shapefile including all of the documented animal operations from the NC OneMap geospatial portal was clipped to only display those CAFOs within the newly defined watershed area. After establishing these boundaries and existing CAFOs (primarily swine operations), 2012 orthophotography from the North Carolina OneMap service was analyzed for undocumented CAFOs. The signature shape of the farm buildings (long rectangles side by side) was used to identify these locations, which were presumed to be poultry CAFOs. These were manually digitized as polygons superimposed on the aerial photos, and added to the existing CAFO location data to provide a more accurate assessment of the total number of animal operations within the Stocking Head Creek watershed. Besides the lack of inclusion on the NCDENR database, other characteristics that distinguish North Carolina poultry from swine CAFOs from the air include a lack of waste lagoons for poultry (all swine CAFOs contain waste lagoons but few poultry CAFOs do—egg-laying facilities only). Also, based on aerial photography, poultry CAFO structures are generally longer than swine

Table 1 Description and location of sampled sites, roughly in descending order from headwaters downstream in Stocking Head Creek. See Fig. 1 for locations, nearby roads, and CAFOs

SHC-GDR (Stocking Head Creek at Graham Dobson Road): N 34.91197, W 77.94507. This location collects the uppermost branch of Stocking Head Creek; a swine CAFO and sprayfields are present several hundred of meters upstream from the sampling site. Aerial photos indicate that this stream initiates in what is now a swine CAFO sprayfield.

TR-CSR (unnamed first-order tributary at Cool Springs Road): N 34.90279, W 77.94440. This site had no immediately adjoining CAFOs or sprayfields, but the GIS map (Fig. 1) indicates a large swine CAFO and a large poultry CAFO upstream.

TR-SDCR (unnamed first-order tributary entering Stocking Head Creek at South Dobson Chapel Road): N 34.88878, W 77.94453. Grazing cattle were occasionally present upstream within 75 m of this site, and waste spraying equipment was stationed within 50 m upstream on several sampling dates.

SHC-SDCR (Stocking Head Creek at South Dobson Chapel Rd.): N 34.89796, W 77.93628. Numerous CAFOs, sprayfields, and grazing cattle were located within 200 m of the stream at this site.

SHC-SHCR (Stocking Head Creek at Stocking Head Road): N 34.88710, W 77.91124. A large CAFO sprayfield was located within 50 m of the stream, with a ditch carrying sprayfield runoff that emptied directly into the stream at this location.

MC-50 (Maxwell Creek at SR 50): N 34.87950, W 77.89438. This sampling site adjoined a wetland area which was hydrologically connected to Stocking Head Creek. The Maxwell Creek watershed also contains CAFOs, although fewer than those in Stocking Head Creek watershed (Fig. 1).

SHC-PBR (Stocking Head Creek at Pasture Branch Road): N 34.87043, W 77.86539. This location was the farthest downstream site sampled. This downstream area also likely receives inputs from CAFOs in the Maxwell Creek drainage. There was also an adjoining forested wetland that supplied flow to the stream here.

CAFOs and have the feeding silo located at the building midpoint, while swine CAFOs have feeding silos located at the building's end.

The dimensions of each poultry building were computed from the digitized aerial photographs. Maximum bird (considered as broiler chickens) populations per building were estimated by assuming 743 cm^2 (0.80 ft^2) of space allotted per bird as is standard for a major poultry producer (Sanderson Farms 2007). The United Egg Producers (2010) recommend 436–557 cm^2 (0.47 to 0.60 ft^2) of space per egg-laying chicken; thus, we feel our counts are conservative. As there is no way to distinguish chicken from turkey operations from the air, for the purposes of this study, we assumed all broiler chickens. As a comparative reference regarding livestock manure production, the National Resources Conservation Service within the US Department of Agriculture uses animal units, i.e., 1 cow=9 hogs=455 broiler chickens=67 turkeys (NRCS 2014b).

3 Results

The Stocking Head Creek watershed (excluding Maxwell Creek) contains 13 swine CAFOs that are permitted by NCDENR for collectively 108,068 heads of swine. This watershed also contains 11 poultry CAFOs, consisting of a total of 42 individual buildings. Average poultry house size was approximately 2323 m^2 (25,000 ft^2), with an average capacity of 31,250 birds. Thus, the watershed can house a maximum of 1,312,500 broiler chickens or equivalent turkeys using the animal unit conversions above. Grazing cattle were visibly present in this watershed (with some photographed grazing directly under swine waste sprays), but an accurate count is beyond the capability of this study. Confined swine, poultry, and cattle produce large quantities of manure; conversion factors of excreted waste into total nitrogen, phosphorus, and fecal bacteria for these three livestock types can be found in Mallin and Cahoon (2003). While the local human population relies on septic systems for sewage treatment, aerial photography revealed only 67 human dwellings in the watershed, yielding a scant 0.03 septic systems/ha.

Summer water temperatures ranged between 22.0 and 28.0 °C, and fall water temperatures ranged from 16.1 to 22.6 °C. Most sampling events reflected neutral stream pH conditions ranging from 6.5 to 7.3. Dissolved oxygen concentrations ranged from mildly hypoxic (3.5 mg/L) to supersaturation (17.0 mg/L) during an algal bloom. Average turbidity by station ranged from 1.1 to 21.0 NTU (nephelometric turbidity units). Total suspended solids (TSS) in most cases were less than 25 mg/L (Table 2). Elevated TSS concentrations occurred a few times primarily at the tributary station TR-SDCR.

Ammonium in Stocking Head Creek during the 10 sample trips ranged from the detection limit (0.05 mg/L) to 37.8 mg/L (Table 2). Highest ammonium concentrations were found at station TR-SDCR, followed by station SHC-SHCR. These stations are both within 50 m of swine CAFO sprayfields (Table 1, Fig. 1). Nitrate concentrations in Stocking Head Creek were very high (Table 2). Whereas the highest ammonium

Table 2 Water quality parameter concentrations in Stocking Head Creek, 2013, given as mean±standard deviation/median/range; fecal coliforms as geometric mean/range. $n=70$, except for TOC where $n=35$

Parameter	Station						
	TR-SDCR	SHC-GDR	TR-CSR	SHC-SDCR	SHC-SHCR	MC-50	SHC-PBR
Turbidity	25.6+20.1	4.5±2.2	11.4±9.2	9.5±5.4	12.4±5.8	1.0±2.3	4.0±2.5
NTU	21.0	4.1	9.5	10.0	12.0	1.1	3.8
	4.0–72.0	2.0–10.0	1.0–31.0	2.0–22.1	6.3–22.0	0.0–8.0	1.0–8.0
TSS	23.9±18.2	5.6±2.4	15.0±28.3	9.5±3.6	10.9±4.4	3.2±1.6	4.2±3.5
mg/L	21.3	5.4	6.4	9.9	11.3	3.4	3.4
	5.8–56.7	3.3–10.8	1.4–94.0	2.9–14.9	5.2–19.0	1.4–6.1	1.3–12.1
DO	7.4±4.0	5.9±0.8	7.2±0.5	7.9±0.8	7.4±0.3	6.0±0.9	6.4±0.8
mg/L	5.8	5.8	6.9	7.7	7.4	5.9	6.1
	3.5–17.0	4.7–7.3	6.8–8.4	7.0–9.3	6.9–7.9	5.0–7.7	5.6–7.9
Ammonium	10.5±13.6	0.1±0.1	0.3±0.2	0.2±0.2	3.3±4.1	0.1±0.1	0.4±0.5
mg-N/L	3.6	0.1	0.2	0.1	1.0	0.1	0.1
	0.2–37.8	0.1–0.2	0.1–0.7	0.1–0.8	0.2–10.9	0.1–0.1	0.1–1.6
Nitrate	2.9±3.6	6.8±4.2	7.9±2.2	3.6±2.2	6.1±2.1	0.3±0.2	1.3±0.6
mg-N/L	1.4	6.0	8.4	3.9	6.3	0.2	1.1
	0.1–10.0	1.6–13.6	3.0–10.5	0.6–7.4	1.1–8.4	0.1–0.7	0.8–2.4
TN	15.7±16.7	7.2±4.2	8.4±1.8	3.9±2.2	8.7±4.1	0.5±0.3	1.8±0.9
mg-N/L	7.6	6.2	8.6	4.2	7.9	0.5	1.6
	0.5–46.6	2.1–13.6	4.3–10.8	0.8–7.4	2.1–16.1	0.1–0.9	0.8–3.5
OP	1.8±1.7	0.1±0.0	0.1±0.1	0.2±0.1	0.4±0.2	0.3±0.1	0.3±0.1
mg-P/L	1.6	0.1	0.1	0.2	0.3	0.3	0.3
	0.1–5.5	0.1–0.2	0.1–0.4	0.1–0.3	0.2–0.6	0.2–0.4	0.2–0.4
TP	2.8±8.3	0.2±0.1	0.2±0.2	0.2±0.1	0.5±0.2	0.3±0.1	0.4±0.1
mg-P/L	1.7	0.2	0.1	0.2	0.4	0.3	0.4
	0.2–10.7	0.1–0.3	0.1–0.6	0.1–0.3	0.3–0.8	0.2–0.4	0.3–0.6
TOC	36.1±13.9	14.2±1.2	10.9±0.9	13.7±1.6	19.0±3.9	17.5±1.4	16.2±0.8
mg-C/L	39.9	13.5	11.2	13.0	17.4	18.1	15.7
	13.1–50.4	13.2–15.5	9.6–11.9	12.5–16.3	14.3–23.1	15.1–18.4	15.5–17.4
Chlorophyll *a*	12.3±11.8	10.1±8.4	2.9±2.1	5.2±2.8	10.7±11.9	6.1±8.2	1.2±0.6
μg/L	8.5	8.0	2.0	5.0	7.0	2.0	1.0
	1.0–40.0	2.0–28.0	1.0–8.0	1.0–12.0	3.0–44.0	1.0–25.0	0.0–2.0
BOD5	18.7+25.7	2.0±1.2	1.7±0.8	2.7±3.5	7.4±8.3	3.2±6.3	1.4±0.5
mg/L	11.0	1.5	1.5	1.0	3.5	1.0	1.0
	1.0–88.0	1.0–4.0	1.0–3.0	1.0–12.0	1.0–25.0	1.0–21.0	1.1–2.0
Fecal col.	9126	1184	1470	1772	5863	220	391
CFU/100 mL	455–60,000	330–3000	546–5000	728–8000	1182–60,000	91–1360	55–4000

concentrations were found at the two sites located closest to waste sprayfields, several sites showed high nitrate, including sites distant from sprayfields (Table 2; Fig. 1). Concentrations ranged from 0.08 to 13.60 mg-N/L, with station means ranging from 0.30 to 7.94 mg-N/L. Particularly high nitrate concentrations were documented at these four sites: SHC-GDR, TR-CSR, SHC-SDCR, and SHC-SHCR. On 12 of 70 sampling occasions, stream nitrate concentrations exceeded 8 mg-N/L. Total nitrogen (TN) concentrations ranged

from 0.11 to 46.70 mg-N/L, while highest individual station average TN concentrations occurred at TR-SDCR, TR-CSR, and SHC-SHCR. The TN values in this stream were dominated by inorganic nitrogen (i.e., nitrate and ammonium) rather than organic nitrogen, with average percent inorganic N ranging from 80 to 100 % of TN, depending upon station.

Orthophosphate concentrations in Stocking Head Creek ranged from 0.04 to 5.45 mg-P/L, with station means ranging from 0.11 to 1.78 mg-P/L (Table 2). Highest concentrations were found at station TR-SDCR, followed by SHC-SHCR. Total phosphorus ranged from 0.040 to 10.70 mg-P/L, and station means ranged from 0.15 at SHC-GDR to 2.83 mg-P/L at TR-SDCR, with SHC-SHCR second highest at 0.50 mg-P/L (Table 2). Most TOC concentrations were in the 10–20 mg/L range; however, higher TOC concentrations occurred at TR-SDCR and SHC-SHCR, the stations nearest to sprayfields (Table 2).

Chlorophyll *a* represents the amount of suspended live microalgal biomass found in a sample of water (Wetzel 2001). Elevated chlorophyll *a* concentrations (algal blooms) occurred at TR-SDCR on July 29 (40 μg/L) and at this same site on September 18 (44 μg/L), with smaller blooms occurring several times at other sites. Thus, algal blooms occurred within Stocking Head Creek, but were inconsistent in time and among sampling sites (Table 2).

Biochemical oxygen demand (BOD) is a measure of the organic matter available for consumption by the bacteria in a body of water during respiration; excessive BOD can lead to hypoxia. Five-day BOD (BOD5) varied widely (Table 2), from background concentrations of 1.0 mg/L up to high values of 21 mg/L at MC-50, 25 mg/L at SHC-SHCR, and the maximum of 88 mg/L at station TR-SDCR. That station maintained the highest overall BOD5 concentrations (Table 2), reaching 10 mg/L or more on six of 10 dates, while station SHC-SHCR exceeded 10 mg/L on three dates. The stream stations with highest average BOD concentrations were those in closest proximity to swine waste sprayfields (Table 1; Fig. 1).

North Carolina uses fecal coliform bacteria counts as a proxy for potentially pathogenic bacteria in fresh water bodies; this standard is commonly used throughout the southeast of the USA (EPA Region 4) for freshwater contact. The NC protocol (NCDENR 1999) for sampling and the means for determining fecal impairment of a water body state that fecal coliform counts shall not exceed a geometric mean of 200 CFU/100 mL based on at least five consecutive samples during any 30-day period nor exceed 400 CFU/100 mL in more than 20 % of the samples examined during such period. Fecal coliform counts for Stocking Head Creek were generally very high (Fig. 2). During summer 2013, the upper five stations exceeded 400 CFU/100 ml on 100 % of the time sampled, and the geometric means for all seven stations exceeded 200 CFU/10 mL for five samples in 30 days. Fecal coliform counts for Stocking Head Creek in fall 2013 were even higher than those in summer; the upper five stations exceeded 400 CFU/100 ml on 96 % of the time sampled, and the geometric means for six of the seven stations exceeded 200 CFU/10 mL for five samples in 30 days. During both the summer and the fall sampling periods, fecal coliform criteria for impaired waters were well exceeded. Elevated fecal coliform counts occurred during both wet and dry periods. Highest fecal coliform counts occurred at TR-SDCR and SHC-SHCR, the stations nearest to sprayfields. Most other stations also had high counts, with geometric means exceeding 1000 CFU/100 mL (Table 2, Fig. 2). While lower Maxwell Creek (MC-50) maintained the lowest counts, it still exceeded state criteria for impaired waters.

An important consideration is whether or not the high pollutant values measured in Stocking Head Creek were the result of acute stormwater-driven surface runoff into the creek or a result of chronic, long-term pollution impacting groundwater as well as surface waters. As such, we analyzed whether or not rainfall produced higher pollutant parameter concentrations than occurred

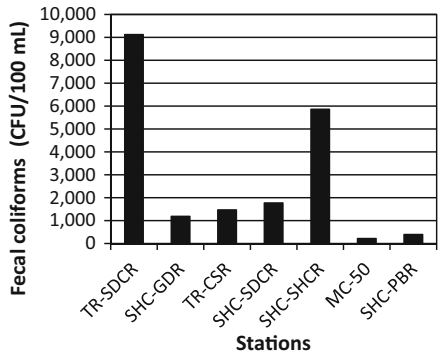


Fig. 2 Fecal coliform bacteria counts (as colony-forming units/100 mL) for Stocking Head Creek watershed sampling sites, presented as geometric mean of 10 samples per site. Note that the NC freshwater recreational standard is 200 CFU/100 mL

on non-rain periods. For all non-rain sample dates and stations, the fecal coliform geometric mean was 1455 CFU/100 mL, and counts exceeded 200 CFU/100 mL on 31 of 35 samples with 89 % exceedence of the state standard. For all rain periods and stations combined, the fecal coliform geometric mean was 1467 CFU/100 mL, and counts exceeded 200 CFU/10 mL on 30 of 35 samples with 86 % exceedence of the state standard. *T* test results showed no significant difference in means between wet and dry periods (p=0.49; df=68). Thus, fecal coliform pollution of Stocking Head Creek was not rain dependent; rather, fecal coliform pollution was a *chronic* condition.

Ammonium concentrations during non-rain periods were 2.67±7.59 mg-N/L (mean±standard deviation) vs. rain period concentrations of 1.56±4.65 mg-N/L. *T* test results on log-transformed data showed no significant difference in means (p=0.64; df=68). Nitrate concentrations during non-rain periods were 4.45±3.68 mg-N/L vs. rain concentrations of 3.82±3.56 mg-N/L. *T* test on log-transformed nitrate data showed no significant difference in means (p=0.38, df=68). Thus, inorganic nitrogen concentrations were not increased by rainfall-driven surface runoff, but instead they were a chronic condition in Stocking Head Creek, indicating groundwater pollution.

4 Discussion

Ammonium is a reduced form of inorganic nitrogen that is a major component of fresh human sewage or animal excreta (Clark et al. 1977). It is readily used by algae and bacteria, and an overabundance of ammonium can stimulate eutrophication (Wetzel 2001). Research in coastal plain blackwater streams and rivers has indicated that ammonium concentrations of 0.5 mg/L (ppm) or higher can stimulate algal blooms (Mallin et al. 2004). Additionally, ammonium exerts a significant chemical oxygen demand in sewage treatment plant discharges (Clark et al. 1977), as it is oxidized to nitrate. Thus, excess ammonium can lead to aquatic ecosystem deterioration through more than one pathway. The ammonium concentrations found in Stocking Head Creek, particularly at the sites nearest to sprayfields, greatly exceeded ammonium concentrations typically found in other coastal plain streams and rivers (Smock and Gilinsky 1992; Mallin et al. 2004, 2006). Previously, only during swine or poultry lagoon breaches have such concentrations been found in receiving streams in this region (Burkholder et al. 1997; Mallin 2000).

Ammonium pollution from CAFOs is not limited to runoff or seepage entering waterways. Volatilization of ammonia from CAFOs releases vast amounts of inorganic nitrogen to the atmosphere. On the North Carolina Coastal Plain alone, annual ammonia emissions from swine and poultry have been estimated as 73,500 and 22,900 metric tons (Costanza et al. 2008). Regionally, ammonia volatilization from waste lagoons, sprayfields, and litterfields carries ammonia well outside of the watershed of origination (Walker et al. 2000; Costanza et al. 2008) and is reflected in elevated ammonium concentrations in rainfall measurements downwind (Willey et al. 2006). In a study of the two most CAFO-rich North Carolina watersheds, ammonium concentrations were found to have increased approximately 500 % in the Neuse River and 315 % in the Northeast Cape Fear River between 1995 and 2005 (Burkholder et al. 2006).

Ammonium at the concentrations found in Stocking Head Creek can have other impacts besides increasing algal blooms and chemical oxygen demand. Recent studies (see review by Glibert et al. 2015) have indicated that ammonium at these concentrations can stimulate cyanobacterial production as well as increase the production of toxic microcystin, while suppressing growth of diatoms which are generally benign organisms that support the higher trophic levels. Ammonium has been found to preferentially enhance cyanobacterial growth in locales as diverse as San Francisco Bay (Glibert et al. 2014) to the South Carolina Coastal Plain (Siegel et al. 2011). Interestingly, in July 2011, an unprecedented (during 23 years of monitoring) bloom of cyanobacteria (mostly *Anabaena planctonica*) occurred in the blackwater Northeast Cape Fear River downstream from its confluence with Stocking Head Creek (and several other CAFO-impacted watersheds). The bloom lasted for several weeks and, upon decomposition, resulted in a BOD that decreased river DO from 5.3 to 0.7 mg/L (S. Petter Garrett, NCDENR, personal communication August 4, 2011).

Nitrate is likewise readily used by visible plants and algae for growth. It is mobile in soils and readily moves through the water table to enter streams (Keeney 1986). Average nitrate concentrations at six of seven stations well exceeded levels known to stimulate algal production and lead to elevated BOD in blackwater streams (Mallin et al. 2004). Nitrate concentrations in this stream

were well in excess of those reported from other streams in the southeast USA (Edwards and Meyer 1987; Smock and Gilinsky 1992; Mallin et al. 2004, 2006; Carey et al. 2007), but in line with nitrate concentrations reported from Ohio watersheds impacted by runoff from combined row crop and dense CAFO presence (Hoorman et al. 2008). Regarding human health, there is a US EPA drinking well nitrate standard of 10 mg-N/L to prevent blue baby syndrome (also called methemoglobinemia). It is notable that on three occasions, even the 10-mg/L standard for drinking well water was exceeded, and in seven of 70 samples collected, stream nitrate concentrations exceeded 9 mg/L, close to the methemoglobinemia standard.

There are no point-source discharges entering this creek. The local human population uses septic systems, but the 67 human dwellings in the watershed are spaced well away from the creek, with sprayfields located between human dwellings and riparian areas. Thus, the principal sources of nitrate are swine CAFO waste (either runoff from sprayfields, or subsurface movement into the stream), poultry litter spread on fields, and cattle manure deposited on land. Nitrate concentrations of similar magnitude have been documented from subsurface waters draining sprayfields and surface streams passing through or near swine sprayfields (Evans et al. 1984; Stone et al. 1995). Total nitrogen concentrations in Stocking Head Creek were very high compared to available data from other blackwater coastal plain streams (Smock and Gilinsky 1992; Mallin et al. 2004, 2006). To provide a wider perspective, using a large data set of 1070 streams, Dodds et al. (1998) determined that average TN concentrations >1.5 mg/L were characteristic of eutrophic conditions; this level was well exceeded according to average station TN at six of the seven sites (Table 2).

Orthophosphate is the most common form of inorganic phosphorus directly used by algae. It is not very mobile in soils and adsorbs readily to soil particles (Wetzel 2001). Orthophosphate station means were generally 2–10 times the average levels found in a selection of less-impacted blackwater coastal plain streams (Edwards and Meyer 1987; Mallin et al. 2004, 2006; Carey et al. 2007). Average orthophosphate concentrations in Stocking Head Creek were similar to those in streams draining mixed row crop and CAFO watersheds in Ohio (Hoorman et al. 2008).

Concentrations of TP≥0.50 mg-P/L or greater can increase BOD in blackwater streams by serving as a substrate assimilated by ambient bacteria (Mallin et al. 2004). In the present study, TP was higher than 0.50 mg-P/L in 11 of 70 samples. Using data from 1366 streams, Dodds et al. (1998) concluded that TP concentrations >0.075 mg/L were characteristic of eutrophic streams; average TP at all sites exceeded this threshold (Table 2). Additionally, a study of soils in eastern North Carolina using a soil phosphorus index developed by the N.C. Division of Agronomy found that the soils in counties where CAFOs were abundant (including Duplin County) contained excessively high index values (Cahoon and Ensign 2004). We note that besides direct eutrophication impacts, highly variable nutrient ratios (such as seen with this impacted stream) can lead to changes in taxonomic structure for resident phytoplankton and higher trophic levels (Glibert et al. 2015).

Bacteria require phosphorus both structurally and energetically (Kirchman 1994), and fecal bacteria growth in stream sediments can be stimulated by inputs of phosphate (Toothman et al. 2009). Also, fecal coliform bacteria within the water column can be significantly stimulated by additions of organic or inorganic P inputs >0.100 mg/L, increasing survival and reproduction (Chudoba et al. 2013). Mean and median concentrations of TP in all Stocking Head Creek stations exceeded 0.100 mg-P/L. The data suggest that high phosphorus inputs to stream waters polluted by fecal bacteria can magnify human health risks, as well as ecosystem impacts.

BOD5 concentrations at times were very high in Stocking Head Creek (Table 2). Comparison of BOD5 from many streams and rivers in coastal North Carolina indicates that concentrations of 1 to 2 mg/L are background for minimally impacted streams (Mallin et al. 2006). Elevated BOD can be stimulated by several causes. One common cause of elevated BOD is the introduction of organic materials such as human sewage or animal waste into the water; thus, dissolved organic carbon, if labile, can stimulate BOD (Clark et al. 1977). Another cause is algal blooms, which upon death and decay create a source of labile organic matter available for bacterial consumption. In a variety of coastal plain freshwater streams, tidal creeks, and lakes, Mallin et al. (2006) found strong statistical correlations between BOD and chlorophyll *a*. Ammonium pollution can exert a significant chemical oxygen demand in waterways, and elevated phosphorus concentrations can lead to elevated BOD by directly stimulating bacteria growth. In Stocking Head Creek, BOD5 was positively

correlated with TOC (r=0.833. p<0.0001), ammonium (r=0.666, p<0.0001), TP (r=0.626, p<0.0001), orthophosphate (r=0.569, p<0.0001), chlorophyll *a* (r=0.316, p=0.008), and TN (r=0.284, p=0.017). Multiple regression analyses indicated that the best predictive linear model for BOD5 in this stream was (as log-transformed data)

$$\mathrm{BOD5} = 0.952(\mathrm{TOC}) + 0.367(\mathrm{AMM}) - 3.961,\ r^2 = 0.85,\ p < 0.0001$$

Thus, the high BOD in Stocking Head Creek is directly related to common components of animal waste (TOC, ammonium, phosphorus) as well as to chlorophyll *a*, a response variable to nutrient inputs. As mentioned, the lower Cape Fear River and its estuary are on the 303(d) list due to DO violations. Stocking Head Creek enters the Northeast Cape Fear River, which enters the lower Cape Fear River at Wilmington. The high levels of BOD observed in Stocking Head Creek as well as the high nitrate, ammonium, and fecal bacteria loads contribute to the low DO concentrations frequently occurring in summer in the Northeast Cape Fear River.

Most troublesome from a human health perspective is the data indicating that Stocking Head Creek is highly polluted by fecal bacteria, by both measures of the NC criteria for impaired waters. The upper five stations exceeded 400 CFU/100 ml on 96–100 % of the time sampled, and six of seven stations exceeded a geometric mean of 200 CFU/10 mL for five samples in both 30-day periods. Importantly, elevated fecal coliform counts occurred during both wet and dry periods; this creek is chronically polluted by fecal bacteria. The stimulatory effect of phosphorus loading on fecal bacteria (Chudoba et al. 2013) further exacerbates the potential human health issues. Fecal bacteria generated by livestock within the watershed are not confined to the immediate watershed but are likely to be carried downstream into higher order streams. A bacterial source-tracking study using molecular techniques demonstrated swine waste contamination at Cape Fear River system sites well downstream from swine CAFOs (Arfken et al. 2013).

In addition to surface waters, groundwater under and near swine and poultry CAFOs can contain very high inorganic nitrogen concentrations. Ritter and Chirnside (1990) found ammonium concentrations up to 960 mg-N/L and nitrate up to 50 mg-N/L in test wells in close proximity to swine waste lagoons on the Delmarva Peninsula. In North Carolina, Westerman et al. (1995) analyzed seepage from two swine waste lagoons and found ammonium concentrations in nearby wells averaged more than 50 mg-N/L, with nitrate of 6–15 mg-N/L. In other areas, it has also been observed that both spreading and spraying of livestock waste on the landscape will lead to excessive nitrate in groundwater (Liebhardt et al. 1979).

The water table in this area varies seasonally but is relatively near the land surface on average. No groundwater level monitoring wells are immediately on-site, but the US Geological Survey operates a well 10 km southwest at Rose Hill (Well DU-157). At that well, annual average depth to the surficial water table from 2004 to 2014 ranged from 1.3 to 2.7 m, with an average of 2.2 m. The North Carolina Division of Water Resources operates a monitoring well 10 km southeast at Chinquapin (Well W29D9), and 2013 data showed depth to surficial water table ranging from 1.4 to 1.8 m below the land surface. The local predominating sandy loam soils (NRCS 2014a) have moderate to rapid permeability with permeability rates of 0.5–1.5 m/day and 1.5–3.0 m/day, respectively (USDA 2014b). Thus, following a swine waste spray event, nitrate (and likely some portion of the fecal bacteria load) could migrate into the water table in as little as a day or two and from there move laterally to the nearest stream. Thus, groundwater in a CAFO-rich watershed such as that of Stocking Head Creek is a source of nitrogen and fecal bacterial pollution to the stream waters, and continual (including non-storm event) groundwater inputs into the stream at selected locations results in chronic pollution. Simply considering overland runoff will underestimate the N flux to aquatic systems as this ignores infiltration and leaching (Carpenter et al. 1998). The lack of concentration differences in fecal coliform, ammonium, and nitrate concentrations between rainy and dry periods shows that the stream pollution is chronic and a result of normal CAFO operations and presently accepted waste disposal techniques.

This research has demonstrated that drainage basins rich in CAFOs cause chronic pollution that has both human health and ecosystem impacts. However, the scope of US confined animal operations is nationwide. Many CAFO-rich watersheds pollute freshwater streams and rivers, which eventually enter estuaries located on the Atlantic and Gulf coasts. For instance, poultry CAFO-rich Delaware, Maryland, and Virginia, and poultry and swine CAFO-rich North Carolina drain

into middle-Atlantic estuaries. Major swine, poultry, and cattle-producing states such as Arkansas, Alabama, Iowa, Illinois, Minnesota, Missouri, and Texas in the Mississippi River drainage feed the Gulf of Mexico. As such, Weldon and Hornbuckle (2006) determined that for four major agricultural watersheds in Iowa, nitrate was strongly correlated with CAFO densities, and these watersheds made an outsized contribution to nitrate loading to the Mississippi River.

An extensive study covering 90 % of estuarine surface area in the USA (Bricker et al. 1999) concluded that severe eutrophication conditions (toxic algal blooms, bottom-water hypoxia, losses of submersed aquatic vegetation) were most prevalent along the middle Atlantic and Gulf Coast estuaries. Howarth et al. (2012) have demonstrated that estuarine nitrogen discharge from a wide selection of rivers in Europe and North America is positively correlated with net watershed nitrogen inputs. That study showed that for watersheds that have positive increases in animal feed from outside the system, there is a strong correlation with riverine N flux. Many of those rivers drain watersheds rich in poultry CAFOs, swine CAFOs, or both. The magnitude of industrial livestock production indicates that not only are immediate watersheds severely polluted but the collective impacts of the numerous subwatersheds draining CAFO-rich areas contribute to major ecosystem impacts far downstream as well. As the magnitude of the CAFO style of industrial livestock production grows beyond the USA and Europe into developing nations (Thorne 2007), highly concentrated nutrient and fecal microbial pollution from these sources will similarly expand.

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References

American Public Health Association (1995). Standard methods for the examination of water and wastewater, 19th edition. 1015 Fifteenth St. NW, Washington, DC 20005.

Arfken, A.M., Mallin, M.A., Cahoon, L.B., Song, B. (2013). Monitoring swine fecal contamination in the Cape Fear River Watershed based on the detection and quantification of hog-specific *Bacteroides-Prevotella* 16S rRNA genes. Report No. 436. Water Resources Research Institute of the University of North Carolina.

Bricker, S.B., Clement, C.G., Pirhalla, D.E., Orlando, S.P. & Farrow, D.R.G. (1999). National estuarine eutrophication assessment: effects of nutrient enrichment in the nation's estuaries. NOAA, National Ocean Service, Special Projects Office and the National Centers for Coastal Ocean Science

Burkholder, J. M., Mallin, M. A., Glasgow, H. B., Jr., Larsen, L. M., McIver, M. R., Shank, G. C., Deamer-Melia, N., Briley, D. S., Springer, J., Touchette, B. W., & Hannon, E. K. (1997). Impacts to a coastal river and estuary from rupture of a swine waste holding lagoon. *Journal of Environmental Quality, 26*, 1451–1466.

Burkholder, J.M., Dickey, D.A., Kinder, C., Reed, R.E., Mallin, M.A., Melia, G., McIver, M.R., Cahoon, L.B., Brownie, C., Deamer, N., Springer, J., Glasgow, H.B., Toms, D. & Smith, J. (2006). Comprehensive trend analysis of nutrients and related variables in a large eutrophic estuary: a decadal study of anthropogenic and climatic influences. *Limnology and Oceanography* 51(1, part 2), 463–487.

Burkholder, J. M., Libra, B., Weyer, P., Heathcote, S., Kolpin, D., Thorne, P. S., & Wichman, M. (2007). Impacts of waste from concentrated animal feeding operations on water quality. *Environmental Health Perspectives, 115*(2), 308–312.

Cahoon, L. B., & Ensign, S. H. (2004). Excessive soil phosphorus levels in eastern North Carolina: temporal and spatial distributions and relationships to land use. *Nutrient Cycling in Agroecosystems, 69*(2), 111–125.

Cahoon, L. B., Mickucki, J. A., & Mallin, M. A. (1999). Nutrient imports to the Cape Fear and Neuse River basins to support animal production. *Environmental Science & Technology, 33*(3), 410–415.

Campagnolo, E. R., Johnson, K. R., Karpati, A., Rubin, C. S., Kolpin, D. W., Meyer, M. T., Esteban, J. E., Currier, R. W., Smith, K., Thu, K., & McGeehin, M. (2002). Antimicrobial residues in animal waste and water resources proximal to large-scale swine and poultry feeding operation. *Science of the Total Environment, 299*(1–3), 89–95.

Carey, R. O., Vellidis, G., Lowrance, R., & Pringle, C. M. (2007). Do nutrients limit algal periphyton in small blackwater coastal plain streams? *Journal of the American Water Resources Association, 43*(5), 1183–1193.

Carpenter, S. R., Caraco, N. F., Correll, D. L., Howarth, R. W., Sharpley, A. N., & Smith, V. H. (1998). Nonpoint pollution of surface waters with phosphorus and nitrogen. *Ecological Applications, 8*(3), 559–568.

Chudoba, E. A., Mallin, M. A., Cahoon, L. B., & Skrabal, S. A. (2013). Stimulation of fecal bacteria in ambient waters by experimental inputs of organic and inorganic phosphorus. *Water Research, 47*(10), 3455–3466.

Clark, J. W., Viessman, W., Jr., & Hammer, M. J. (1977). *Water supply and pollution control* (3rd ed.). New York: IEP-A Dun-Donnelley Publishers.

Cole, D., Todd, L., & Wing, S. (2000). Concentrated swine feeding operations and public health: a review of occupational and community health effects. *Environmental Health Perspectives, 108*(8), 685–699.

Costanza, J. K., Marcinko, S. E., Goewert, A. E., & Mitchell, C. E. (2008). Potential geographic distribution of atmospheric nitrogen deposition from intensive livestock production in

North Carolina, USA. *Science of the Total Environment, 398*(1–3), 76–86.

Dodds, W. K., Jones, J. R., & Welch, E. B. (1998). Suggested classification of stream trophic state: distributions of temperate stream types by chlorophyll, total nitrogen, and phosphorus. *Water Research, 32*, 1455–1462.

Edwards, R. T., & Meyer, J. L. (1987). Metabolism of a subtropical low gradient blackwater river. *Freshwater Biology, 17*(2), 251–263.

Evans, R. O., Westerman, P. W., & Overcash, M. R. (1984). Subsurface drainage water quality from land application of swine lagoon effluent. *Transactions of the American Society of Agricultural Engineers, 27*(2), 473–480.

Glibert, P.M., Wilkerson, F.P., Dugdale, R.C., Parker, A.E., Alexander, J., Blaser, S., Murasko, S. 2014. Microbial communities from San Francisco Bay Delta respond differently to oxidized and reduced nitrogen substrates—even under conditions that would otherwise suggest nutrient sufficiency. Frontiers in Marine Science 1, Article 17, doi:10.3389/fmars.2014.00017.

Glibert, P.M., Wilkerson, F.P., Dugdale, R.C., Raven, J.A., Dupont, C.L., Leavitt, P.R., Parker, A.E., Burkholder, J.M., Kana, T.M. 2015. Pluses and minuses of ammonium and nitrate uptake and assimilation by phytoplankton and implications for productivity and community composition, with emphasis on nitrogen-enriched conditions. *Limnology and Oceanography* (2015).

Harden, S.L. (2015). Surface-water quality in agricultural watersheds of the North Carolina Coastal Plain associated with concentrated animal feeding operations. U.S. Geological Survey, Scientific Investigations Report 2015–5080. Doi: 10.3133/sir20155080.

Hoorman, J., Hone, T., Sudman, T., Jr., Dirksen, T., Iles, J., & Islam, K. R. (2008). Agricultural impacts on lake and stream water quality in Grand Lake St. Marys, western Ohio. *Water, Air, & Soil Pollution, 193*(1–4), 309–322.

Howarth, R., Swaney, D., Billen, G., Garnier, J., Hong, B., Humborg, C., Johnes, P., Mörth, C. M., & Marino, R. (2012). Nitrogen fluxes from the landscape are controlled by net anthropogenic nitrogen inputs and by climate. *Frontiers in Ecology and the Environment, 10*(1), 37–43.

Karr, J. D., Showers, W. J., Gilliam, J. W., & Andres, A. S. (2001). Tracing nitrate transport and environmental impact from intensive swine farming using delta nitrogen-15. *Journal of Environmental Quality, 30*(4), 1163–1175.

Keeney, D. (1986). Sources of nitrate to ground water. *CRC Critical Reviews in Environmental Control, 16*(3), 257–304.

Kirchman, D. L. (1994). The uptake of inorganic nutrients by heterotrophic bacteria. *Microbial Ecology, 28*(2), 255–271.

Liebhardt, W. C., Golt, C., & Tupin, J. (1979). Nitrate and ammonium concentrations of ground water resulting from poultry manure applications. *Journal of Environmental Quality, 8*(2), 211–215.

Mallin, M. A. (2000). Impacts of industrial-scale swine and poultry production on rivers and estuaries. *American Scientist, 88*, 26–37.

Mallin, M. A., & Cahoon, L. B. (2003). Industrialized animal production—a major source of nutrient and microbial pollution to aquatic ecosystems. *Population and Environment, 24*(5), 369–385.

Mallin, M. A., Posey, M. H., Shank, G. C., McIver, M. R., Ensign, S. H., & Alphin, T. D. (1999). Hurricane impacts on water quality and benthos in the Cape Fear watershed: natural and anthropogenic impacts. *Ecological Applications, 9*(1), 350–362.

Mallin, M. A., McIver, M. R., Ensign, S. H., & Cahoon, L. B. (2004). Photosynthetic and heterotrophic impacts of nutrient loading to blackwater streams. *Ecological Applications, 14*(3), 823–838.

Mallin, M.A., Johnson, V.L., Ensign, S.H. & MacPherson, T.A. (2006). Factors contributing to hypoxia in rivers, lakes and streams. *Limnology & Oceanography* 51(1, part 2), 690–701.

NC DENR (1999) Administrative Code Section: 15A NCAC 2B .0200 Classifications and water quality standards applicable to surface waters and wetlands of North Carolina. State of North Carolina Department of Environment and Natural Resources, Division of Water Quality, Raleigh, N.C.

NRCS (2014a) Web soil Survey, National Resources Conservation Service, U.S. Department of Agriculture. On-line tool. http://websoilsurvey.nrcs.usda.gov/app/

NRCS (2014b) Appendix II, Manure characteristics. National Resources Conservation Service, U.S. Department of Agriculture. (information downloaded April 2014). http://www.nrcs.usda.gov/wps/portal/nrcs/detailfull/national/technical/nra/rca/?cid=nrcs143_014154.

Ritter, W. F., & Chirnside, E. M. (1990). Impact of animal waste lagoons on ground-water quality. *Biological Wastes, 34*, 39–54.

Sanderson Farms (2007) Sanderson Farms, Inc., Contract Producer Meetings, Company Overview and Financial Summary, 2007.

Schlotzhauer, S.D. & Littell, R.C. (1987). SAS system for elementary statistical analysis. SAS Institute, Inc., SAS Campus Dr., Cary, N.C.

Siegel, A., Cotti-Rausch, B., Greenfield, D. I., & Pinckney, J. L. (2011). Nutrient controls of planktonic cyanobacteria biomass in coastal stormwater detention ponds. *Marine Ecology Progress Series, 434*, 15–27.

Smock, L. A., & Gilinsky, E. (1992). Coastal plain blackwater streams. In C. T. Hackney, S. M. Adams, & W. H. Martin (Eds.), *Biodiversity of the Southeastern United States*. New York: Wiley.

Stone, K. C., Hunt, P. G., Coffey, S. W., & Matheny, T. A. (1995). Water quality status of a USDA water quality demonstration project in the eastern coastal plain. *Journal of Soil and Water Conservation, 50*(5), 567–571.

Thorne, P. S. (2007). Environmental health impacts of concentrated animal feeding operations: anticipating hazards—searching for solutions. *Environmental Health Perspectives, 115*(2), 296–297.

Thu, K. M., & Durrenberger, E. P. (1998). *Pigs, profits, and rural communities*. Albany: State University of New York Press.

Toothman, B. R., Cahoon, L. B., & Mallin, M. A. (2009). Phosphorus and carbohydrate limitation of fecal coliform and fecal enterococcus within tidal creek sediments. *Hydrobiologia, 636*(1), 401–412.

United Egg Producers (2010). United Egg Producers Animal Husbandry Guidelines for U.S. Egg Laying Flocks. Animal Husbandry Guidelines, 2010 Edition.

USDA (2014a) 2012 Census of Agriculture, United States Department of Agriculture, Natural Resources Conservation Service. http://www.agcensus.usda.gov.

USDA (2014b) Official Soils Descriptions, United States Department of Agriculture, Natural Resources Conservation Service, Soil Survey Division. http//soilseries.sc.egov.usda.gov/osdname.asp.

USEPA (1983). *Methods for chemical analysis of water and wastes*. Environmental Monitoring and Support Laboratory, U.S. Environmental Protection Agency, EPA-600/4-79-020.

USEPA (1997). Methods for the determination of chemical substances in marine and estuarine environmental matrices, 2nd Ed. National Exposure Research Laboratory, Office of Research and Development, U.S. Environmental Protection Agency, Cincinnati, Ohio, EPA/600/R-97/072.

USEPA (2014) United States Environmental Protection Agency, National Pollutant Discharge Elimination system (NPDES). On-line. http://cfpub1.epa.gov/npdes/search.cfm.

Walker, J., Aneja, V., & Dickey, D. (2000). Atmospheric transport and wet deposition of ammonium in North Carolina. *Atmospheric Environment, 34*(20), 3407–3418.

Weldon, M. B., & Hornbuckle, K. C. (2006). Concentrated animal feeding operations, row crops, and their relationship to nitrate in eastern Iowa rivers. *Environmental Science & Technology, 40*(10), 3168–3173.

Welschmeyer, N. A. (1994). Fluorometric analysis of chlorophyll *a* in the presence of chlorophyll *b* and phaeopigments. *Limnology and Oceanography, 39*(8), 1985–1993.

Westerman, P. W., Huffman, R. L., & Feng, J. S. (1995). Swine-lagoon seepage in sandy soils. *Transactions of the American Society of Agricultural Engineers, 38*(6), 1749–1760.

Wetzel, R. G. (2001). *Limnology: lake and river ecosystems* (3rd ed.). San Diego: Academic.

Willey, J. D., Kieber, R. J., & Avery, G. B., Jr. (2006). Changing chemical composition of precipitation in Wilmington, North Carolina, U.S.A: implications for the continental U.S.A. *Environmental Science & Technology, 40*(18), 5675–5680.

Wing, S., & Wolf, S. (2000). Intensive livestock operations, health, and quality of life among eastern North Carolina residents. *Environmental Health Perspectives, 108*(3), 233–238.

Wing, S., Freedman, S., & Band, L. (2002). The potential impact of flooding on confined animal feeding operations in eastern North Carolina. *Environmental Health Perspectives, 110*(4), 387–391.

Appendix B-3

Minnesota Pollution Control Agency

West River Dairy Expansion
Environmental Assessment Worksheet (EAW)

Comment Letters Received and Attachments

Attachments to Letter 1311 Willis Mattison Izaak Walton League of America – Prairie Woods Chapter

Prairie Woods Chapter

Dr. Bill Henke, President
962 South Shore Drive
Detroit Lakes, Minnesota 56501

May 7, 2026

Minnesota Pollution Control Agency
c/o Charles Peterson
520 Lafayette Road North
Saint Paul, MN 55155

Re: Izaak Walton League Comments on the West River Dairy Expansion Draft EAW

Dear Mr. Peterson,
Thank you and the Minnesota Pollution Control Agency staff for inviting comments on the draft West River Dairy Expansion Environmental Assessment Worksheet (EAW) and for holding a public meeting in Morris, Minnesota on April 28th.

Based on the history of past Riverview projects and confined animal feeding operations (CAFOs) in general, our review of the draft EAW for this exceedingly large expansion and the applicable criteria we have concluded that an environmental impact statement (EIS) is warranted. We find the draft EAW itself deficient in a lot of ways, but we do not call for its revision. Instead, the information we do find in the draft EAW is more than sufficient justification for moving forward into a full EIS.

Our comments in support of that conclusion are grouped according to the four specific criteria shown in Minnesota Rules 4410.1700, subpart 7. The MPCA, as the Responsible Governmental Unit (RGU) must consider these criteria when determining if a project has the potential for significant environmental effects and therefore warrants an Environmental Impact Statement (EIS):

1. Type, extent, and reversibility of environmental effects;
2. Cumulative potential effects;
3. Degree of mitigation by ongoing public regulatory authority, and;
4. Anticipation and control of effects from other studies.

Below is our summary outline with our comment topics listed as lettered subheadings under each of the four criteria. Following this summary is a more detailed discussion on each topic.

Comment Summary as Outline of Topics Covered

Criterion 1 - Type, extent, and reversibility of environmental effects -

A. EAW vastly under sizes the environmentally relevant area (ERA)
B. EAW fails to acknowledge that polluted groundwater may not be reversible
C. Effects on ground and surface water quantities and flows don't add up;
D. Potential ground water contamination by leachate from manure pits and basins is not quantified
E. Contamination by manure seepage to perimeter tile draining shallow groundwater from under manure pits delivered to storm water basin is unaccounted for
F. A report in EAW minimizes future low flow probability in Pomme de Terre River and is misleading and inconsistent with climate trends stated elsewhere
G. Crop land used for manure spreading may need containment to avoid runoff reaching surface waters
H. The EAW fails to identify potential increases in antibiotic resistance and/or the potential zoonotic infections effects of large CAFOs.

Criterion 2 - Cumulative potential effects

A. Deliberate under sizing the environmentally relevant area cannot be used to avoid impact overlap and claim impacts are not cumulative
B. EAW does not properly characterize past, present and future environmental conditions of the environmentally relevant area
C. EAW fails to account for impacts of feedlots in the impacted areas whether owned or operated by proposer or not.
D. EAW minimizes or ignores proposed project incremental contribution to cumulative potential effects
E. EAW describes purposeful avoidance of potential mitigation offered by "green infrastructure" as part of intentional project design
F. EAW fails to identify impaired waters as evidence of past and present projects

Criterion 3 - Degree of mitigation by ongoing public regulatory authority

A. The EPA has found MPCA's existing feedlot rules and permits to be inadequate
B. MPCA will not have strengthened feedlot rules in time to control this project
C. Local ordinances and county feedlot officers are ineffective
D. Federal Clean Water Act authority remains delegated to the state MPCA
E. MPCA may be in violation of MEPA which prohibits permitting polluting activity when less polluting alternatives exist
F. MPCA fails to extend its authority over pollution caused by manure delivered to other farmers and landowners

G. MPCA has failed to adopt nitrate standards for surface and groundwaters.

Criterion 4 - Anticipation and control of effects from other studies

A. No other EIS has been prepared on a feedlot of this size in the project area or similar setting
B. Compliance with TMDL goals for areas surface waters are not acknowledged
C. Other studies have found large feedlots degrade local economies and community health
D. Economic impacts are not included in EAWs but can be addressed in an EIS

Detailed Discussion of Each Topic

Criterion 1 - Type, extent, and reversibility of environmental effects – The RGU must examine the nature of the impacts, how widespread they are, and whether they can be undone.

A. EAW vastly under sizes the environmentally relevant area (ERA).
The EAW claims the area impacted by the project can be limited to the exact area of the feedlot site, the areas where manure will be spread and a one-mile radius around the off-site wells.

> *"The Environmentally Relevant Area (ERA) for the Project has been delineated to ensure that environmental effects from other projects do not overlap. The ERA is defined as the oversized Project Boundary, all identified manure application fields designated for the Project and Existing Facility, and a one-mile radius surrounding the off-site water-supply well (Attachment 20).*

This claim cannot be supported. Project impacted air, water and soils move freely across these property boundaries and are carried far beyond them, down rivers into aquifers that move and across neighboring properties and into other counties. Climate impacts are global in scale. Surface water impacts are regional and can exceed the bounds of the Pomme de Terre watershed into the Minnesota River. Therefore, the impacts of this exceeding large feedlot project on this larger more realistic and environmentally relevant scale are potentially significant and justify an EIS.

B. EAW fails to acknowledge that polluted groundwater may not be reversible
The potential for manure storage area leakage and field applied manure seepage below the crop root zone into groundwater is likely under the many thousands of acres proposed for this project. Despite the project's inclusion of extra thick clay liners under the manure storage pits, these liners can still be expected to leak up to 100 gallons per acre per day (one fifth of the allowable leakage rate). Manure application (along with commercial fertilizer) to farm fields has been shown to create the potential for seepage into groundwater even when applied at agronomic rates. Agronomic application rates are not designed to prevent excess nutrients or other farm chemicals from reaching groundwater, instead they are designed to maximize production with the least amount of application.

Once contaminated, groundwaters are extremely difficult if not impossible to clean. Drinking water sourced from groundwater may be treated to remove some contaminants but this is not a reversal of the original contamination.

C. Effects on ground and surface water quantities and flows don't add up

The expansion would use 287.5 million gallons per year, almost as much as the city of Morris, population 5,100. The project relies on two well water fields, one on site and one off site that are limited in available supply, either by impact on low river flows or excessive drawdown of aquifer levels. A back up storm and well water storage pond is planned to serve as a temporary water supply in when well extraction limits kick in. No calculations are supplied in the EAW to assure the backup will suffice during extended drought periods lasting several months if not years. An EIS will be required to estimate the probability and frequency at which the project operators may request emergency exemption from well pumping limits to keep their livestock alive. Depopulating such an enormous feedlot in a time of drought is impractical. Such an exemption places other well users and the river at risk for serious water shortages. This alone is a potential for significant impact warranting an EIS to evaluate available alternatives including the no-action alternative.

D. Potential ground water contamination by leachate from manure pits and basins is not quantified

At the public meeting in Morris on April 28th of this year, MPCA officials admitted that manure pit leakage, even at the reduced rates afforded by thicker clay liners, would likely reach groundwater. The MPCA dismissed these impacts as not being significant because "receptors" of this contamination (understood to be private or public wells) were far enough away. These estimates are subject to internal speculation and discussion with the project proposer but have not been made public. The basis for these estimates and the factors contributing to estimate uncertainties should be presented in an EIS and thus subjected to third party scrutiny.

E. Contamination by manure seepage to perimeter tile draining shallow groundwater from under manure pits delivered to storm water basin is unaccounted for

The draft EAW states:

> "To control potential seasonal subsurface saturation near the LMSAs, a drain-tile system will be installed around the perimeter of the LMSAs at an elevation below the LMSA liners. The clean seasonal subsurface water from the perimeter tile system will drain into a nearby stormwater basin, where it combines with Project stormwater.

MPCA acknowledges and allows (permits) manure storage ponds to leak and this leachate is most certain to find its way into the perimeter drain-tile system. The project should not be designed to dispose of manure contaminated seepage in this tile system in a stormwater system. The stormwater system is oversized but still can be predicted

to need discharge during wetter years. The EAW form fails to address the need for wastewater treatment in section 12.B.1. C as follows:

> "12.B.1.c. If the wastewater discharge is to surface water, identify the wastewater treatment methods and identify discharge points and proposed effluent limitations to mitigate impacts. Discuss any effects to surface or groundwater from wastewater discharges, taking into consideration how current Minnesota climate trends and anticipated climate change in the general location of the project may influence the effects."

The RGU's entry here is that this treatment requirement is "Not Applicable" which is interpreted to mean no wastewater discharge is planned. An EIS would need to resolve this contradiction/omission and either describe total containment of contaminated manure pit leachate which would seem impractical or the proposed treatment of this wastewater, possibly by land irrigation or other means.

F. <u>A report in EAW minimizes future low flow probability in Pomme de Terre River and is misleading and inconsistent with climate trends stated elsewhere</u>

> "Riverview LLP requested Moore Engineering Inc. (Moore) to evaluate discharge flows from Pomme de Terre River (River) in Appleton, MN. Moore assessed historic data from USGS Gage #05294000 to determine the percentage of time the flow in the River was less than three specified flow parameters. Historically, the trend of the Rivers minimum discharge has increased. This is most evident after 1991, as can be seen on Figure 1. Between 1931 and 1991, average minimum flow was approximately 8.5 cfs. After 1991, the average minimum flow increased to 50 cfs.

In the climate impacts section of the EAW, river flows are predicted to continue decreasing as average temperatures increase. These inconsistencies are confusing to the public and should be clarified in an EIS.

G. <u>Crop land used for manure spreading may need containment to avoid runoff reaching surface waters:</u>

The EAW states:

> "Increased precipitation may cause the loss of some acres of cropland due to saturation of low spots within fields or localized flooding after rain events. New drainage or water impoundment systems may need to be developed by landowners to handle increased volumes of stormwater in fields. If these structures are built on any of the manure application fields, they would take land out of crop production to convert to water management structures. With a contingency of over 3,000 additional manure application acres beyond what is needed each year, there is abundant operational flexibility if some portions of the fields are no longer available due to weather condition impacts.

This is a very important revelation that has potential for significant future effects that are a direct result of this project. If 3,000 acres of prospective manure application fields have known drainage issues that will not be identified and remedied until after some

future rain events this should be a red flag. Rainstorms that are increasing in frequency and severity due to climate change and cause localized flooding should not be relied upon as the trigger for corrective action. Surface or groundwater pollution is likely to have already happened. Simply eliminating these areas from future manure application after the drainage problem has been experienced will not prevent this pollution. Here, the EAW can serve its true function and trigger an EIS that can explore this issue more thoroughly and evaluate alternatives that would avoid predictable pollution.

H. The EAW fails to identify potential increases in antibiotic resistance and/or zoonotic infections effects of large CAFOs.

A report in 2020 by the Natural Resources Defense Council[1] (NRDC), reveals that US cattle producers use more than 40% of all medically important antibiotics—those that are also used in human medicine—sold for use in US livestock, and use them three to six times more intensively than many of their European counterparts.

NRDC says this overuse of antibiotics is a strategy used by the beef industry to offset heightened disease risks in feedlots, where cattle are routinely fed antibiotics to prevent disease whether or not they are ill, a practice that the World Health Organization discourages and that the European Union will no longer allow starting in 2022.
The reports also argues that there is little transparency or accountability in the beef industry regarding its use of medically important antibiotics, and little urgency to rectify the problem.

"Many infectious disease and antibiotic resistance experts believe such use is improper and helps contribute to reservoirs of drug-resistant bacteria on farms that can spread easily to humans through consumption of meat, exposure to soil or water contaminated with manure containing antibiotic-resistant pathogens or contact with animals. They also worry that it reduces the effectiveness of antibiotics that are needed to fight infections in people."

A 2023 report in the Journal of Dairy Science[2] states:

"Antibiotics are used in the dairy industry mainly to treat mastitis, respiratory illness, lameness, and enteric diseases (Andrews, 2000; Dodd and Booth, 2000; Alliance to Save Our Antibiotics, 2016). Some of the antibiotics used are particularly important in treating human infections; therefore, their continued use in dairy cattle is predicted to have dangerous implications for human and animal health (Alliance to Save Our Antibiotics, 2016). One of the main uses of antibiotics in dairy cattle is "dry cow" treatment, which involves a long-

[1] **Report slams beef industry for overuse of antibiotics -** *Chris Dall | News Reporter | CIDRAP News June 26, 2020* Antimicrobial Stewardship

[2] Factors influencing dairy farmers' antibiotic use: An application of the COM-B model - Journal of Dairy Science Volume 106, Issue 6, June 2023, Pages 4059-4071

*acting intramammary antibiotic infusion given to cows between lactation cycles, with the intention of treating existing infections and preventing new infections (Dodd and Booth, 2000). Blanket dry cow therapy (**BDCT**) involves the prophylactic antibiotic treatment of every cow at drying off to prevent infection; BDCT has historically has been used in mastitis control (Biggs, 2017). As this involves giving antibiotics to all cows, even those who are not infected at drying off, BDCT has been linked to the threat of AMR development (Brunton et al., 2012; Higham et al., 2018).*

With regard to zoonotic infection risks on large dairy farms, a 2017 article by Michigan State University[3] states that:

> *"People that work with dairy cattle can be at risk of becoming infected with a zoonotic disease. However, families of employees and people in close contact with dairy personnel can be at risk too. The compliance of preventive measures protects not only people in direct contact with animals, but also people in their homes. Prevention is especially important if there are children under 5 years old, elderly or people with weak immune systems in the families of the dairy personnel, since they can get sick more easily and could have more severe symptoms of the disease.*
>
> *Contracting a zoonotic disease not only has consequences on the health and wellbeing of the person affected, it also impacts the normal operation of a dairy farm. In times when the work force is very limited, producers cannot afford to have a valuable worker off the farm due to a preventable disease."*

Because these issues are highly complex, were not addressed at all in the EAW and because research has shown the overuse of antibiotics and failure to employ proper and consistent biological safeguards in feedlots can present significant threats to human health that may not be reversable, an EIS is warranted to fully inform the public and inform the permitting of an industrial scale livestock facilities like the one proposed.

Criterion 2 – Cumulative potential effects – The RGU must consider whether the project's impact is significant when added to other past, present, and reasonably foreseeable future projects, including those by other entities.

A. Deliberate under sizing the environmentally relevant area cannot be used to avoid impact overlap and then claim impacts are not cumulative

As was previously referenced above the EAW states:

> "The Environmentally Relevant Area (ERA) for the Project has been delineated to ensure that environmental effects from other projects do not overlap. The ERA is defined as the oversized Project Boundary, all identified manure application fields designated for the Project and Existing Facility, and a one-mile radius surrounding the off-site water-supply well (Attachment 20). **The**

[3] **Prevent Zoonotic Diseases on your Dairy Farm -** Paola Bacigalupo Sanguesa, Michigan State University Extension - November 29, 2017

established ERA for the Project avoids cumulative potential effects (CPE) as detailed in Item 21." (bold added for emphasis).

This is a conspicuous but unacceptable attempt to avoid having to disclose effects that are most certainly cumulative. The project is not proposed for a pristine, isolated island, it will be situated in an already degraded environment, part of which is caused by the existing feedlot that is being expanded. And degradation by the landscape having been converted to agriculture is evidence of past effects. If the air and water in the vicinity are not clean and the native ecosystems are not fully functioning, this project's impacts must be added to these "past and present" actions and then added to the impacts of reasonably foreseeable actions. The incremental degradation attributable to this project is certainly greater than most but it cannot escape its cumulative significance by simply declaring it does "overlap" with other "projects. These cumulative effects should be more honestly and accurately assessed by preparing an EIS.

B. EAW does not properly characterize past, present and future environmental conditions of the environmentally relevant area

The existing dairy and other farming operations are near the Pomme de Terre River, which flows into the Minnesota River. State testing has found E. coli in the Pomme de Terre watershed, as well as nutrients that can lead to algae blooms. Already, several sections of the river do not support aquatic life or human recreation. The river starts out clean but gets more and more polluted as it passes through farmland. TMDLs have been prepared to document the problems directly associated with animal agriculture in several streams and wetlands in the vicinity and the remedial measure needed to restore them to the fishable and swimmable condition required by law. A fair determination of the cumulative effects of this project requires the effects of all past, present and future projects be accurately characterized so this project's impacts can be added to them. An EIS is the appropriate tool for correcting this oversight in the EAW and informing the MPCA and the public as to whether a permit can be issued.

C. EAW fails to account for impacts of feedlots in the potentially affected areas whether owned or operated by proposer or not.

As stated in our comments above, Riverview owns and operates numerous other large feedlots, many of which in the same watershed as the proposed expansion. And other smaller feedlots not owned by Riverview are identified in maps included in the EAW. These feedlots are also in the same watershed and potentially are affecting the same wetlands, groundwater, habitat and air quality. Quantifying and accounting for the collective impacts of these existing livestock operations is usually beyond the scope and purpose a of an EAW. The EAW must identify and locate these feedlots but does not need to quantify their impacts. This is an appropriate function of an EIS.

D. EAW minimizes or ignores proposed project incremental contribution to cumulative potential effects

By declaring the environmentally affected area of the project so narrowly, as described above, the proposer attempts to side-step the need to acknowledge the incremental addition of the project to the effects of its own operations and those like it in the vicinity. This error should be corrected and the incremental impacts quantified in an EIS.

E. EAW describes purposeful avoidance of potential mitigation offered by "green infrastructure" as part of intentional project design

The EAW states:

> "The Project is not proposing to incorporate typical green infrastructure or planting trees at or around the Project site due to the negative effects they bring to the dairy cows. Common green infrastructure includes landscaping features such as trees, shrubs, and standing water that attract insects. In turn, this attracts birds and/or other animals. The United States Department of Agriculture (USDA) recommends incorporating enhanced biosecurity features into new dairy operations to avoid unwanted diseases. West River Dairy Expansion measures included designing the facility to minimize livestock exposure to birds and further prevent disease transmission, such as Highly Pathogenic Avian Influenza."

Landscaping with trees, shrubs, pollinator friendly plants near constructed ponds could provide aesthetic mitigation for the adverse effects of the enormous built infrastructure proposed in this project while providing a modicum of natural habitat for birds, insects and many other forms of important wildlife. As described above, this entire region has had its wildlife populations of all kinds, decimated by loss of these types of habitats. While this biosecurity practice may be recommended by the USDA, alternatives to these environmentally harmful biosecurity measures should be evaluated with an EIS.

F. EAW fails to identify impaired waters and loss of biodiversity as evidence of past and present projects

The writers of the EAW miss an opportunity to utilize comments from other agencies to document how past projects have degraded several aspects of the environment in the vicinity of this project.

The DNR letters and emails attached to the EAW identified several areas with high potential for restoration **very near the project** and recommended the project include plans to implement designs to prevent surface runoff or invasive species from damaging these areas:

> "The Minnesota Biological Survey (MBS) considered several areas very near the proposed project for Sites of Biodiversity Significance that did not meet the minimum biodiversity threshold for statewide significance. Despite being Below the statewide threshold, these areas may have conservation value at the local level as habitat for native plants and animals, corridors for animal movements, buffers surrounding higher quality natural areas, or as areas with high

potential for restoration of native habitat. **As such, indirect impacts from surface runoff or the spread of invasive species should be considered during project design and implementation**.

The project, as presently designed, does not specify any special designs or alternative measures intended to effectively avoid these impacts. This is an appropriate function of the EIS and underscores the need for that higher level of review that we support.

And the DNR identified several areas of high biological significance near the project largely due to bird populations, but mollusks and plant species were also mentioned:

> Ecologically Significant Areas • Three lakes near the proposed project area have been identified as Lakes of **High Biological Significance**. **These are Gorder Lake, Clear Lake, and an unnamed lake in T124N R43W Section 13**. Lakes of Biological Significance were ranked as Outstanding, High, or Moderate based on unique plant and animal presence. These lakes received their rank largely due to their bird populations.
>
> Elktoe (Alasmidonta marginata), a state-listed threatened mussel; Small white lady's-slipper (Cypripedium candidum) and prairie mimosa (Desmanthus illinoensis), both state-listed plant species of special concern
>
> • To benefit all of the above rare species and features, **we recommend that manure application rates and timing be carefully determined to ensure that nutrient input does not exceed the ability for crop nutrient uptake on the fields where it is applied.**
>
> The Environmental Assessment Worksheet should **address whether the proposed project has the potential to adversely affect the above rare features and, if so, it should identify specific measures that will be taken to avoid or minimize disturbance**. Sufficient information should be provided so the DNR can determine whether a takings permit will be needed for any of the above protected species."

Here the DNR recommends the EAW establish whether the proposed project has potential to affect these species but it does not. While buffers are shown around manure application fields near wetlands and water courses no analysis is provided to assure these buffers are sufficient to avoid or minimize the effects the DNR is concerned about. An EIS should be prepared to answer the question the DNR poses in order to inform the Department whether a takings permit will be needed. The EAW did not and likely could not provide this level of analysis.

The EAW reveals specific water body impairments near the project that included Lake Hattie had a nutrients TMDL plan approved in 2015 and the Pomme de Terre River identified turbidity (2002) and fecal coliform (1994) impairments. Muddy Creek has excessive E. Coli (2020) while Dry Wood Creek has listed impairments for dissolved oxygen (2012) benthic macroinvertebrates bioassessments (2012) Turbidity (2010) E. Coli (2010) with TMDL plans approved for all impairments in 2015.

The proposed project can be predicted to exacerbate these impairments given the EPA's finding that the state's feedlot rules are ineffective for protecting water quality (see item 3-A below). These impairments are, as evidenced by the TMDL plans prepared for

them, significant and in need of reduced loading primarily from improper handling of livestock wastes in their respective watersheds. An EIS is necessary to explore alternative methods for land application of livestock wastes from this facility as part of the remedial actions called for in the TMDLs.

Criterion 3 - Degree of mitigation by ongoing public regulatory authority - The RGU evaluates if existing, specific regulatory permits or processes can effectively mitigate the environmental impacts.

A. The EPA has found MPCA's existing feedlot rules and permits to be inadequate

The Minnesota Division of the Izaak Walton League of America on the advice of the Prairie Woods Chapter in Detroit Lakes joined with the MCEA, Trout Unlimited and the Minnesota Well Owners Organization (MnWOO) and others in signing a petition to the U.S. Environmental Protection Agency (EPA) that successfully convinced the EPA that the MPCA's current rules and permit requirements for feedlots were inadequate to protect water quality and the human environment as required by the Federal Clean Water Act. The EPA instructed the MPCA to revise or amend their rules and write more effective permits. While the MPCA is in the process of making these improvements, the proposed project is subject to the very same existing rules the EPA found inadequate.

The petition to EPA did focus on karst and sand plain regions of Southeaster and Central Minnesota but similar alluvial sands exist in the areas in and around Stevens County where manure application fields have been identified for this project.

While this fourth criterion is primarily intended to require identification of regulatory authority in place that could mitigate potential environmental impacts it can also function to identify shortcomings of existing regulations. That is precisely the situation we have here. There is no more compelling argument for ordering an EIS on this and any other large feedlot proposed in Minnesota than this finding by the highest environmental authority in the nation, the U.S. Environmental Protection Agency.

B. MPCA will not have strengthened feedlot rules in time to control this project

As stated in item 3-A above, the MPCA's rules and permit requirements for feedlots are in the process of being improved to satisfy the EPA and the public that they will adequately protect water quality. However, those improvements have not yet been made. Yet the MPCA has proceeded to draft an EAW and a prospective permit for this project under these decidedly inadequate rules.

In a footnote to a table showing depths to groundwater under the projects manure application fields the EAW states:

> **The Proposer has agreements with landowners for manure application covering over 16,500 acres. Depth to groundwater will vary throughout these acres.* ***There are no rules prohibiting***

manure application onto high water table soils. *The Proposer uses and exceeds BMPs for manure application and follows all state rules and local ordinances. (bolding added for emphasis)*

This declaration (in bold) by the project proposer demonstrates how feedlot operators can take advantage of the agency's overly lax feedlot rules to apply manure where shallow water tables are vulnerable.

The MPCA's moving this project forward to this point may be required by laws intended to streamline the permitting process. But by ordering an EIS on this and any other feedlot seeking a permit in the interim, the MPCA has the choice of forestalling inadequately designed feedlots from being constructed and operated until more adequate rules are in place. While not the intended purpose of the document, an EIS can serve as an effective guide in crafting rules and permit conditions that meet the EPA's requirements and fulfil the goals of the Clean Water Act.
This in effect, would declare a moratorium on large feedlot permits until such time as the rules are deemed adequate to protect the state's water quality.

We request the MPCA respond to this proposition by exploring their own and possibly the Environmental Quality Board's statutes and rules to assure the Agency has the authority and willingness to temporarily hold permits in abeyance for this purpose.

C. Local ordinances and county feedlot officers are ineffective

Here again, we apply this criterion to demonstrate the lack of regulatory authority at the local county or township level to mitigate identified environmental effects not otherwise addressed by state or federal rules. The Izaak Walton League's experience in Becker County and other rural counties has demonstrated local governments reluctance to effectively control water pollution from feedlots through local land use ordinances. In fact, these counties defer to the MPCA on these matters insisting that they control land use conflicts through ordinances, but they do not and will not control water pollution from these activities.

D. Federal Clean Water Act authority remains delegated to the state MPCA

While the EPA did find the MPCA feedlot rules inadequate the federal agency has not revoked the state's authority to continue issuing permits under the existing rules while the state's feedlot rules are undergoing amendments. Thus, citizens cannot depend on the federal government to prevent feedlot pollution.

E. MPCA may be in violation of MEPA which prohibits permitting polluting activity when less polluting alternatives exist

Minnesota Statutes 116D.04 (the Minnesota Environmental Policy Act or MEPA) in Subdivision 6 – Prohibitions states:

"No state action significantly affecting the quality of the environment shall be allowed, nor shall any permit for natural resources management and development be granted, where such action or permit has caused or is likely to cause pollution, impairment, or destruction of the air, water, land or other

natural resources located within the state, so long as there is a feasible and prudent alternative consistent with the reasonable requirements of the public health, safety, and welfare and the state's paramount concern for the protection of its air, water, land and other natural resources from pollution, impairment, or destruction. Economic considerations alone shall not justify such conduct."

Given that the EPA has officially notified the MPCA, the petitioners and the public (including Riverview Farms that the agency's feedlot rules are inadequate to protect water quality it is likely that if the agency does proceed to issue a permit for the project it will, in this federal agency's opinion, cause the pollution, impairment or destruction expressly prohibited by this section of MEPA when and if the project is constructed and operated as planned.

We agree with the EPA and also believe that this project will cause or is likely to cause pollution, impairment, or destruction of the air, water, land or other natural resources located within the state and that feasible and prudent alternatives to the issuance of this permitting action by the state exist including the no action (no permit) alternative. And, as MEPA states; any economic hardship such permit denial may inflict on permit applicants shall not be used to justify issuance of a permit for this or other similar projects.

Should the MPCA choose to issue this, or other large animal feedlot permits before it has properly amended its feedlot rules, we assert that such state agency action would be in violation of this prohibition section of MEPA.

In its response to these comments, we request the MPCA address this assertion and explain to us and the public why they should be considered in violation of MEPA in this situation.

F. <u>MPCA fails to extend its authority over pollution caused by manure delivered to other farmers and landowners</u>

MPCA feedlot permit writers and enforcement staff admit they have not attempted to extend permit conditions for land application of manure to secondary users. This means these secondary users have been knowingly allowed complete immune from compliance with the permittees manure management plan. This is an obvious failing of the MPCA's current feedlot rules and permits or the agency's enforcement policy.

The MPCA should not issue feedlot permits or approve manure management plans that allow this loophole that has significant potential for adverse effects on water quality. An EIS may be useful for exploring the jurisdictional options and authority the MPCA has or may need to close this loophole.

G. <u>MPCA has failed to adopt nitrate standards for surface and groundwaters.</u>

The Minnesota legislature granted the MPCA the authority and resources to develop nitrate standards to protect aquatic life uses for the state's surface waters and regulate

non-fertilizer sources of nitrates (primarily manure) from large feedlots decades ago but the agency has not completed the necessary rulemaking to implement this authority.

An EIS for this project that calculates nitrate loading to area surface waters (and groundwater) from the project may help underscore the urgency for the agency and the Minnesota Department of Agriculture to complete the rulemaking in effective way to control manure borne nitrates from polluting both surface and groundwaters.

Criterion 4 - Anticipation and control of effects from other studies - The RGU considers if the effects can already be managed through other available environmental studies or previous EISs conducted for the project or area

A. No other EIS has been prepared on a feedlot of this size in the project area or similar setting

This is an important fact and should be considered support for preparing an EIS for this project. The food industry in general has avoided formal environmental scrutiny by local, state or federal governments. Scientific studies of this industry's impacts are widely available in literature, and the impacts are myriad and widespread. We believe the MPCA is capable of a thorough literature search for these studies to corroborate this assertion. But, to assist the agency we've attached a report prepared by the Prairie Woods Chapter of the Izaak Walton League of America for Becker County's planned update of its comprehensive land use plan as it was dealing with a proposed CAFO in 2024. The report cites a number of environmental impacts identified by scientific studies.

The MPCA would be well justified in selecting this, the largest ever proposed CAFO in the state for the very first EIS.

B. Compliance with TMDL goals for areas surface waters are not acknowledged

C. Other studies have found large feedlots degrade local economies and community health

The following is taken from the abstract of Kelley J. Donham, et al article entitled: "*Community Health and Socioeconomic Issues Surrounding Concentrated Animal Feeding Operations"* [4]*.*

A consensus of the Workgroup on Community and Socioeconomic Issues was that improving and sustaining healthy rural communities depends on integrating socioeconomic development and environmental protection. In workshop sessions the following recommendations were developed:

"Workshop Recommendations

[4] Environmental Health Perspectives • VOLUME 115 | NUMBER 2 | February 2007

Priority research needs.
Community health studies. *Although sufficient research supports actions to protect rural residents from the negative impacts of CAFOs on community health, additional research could be conducted to further delineate mechanisms of effects and impacts on susceptible subgroups. These areas include psychophysiologic impacts of malodor; impacts of malodor on mental health and quality of life; and respiratory impacts of bioaerosol mixtures, especially among asthmatics, children, and the elderly. Wider and more effective application of community-based participatory research will be important to advance research in these areas.*

Sustainability of livestock production.
Federal funding for agricultural research should be reoriented to promote innovation in sustainable livestock production.

Translation of science to policy.
Requirements for issuing permits for CAFOs should include increased protections for health and the environment including the following:

• CAFOs should be sited and issued permits on the basis of total animal density allowed in a given watershed as determined by the carrying capacity.

• Environmental impact statements should be mandated for all new CAFOs. These should include environmental health, social justice, and socioeconomic issues.

• Decisions to issue permits for CAFOs should be considered in public meeting and decided at the local level.

• CAFOs should be regulated using standards applied to general industry based on the level of emissions and type of waste handling.

• Permits for manure storage basins should require bonding for performance and remediation.

• The current state of knowledge of community impacts of CAFOs warrants support for the American Public Health Association recommendation for a moratorium on all new CAFO construction."

D. Economic impacts are not included in EAWs but can be addressed in an EIS

Dr. John Ikerd, who holds a PhD in Agricultural Economics, now retired from University of Missouri-Columbia, in a Freshwater Futures May 15, 2024, webinar presentation entitled "Economic Fallacies of CAFOs", presented the following conclusions from multiple studies:

- 2008 Review: Reams of research dating to the 1940's show local economies

suffer economically and socially from industrial agriculture;

- 2001 Study: Many CAFO counties are forced to raise taxes to offset increased
  costs of repairs to rural roads and bridges;

- 2008 Study: Lower income, greater income inequality, more poverty, less active
  "Main Street", fewer stores, and less retail trade in CAFO counties;

- 2015 Study: Property values up to 7 miles from CAFO lowered by 3.1% to 26%;
  properties next to CAFOs down 88%;

- 2022 Study: Personal incomes dropped 8% from 1982 to 2017 in Iowa counties
  with most CAFOs. Other rural counties rose 41%.

Dr. Ikerd, in his own paper entitled: Economic Realities of CAFOs[5] draws the same conclusions and more. He includes an extensive list of reference publications that support his findings. Below are some excerpts from that paper on rural community impacts:

> *"Defenders claim that regardless of the need for CAFOs to meet the needs of consumers, CAFOs are necessary for the economic survival of many farming communities. They point specifically to community economic benefits from local investments in CAFOs, local sales of animals and animal products, and local employment in CAFOs and related local industries. However, decades of socioeconomic research and actual experience in CAFO communities reveal something very different. Whatever CAFOs contribute to local tax bases is more than offset by increased costs of maintaining rural roads and bridges that were not built to accommodate the heavy truck traffic associated with CAFOs. Also, local CAFOs operators typically source construction materials and labor from outside their local communities. Feeder animals, feed, and other supplies are shipped in from elsewhere. Even animal health care is typically provided by corporate veterinarians. Few of the economic benefits from CAFOs remain in local communities.*
>
> *The most frequent claim for community benefits is probably that CAFOs will increase local employment, which is sorely needed in many farming communities. However, the economic reality is that CAFOs employ far fewer people per dollar invested or unit of production than do the independent family farms they inevitably displace. The first research I personally did on this subject was an evaluation of CAFOs as a rural*

[5] "Economic Reality of CAFOs and Rural Communities" - Dr. John Ikerd - University of Missouri - Prepared in May 2020 for discussion at screenings of the CAFO documentary film, Right to Harm, and other uses.

economic development strategy. I evaluated the employment implications of PSF's planned operation in north Missouri. My conclusion was that if PSF came into Missouri, their CAFOs would displace up to three independent Missouri hog farmers for every job they created.[26] CAFOs came to Missouri, and Missouri lost more than 90% of its independent hog producers. I doubt that the number of workers employed in CAFOs in Missouri exceeds more than one-third of the independent hog farmers they displaced. In the case of CAFOs, once livestock and poultry production became specialized, previously diversified family farms became specialized producers of either livestock or crops.

Livestock and poultry were major sources of farm income that had made many diversified family farms economically viable. So, farmers who specialized in grain production were forced to farm more acres of land than before to maintain adequate family incomes. Larger crop and livestock operations meant fewer economic opportunities for farmers. With the industrialization of agriculture, the percentage of the U.S. labor force employed in agriculture dropped from 4.4% in 1970 to less than 1.5% in recent years. Even in the communities where they locate, CAFOs do not actually create jobs. They simply relocate and concentrate fewer lower-paying jobs in CAFO communities than had previously existed on family farms elsewhere.

In addition, this loss of farm families cannot be offset by people moving into rural communities from elsewhere. No one really wants to move to a CAFO community. A 2015 study reviewed thousands of assessed property values for residences located up to 7 miles distant from CAFOs. The review concluded: "Overall, the new studies confirm the [negative] valuation impacts reported in earlier studies, as they range from 3.1% to 26% losses depending on multiple factors, and that properties immediately abutting an AO [CAFO] can be diminished as much as 88%."

It takes people, not just production, to support rural communities. It takes people not only to buy farm supplies and equipment but also to shop on Main Street for cars, clothes, shoes, and haircuts. It takes people to send their kids to local schools, to attend local churches, and to serve on volunteer fire departments and local town councils. When independent family farmers are displaced by CAFOs, it's not just a matter of losing employment; it's a matter of losing the essence of what it takes to be a viable rural community."

After detailing our specific comments on the EAW above, it is important that we make some broader statements here about the deficiencies of Minnesota's environmental review process itself. The worksheets used to make preliminary determination on the potential significance of a project's environmental effects have evolved to be so focused on categorical details as to miss the big picture. The public who reads these lengthy EAWs gets lost in minute details and is never informed of the devastating, incrementally small but cumulatively significant destructions of nature that humans have committed.

The ecological setting for this massive, multifaceted food (milk) industry enterprise is one that has, over many decades, been incrementally degraded to such an impoverished level that the beneficial functions (services) original ecosystems once provided have been all but obliterated. These are the very services nature delivers for free that are essential for all life forms including humans. Pure clear air, clean and plentiful water, fish and wildlife once abounded here. Remnants of the tall grass prairie and wetland complex ecosystems that existed prior to its near total conversion to agriculture (dotted by small human communities) remain only in small insignificant patches here and there. This EAW hints at what the area used to be and in subtle ways justifies the projects contribution to the ecological destruction by explaining that the land is now only used for agriculture and therefore there is little measurable impact on the parts which remain in their "natural" state. That is to say that if natural attributes of our property have already been destroyed, our project's further contribution to that destruction can only be described as minimal or insignificant. Our proposed use is consistent with current land use. We find phrases like this used frequently in this and many other EAWs.

If the setting, the natural backdrop of this project was to be fairly described, it would have to disclose the plummeting populations of insects, birds, fish, reptiles, amphibians, fish and macroinvertebrates. It would have to describe soils that are no longer thriving ecosystems teeming with microscopic life forms important to healthy crops or native prairie. This is known science but this and other EAWs avoid mention of it. Thus, the public largely remains unaware of the apocalyptic declines and a projects likely role in continued declines. Only when a species for which we have some measure of its population trend (which is few) reaches a near extinction level to we call attention to in in EAWs and that is because it is required by law. There is no requirement to acknowledge mass declines on most all other wildlife and plant populations that are rapidly nearing extinction.

It was astonishing but revealing that the project proposer (who we all understand is allowed to draft the EAW) claims that natural vegetation (trees and shrubs) that might provide habitat for birds on or around the area used for confinement buildings would have to be removed in order to prevent the potential for viral infections transmitted by some birds to reach their livestock. When mere vestiges of nature are pronounced a threat to a human enterprise and sanctioned in a government document such an EAW, there is something seriously wrong with the process. It no longer serves the serves the spirit or intent of Minnesota's Environmental Policy Act that authorizes the document.

This is a substantive comment on all EAWs in general, but also on this one in particular. So, we request that the MPCA respond to it in its record of decision.

The scope and scale of the project under review is not fairly represented in the EAW. Riverview Dairy is a very large food industry spread widely across the landscape in Minnesota and other states. The huge dairy operation is but a fraction of the entire corporate food enterprise that, when viewed as a whole, has tremendous potential and

real impact. But current rules allow for segmenting incremental steps, whether large or small, into smaller parts.

We realize this may be allowed by current rules but nevertheless, nature responds (the environment is affected) according to natural rather than human law.

Karen Tolkkinen, a newspaper reporter put the subject project in its proper perspective, one not really allowed by environmental review because, as the EAW states below, the specific project is not presented as a phase or "stage" of any past, existing or future project, it's an expansion. And the proposer's existing facilities have already passed environmental muster so its impacts can no longer be counted.

The EAW states:

> "There are no past stages for the Project. The Existing Facility was permitted in August 2003 after undergoing environmental review and receiving a negative declaration on the need for an Environmental Impact Statement (EIS)."

In nature, serial impacts from a series of similar projects (especially large ones) in the same area add up. This by scientific definition is a "cumulative impact". But this is not definition allowed by Minnesota's environmental rules.

> "There are no planned future stages of the Project beyond what is described in this worksheet."

This statement above is also in the EAW and, for the moment it may be true. But do the public and the MPCA really believe that River View Dairy will not continue to expand and add more feedlots and even milk processing factories? EAWs are not allowed to speculate beyond what is not already in formal planning stages.

We refer to a more realistic assessment of the scope and scale of the no-less-than **fourteen** gigantic subcomponents of the larger project by the same owner. In Tolkkinen's recent Minnesota Star Tribune article she writes, *"the proposed expansion is the latest in a series of large dairies appearing in western Minnesota over the past two decades. Riverview's 13 dairy farms are located in Chippewa, Grant, Kandiyohi, Norman, Stevens, Swift, Traverse and Wilkin counties. A 14th in Traverse County, has been approved for 8,571 cows but not yet built."*

The article goes on to say: "*The Existing Facility in Stevens County was permitted in August 2003 after undergoing environmental review (EAW) and receiving a negative declaration on the need for an Environmental Impact Statement (EIS). The Existing Facility operates under the NPDES General Feedlot Permit and has undergone the addition of an anaerobic digester (2008), dry manure solids storage (2010), and liquid manure storage (2014). Additionally, the Existing Facility has increased its animal unit capacity three times (2008, 2011, and 2018)."*

Our state government's tolerance (it is not the MPCA alone) for siloing a segment of what is obviously a much larger industrial enterprise, that shelters it from closer

environmental scrutiny is a miscarriage of authority and a slow-moving environmental tragedy that is obvious to any student of the science.

It was one of the Izaak Walton League's early members, Aldo Leopold who aptly said:

> *"One of the penalties of an ecological education is that one lives alone in a world of wounds. Much of the damage inflicted on land is quite invisible to laymen. An ecologist must either harden his shell and make believe that the consequences of science are none of his business, or he must be the doctor who sees the marks of death in a community that believes itself well and does not want to be told otherwise."*

It is eminently and very possibly existentially regrettable that even our state agencies who accept and even produce flawed environmental assessments "do not want to be told otherwise".

These comments were prepared by Willis Mattison, professional ecologist, retired MPCA Regional Director now volunteering for the Izaak Walton League of America – Prairie Woods Chapter as chief science advisor. These comments are offered on behalf of the Prairie Woods Chapter with permission.

This concludes with our comments.

[9] Economic Reali es of CAFOs- Dr. John Ikerd, May, 2020

Addressing AFOs and CAFOs in Becker County's Comprehensive Land Use Plan and Zoning Ordinances

A Report to the Becker County Board, Zoning Administrator, the County Planning Commission the Comprehensive Planning Consultants and the Public

from

The Izaak Walton League of America's Prairie Woods Chapter

May 22, 2024

Comprehensive Land Use Planning

Most land use decisions are inherently local. In Minnesota local governments create their own "comprehensive plan" for growth and development. The plan establishes the way development occurs in that area. The primary purposes of the plan and the ordinances that implement it is to "promote and protect the health, safety and general welfare" of the public, to "preserve and enhance the quality of surface waters" and to "provide for the wise use of water and related land resources of the County"[1]

Decisions about local planning and zoning, local utilities and other infrastructure are all made pursuant to that plan. State law requires certain minimum elements in the plans but leaves it to localities to develop and implement them through ordinances. The plan is supposed to be reviewed, updated and approved every 10 years.

The Becker County Public Engagement Survey used to gauge citizen priorities for the current land use planning effort found that 70% of Becker County citizens thought more should be done to protect the water quality of lakes and streams. When the nearly 500 respondents were asked to note their top priorities in terms of issues facing the county 83% considered housing one of the three highest concerns. Further over 70% consider Jobs and economic development a key priority and slightly more than 50% see the environment as an issue to be prioritized.

A county's land-use decisions about the livestock and poultry operations (Animal Feeding Operations, AFOs and Confined Animal Feeding Operations, CAFOs) can

[1] Quotes from statement of purpose section 101 in Becker County Zoning Ordinance

have significant effects on the county's water quality, natural resources and human health, and economy, but impacts vary widely depending on sizes and locations of the operations. The impact of a single livestock or poultry project may seem small, but when we look at the bigger picture, the challenges to the environment and human health from both the small and industrial scale agriculture projects added together can be dramatic.

The livestock industry has experienced increasingly adverse conditions attributable to over-crowding; too many large facilities in close proximity increasing animal disease risks, depletion of available clean water supplies, saturation of available crop lands with manure and growing community animosity stemming from nuisance odor, traffic and insect (fly) populations.

Because industrial scale livestock agriculture is a recent arrival in Becker County the current comprehensive plan update is particularly well timed to perform its purpose of protecting the county's water quality, natural resources and human health as well as its economy.

The information provided here will serve to inform the County Board, the Planning Commission, the Zoning staff and the public that allowing industrial scale animal feeding operations to get established and to expand in Becker County will present a very high risk to the public health and welfare of its current and future residents, is highly likely to degrade the value of the county's natural resources and is a threat to the vitality of the County's rural economy.

Filling the AFO/CAFO Information Gap

Conventional wisdom expressed in recent deliberations about these divisions of government responsibility for livestock facilities led Becker County officials to wrongly defer to state and federal laws, permits and standards to protect surface and ground water as well as look after the general welfare and economic well-being of the county's citizens. And county zoning staff and planning commission members neither had the assignment nor the time or resources to fully research the laws or the literature

on large confined feeding operations. Zoning staff stated that no one had alerted them to issues relating to these operations and invited the public's assist in gathering more information.

The Izaak Walton League's Prairie Woods Chapter located in Detroit Lakes, the Becker County seat has offered to help fill these information gaps and provides the following documentation, resources and references.

CAFOs Are Migrating North Into the Lakes Region– Why?

New industrial scale feeding operations have been migrating north from Iowa and southern Minnesota in northwestern Minnesota in order to reduce disease risks and have access to ample clean water.

> *"The number of large concentrated animal feeding operations, or large CAFOs, in Iowa increased nearly fivefold in the past two decades, a new study from Environmental Working Group reveals, with almost all of the growth from big hog-feeding operations.*
>
> *EWG found that in 1990, Iowa had 789 large CAFOs – those housing 1,000 or more animal units – swelling to 3,963 in 2019. The findings are supported by the federal Census of Agriculture, which reported that Iowa, the top hog-producing state, housed more than 22.7 million hogs in 2017, an increase of 8.5 million since 1992.*
>
> *Swine and other livestock raised in Iowa's large CAFOs now produce 68 billion pounds of manure a year – conservatively, 68 times the total amount of fecal waste produced each year by the state's 3.15 million residents.*
>
> *Large hog CAFOs house a minimum of 2,500 pigs each, and the largest hog CAFO in Iowa houses 24,000 animals. In total, more than 60 percent of the animal waste produced by the largest CAFOs in Iowa comes from hogs. The*

mountains of animal waste produced by these facilities pose a serious and growing threat to human health, the environment and water resources in the state.

EWG used satellite and aerial imagery to pinpoint where and when the new large CAFOs appeared in Iowa. The interactive map (found at the link in footnote 2) below shows their locations, the type of facility, the animals housed there and the growth in facilities over the past two decades.[2]

Industry Claims That They Handle Manure Responsibly Don't Hold Up

Industrial farming representatives often claim farmers don't contribute to water nitrate or phosphorus pollution by over-apply fertilizers or manure because these materials cost too much, and it would be wasteful. However, Jeff Mitchell, Laboratory Supervisor for the Des Moines Iowa Water Works has found ever increasing concentrations of nitrates in the Des Moines and Racoon Rivers, primary sources of the city's drinking water over the past 50 years. In an August 2023 webinar entitled "*Nitrate in Drinking Water – Public and Private*" for the Izaak Walton League, Michell presented nitrate concentration trends for the Raccoon River from 1972-2023 shown in the graph below. By multiplying river concentrations by river flow volumes Michell calculated the total amount of nitrogen flowing past the city in 2018 (if applied as anhydrous ammonia would have cost $10 million and could have fertilized 400,000 acres, over 20% of the watershed. Since 1974, he calculated that 1.8 **Billion** pounds of nitrogen had flowed past the city in the river. Using similar calculations Mitchell demonstrated that in 2015, 116,000,000 pounds of nitrogen was lost to the river at a cost of $35,000,000, and as fertilizer it would have treated 800,000 acres (40% of the watershed).[3]

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[2] EWG Study and Mapping Show Large CAFOs in Iowa Up Fivefold Since 1990 – See interactive map at: https://www.ewg.org/interactive-maps/2020-iowa-cafos/

[3] Jeff Mitchell – 2023 Izaak Walton League Clean Water Webinar Series *"Nitrate in Drinking Water: Public and Private"* at: https://www.youtube.com/watch?v=OpSnuGti2k0

These data clearly show that farmers do over-apply both commercial and manure fertilizers at a great economic loss to the farmers themselves and at great expense to municipal water suppliers such as Des Moines to remove that fertilizer again. Nitrate removal has cost the city over $317,000 in 2016 and over $750,000 in 2015.



	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022
Number of Days in Operation	76	28	177	65	24	3	9	-	-	20
Number of Vessels Operated	313	96	726	265	72	9	58	-	-	70
Marginal Cost Per Vessel	$1,015	$1,015	$1,038	$1,159	$1,045	$1,090	$1,199	$1,199	$1,199	$1,199
Marginal Cost to Operate Facility	$317,695	$97,440	$753,588	$307,135	$75,240	$9,810	$69,542	$0	$0	$83,930

Public water supplies must meet drinking water standards, are tested often and as shown above, treatment can be effective when nitrate contamination is found, but it is very expensive. On the other hand, private well owners in rural areas lack testing, no standards are enforced and well-owners are “on their own” when contamination comes from their neighbor’s activities.

All Manure Pits and Lagoons Leak

In Wisconsin and other states including Minnesota, manure pits and lagoons are designed to limit leakage to less that 500 gallons/acre/day. This means that a three-acre lagoon is allowed to leak 1,500 gallons per day and could total over one half million gallons per year into the groundwater below. This has cause major problems for rural well owners.

A USDA study in Wisconsin examined this problem and found that not only nitrates were reaching private drinking water wells but that fecal coliform bacteria from the manure pits were traveling over three miles from the source.[4]

> *Borchardt's study found that the No. 1 risk factor for contamination was the proximity of a well to a manure storage pit. Borchardt said the closest well in the study was 150 feet from a manure pit, but even wells three miles away still have some risk of being contaminated with coliform.*
>
> *Borchardt called coliform an "indicator bacteria" for the presence of other bacteria and pathogens.*
>
> *According to state regulations, manure lagoons are allowed to leak 500 gallons per acre, per day. Borchardt said contamination of nearby wells may be due to leakage from the lagoon, as well as the tendency of farmers to spread liquid manure close to the location of their pits.*
>
> *According to a spreadsheet of permitted manure storage pits in Kewaunee County from 2017, some of the largest pits for which dimensions were listed span more than 4 acres. Borchardt said there are around 270 manure pits in the county.*
>
> *"(The findings give) policy makers and other stakeholders interested in working on solutions the information they need to think about solutions, instead of just saying 'Hey, your wells are contaminated,' " Borchardt said.*

The Minnesota Pollution Control Agency's construction standards for manure pits and lagoons are "theoretical" rather than practical. This means that if construction standards are followed the pits "should not leak more than allowed but need not demonstrate that they are indeed not leaking. Pits and lagoons are allowed to leak slightly less than 500 gal/acre/day leakage but is generally understood to be 500 non-the-less.

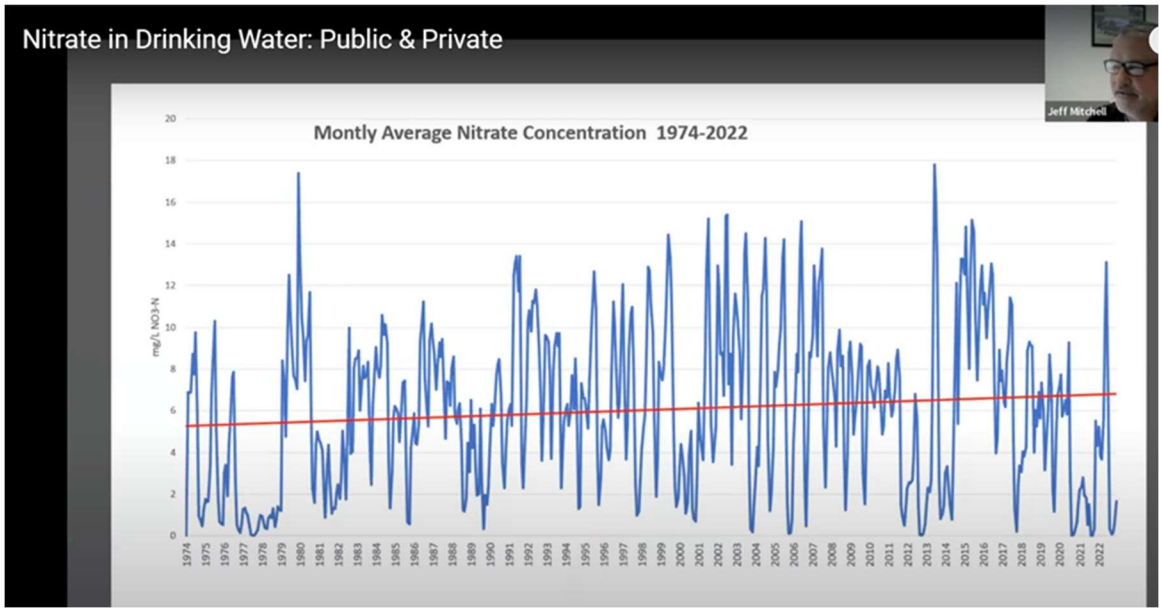
> "Minn. R 7020 requires that non-concrete liners for LMSAs be designed to achieve a theoretical seepage rate of no more than 1/56 of an inch per day. The required seepage standard is routinely considered to be approximately 500 gal/acre/day; however, this is slightly more than the actual 485 gal/acre/day allowed by the rule. Long-term protective

[4] **New research indicates tainted Kewaunee County wells tied to manure pits –** March 4, 2019 – Green Bay Press Gazette at: https://www.greenbaypressgazette.com/story/news/investigations/2019/03/04/tainted-kewaunee-county-drinking-water-wells-tied-manure-pits/3054018002/

and maintenance measures are required to meet this limit throughout the life of the structure."[5]

This maximum leak-rate standard applies to manure storage facilities no matter what kind of liner is provided including concrete, clay, Geotech (bentonite) or petroleum (plastic) liners.

It is important to note that while the MPCA rule requires this leak rate be maintained throughout the life of the pit or lagoon there are no requirements for demonstration that the structures are not leaking more than this rate at the time of construction or with aging over time.



As part of the same Izaak Walton League webinar Jesse Campbell, Private Well Coordinator for the Midwest Assistance Program, shared information the Iowa Environmental Council had gathered about the presence of nitrate in groundwater and the challenges faced by private well users in avoiding nitrate contamination. In a 2019 Water and Land News report Campbell revealed that "more than 6,600 private wells (12% of those tested) had nitrate averages at or above the EPA's legal limit (10 ppm) for drinking water systems and more that 12,330 wells (22%) had nitrate levels at or

[5] **Liquid Manure Storage Areas MPCA guidelines for design, construction, and operation of all types of liquid manure storage areas** – p 30 of 60, found at: https://www.pca.state.mn.us/sites/default/files/wq-f8-04.pdf

above 5 ppm. Natural background nitrate levels in Iowa ground water are generally less than 1 ppm.

Becker County, like most other rural counties, does not have private well protection strategies in policy or ordinances other than well setbacks from on-site sewer systems. And private well owners seldom, if ever have their wells tested to see if drinking water standards are being met. If a neighbor's CAFO should contaminate a private well, the well-owner has little recourse and will only have the choices of continuing to drink the contaminated water, purchase bottled water or drill a deeper well.

Economic Impact of CAFOs on Rural Communities

Dr. John Ikerd[6], who holds a PhD in Agricultural Economics, now retired from University of Missouri-Columbia, in a Freshwater Futures May 15, 2024 webinar presentation entitled *"Economic Fallacies of CAFOs*[7]*,* presented the following conclusions from multiple studies[8]:

- 2008 Review: Reams of research dating to the 1940's shows local economies suffer economically and socially from industrial agriculture;
- 2001 Study: Many CAFO counties are forced to raise taxes to offset increased costs of repairs to rural roads and bridges;
- 2008 Study: Lower income, greater income inequality, more poverty, less active "Main Street", fewer stores, and less retail trade in CAFO counties;
- 2015 Study: Property values up to 7 miles from CAFO lowered by 3.1% to 26%; properties next to CAFOs down 88%;

[6] Dr. John Ikerd - University of Missouri-Columbia, in a Freshwater Futures May 15, 2024 webinar presentation entitled *"Economic Fallacies of CAFOs*

[7] **Freshwater Futures' Great Lakes HABs & CAFO Manure Conference Series** May 9, 2023. YouTube Recordings from the Conference can be found at: https://www.youtube.com/playlist?list=PL_JsLZuTdlRu96Q1tarJmgjsWOHEdoIYv

[8] Studies referenced by Dr. Ikerd are attached to the cover email transmitting this report to Becker County Planning Consultants, to the County Board and to the Zoning Administrator.

- 2022 Study: Personal incomes dropped 8% from 1982 to 2017 in Iowa counties with most CAFOs. Other rural counties rose 41%.

Dr. Ikerd, in his paper entitled: *Economic Realities of CAFOs* draws the same conclusions and more. He includes an extensive list of reference publications that support his findings.[9] Below are some excerpts from that paper on rural community impacts:

> *"Economic Reality of CAFOs and Rural Communities.*
>
> *"Defenders claim that regardless of the need for CAFOs to meet the needs of consumers, CAFOs are necessary for the economic survival of many farming communities. They point specifically to community economic benefits from local investments in CAFOs, local sales of animals and animal products, and local employment in CAFOs and related local industries. However, decades of socioeconomic research and actual experience in CAFO communities reveal something very different. Whatever CAFOs contribute to local tax bases is more than offset by increased costs of maintaining rural roads and bridges that were not built to accommodate the heavy truck traffic associated with CAFOs. Also, local CAFOs operators typically source construction materials and labor from outside their local communities. Feeder animals, feed, and other supplies are shipped in from elsewhere. Even animal health care is typically provided by corporate veterinarians. Few of the economic benefits from CAFOs remain in local communities.*
>
> *The most frequent claim for community benefits is probably that CAFOs will increase local employment, which is sorely needed in many farming communities. However, the economic reality is that CAFOs employ far fewer people per dollar invested or unit of production than do the independent family farms they inevitably displace. The first research I personally did on this subject was an evaluation of CAFOs as a rural economic development strategy. I evaluated the employment implications of PSF's planned operation in north Missouri. My conclusion was that if PSF came into Missouri,*

[9] *Economic Realities of CAFOs- Dr. John Ikerd, May, 2020 at:* https://ikerdj.mufaculty.umsystem.edu/presentation-papers/factory-farms-cafos/economic-realities-of-cafos

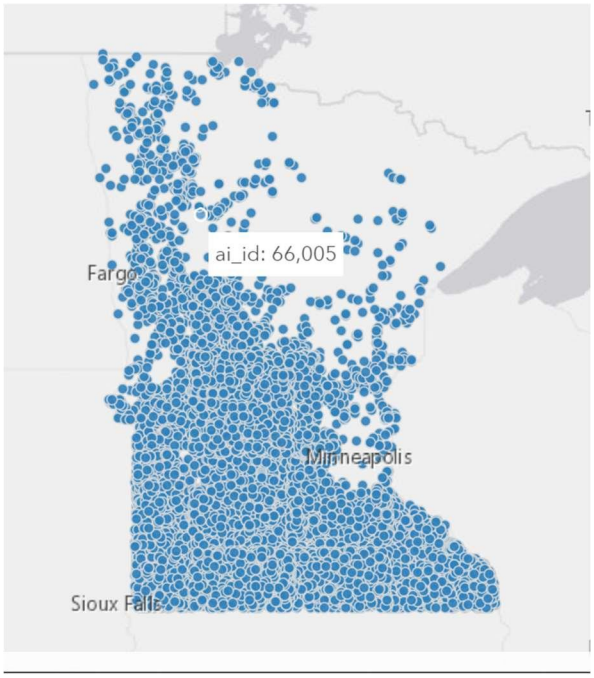
their CAFOs would displace up to three independent Missouri hog farmers for every job they created.[26] CAFOs came to Missouri, and Missouri lost more than 90% of its independent hog producers. I doubt that the number of workers employed in CAFOs in Missouri exceeds more than one-third of the independent hog farmers they displaced.

In the case of CAFOs, once livestock and poultry production became specialized, previously diversified family farms became specialized producers of either livestock or crops. Livestock and poultry were major sources of farm income that had made many diversified family farms economically viable. So, farmers who specialized in grain production were forced to farm more acres of land than before to maintain adequate family incomes. Larger crop and livestock operations meant fewer economic opportunities for farmers. With the industrialization of agriculture, the percentage of the U.S. labor force employed in agriculture dropped from 4.4% in 1970[27] to less than 1.5% in recent years.[28] Even in the communities where they locate, CAFOs do not actually create jobs. They simply relocate and concentrate fewer lower-paying jobs in CAFO communities than had previously existed on family farms elsewhere.

In addition, this loss of farm families cannot be offset by people moving into rural communities from elsewhere. No one really wants to move to a CAFO community. A 2015 study reviewed thousands of assessed property values for residences located up to 7 miles distant from CAFOs. The review concluded: "Overall, the new studies confirm the [negative] valuation impacts reported in earlier studies, as they range from 3.1% to 26% losses depending on multiple factors, and that properties immediately abutting an AO [CAFO] can be diminished as much as 88%."[29] It takes people, not just production, to support rural communities. It takes people not only to buy farm supplies and equipment but also to shop on Main Street for cars, clothes, shoes, and haircuts. It takes people to send their kids to local schools, to attend local churches, and to serve on volunteer fire departments and local town councils. When independent family farmers are displaced by CAFOs, it's not just a matter of losing employment; it's a matter of losing the essence of what it takes to be a viable rural community."[10]

10

The map below suggests the northerly progression of large feeding operations (CAFOs) into Minnesota stretching to the far northwestern corner of the state. [11]



These realities highlight the importance of using local land use plans and ordinances for proper siting, inspection and monitoring of large livestock facilities where the public can have greater confidence that pollutants are not and will not enter surface or groundwaters without detection. Becker County has set an important protective precedent by requiring water sampling for large feedlots needing conditional use permits. But the water sampling regime lacks sufficient sophistication to assure the monitoring would accomplish the intended purpose.

Industrialized Food System Engenders CAFOs.

Over the last 250 years, almost every sector of the American economy has become dominated by a handful of corporations. The forces that drove that trend have also come together to transform the most important sector of the American economy: the

[11] Source: MPCA on-line, data may not be current: https://hub.arcgis.com/datasets/mpca::feedlots-2/explore?layer=3&location=45.932764%2C-92.791165%2C6.00

food system. The way in which the United States produces and distributes is food has a profound effect on worker rights, animal welfare, air quality, water quality, the landscape, rural communities, public health, international trade, and the global climate. Livestock and poultry DNA are now owned, manipulated and sold to American farmers by a handful of corporations. Four companies control 66 percent of the hog genetics; three companies control 95 percent of the broiler chicken genetics; two companies control 99 percent of turkey genetics.[12]

Iowa Select Farms employes more than 7,400 people, including contractors, and brings about five million pigs to market annually. Since Iowa Select was founded in 1992, the states pig population has increased more than 50 percent while the number of hog farms has declined by over 80%. Pigs now outnumber human residents by a ratio of more than seven to one, and they produce a volume of manure equivalent to the waste of nearly eighty-four million people, more than the populations of California, Texas and Illinois combined.[13] One expert estimated that each confinement facility produces "the same amount of waste as a city of 90,000 to 150,000 people," spread over 640 acres with no sewage system.[14]

State and federal laws do regulate some environmental impacts of livestock operations but other than prohibiting siting in flood plains and wetlands, these regulations do not control the location of this particular agricultural land use. Recent findings by a federal agency show that Minnesota's regulations are inadequate to protect surface and groundwaters from nitrate pollution (more details on these findings are found later in this document). Therefore, without local government playing its role for proper siting of livestock facilities the government's protective network is not only incomplete but has been shown to be ineffective. This means that local governments must exercise their authority and responsibility for deciding if and where large

[12] From forward by Eric Schlosser in **Barons – Money, Power, and the Corruption of America's Food Industry –** by Austin Frederick-Island Press 2024

[13] CNBC Interview with Warren Buffet, Feb 27, 2017 quoted in "BARONS" by Fredrick – See footnote #1 above

[14] Natalie Gagliordi, "Walmart CEO outlines Omnichanel Retail Strategy to Stakeholder Associates", SDNET, June 5, 2015 as cited in BARONS by Fredrick – See footnote #1 above.

livestock facilities are located in their county in order close this loophole in the state and federal regulatory scheme.

Under the Federal Clean Water Act, direct discharge of manure to surface waters from livestock holding pits and lagoons is prohibited for large Confined Animal Feeding Operations (CAFOs are over 1000 animal units). However, the controls on land spreading of manure from both the larger CAFOs or smaller AFOs (animal feeding operations under 1000 animal units) for disposal or fertilizer use are strictly voluntary. Manure management plans, whether for CAFOs or AFOs, generally adopt what is known as best management practices (BMPs) for manure spreading based on so-called agronomic rates of application. Such agronomic rates are designed to maximize efficiency of manure application while allowing maximum application for crop production purposes alone and have no scientific basis for surface or groundwater protection. These BMPs have been demonstrated to be ineffective, not only in Minnesota but in a number of states and watersheds around the country.

Once surface and groundwaters are degraded by concentrated livestock feeding operations or other sources little can be done to reverse these impacts. Given the county's location in the heart of the lake country's tourism region, degraded surface water quality has potential significant economic consequences. Therefore, Becker County officials can benefit greatly from the experience in other states and regions by taking a "no-regrets" planning approach.

The League has researched several other states and another region of Minnesota to gather the experience of others with industrial scale agriculture beginning with Chesapeake Bay in Massachusetts.

Chesapeake Bay-

Over forty years ago, bay watchers and state officials noticed significant water quality and aquatic life deterioration. In 2004 studies investigating severely degraded water in the bay revealed the primary causes were increased nitrogen and phosphorus from intensifying livestock agriculture.

"The Chesapeake Bay is choking on nutrient pollution from a myriad of sources – from urban runoff, industry, automobiles, and human sewage, but the largest source is agriculture and, increasingly, from the manure produced by livestock, which now outnumber the watershed's human population by 11 to 1. Most of that manure is spread on the surface of nearby cropland, and studies show that within two years as much as half of its nutrient pollution washes out of the soil and into rivers and streams or seeps into groundwater. Both of these pathways lead to pollution in local waterways and, ultimately, in the Bay.

"Of the nitrogen and phosphorus that reach the Bay, agriculture is the largest source and animal manure is the largest agricultural component. Chemical fertilizers and airborne pollutants such as ammonia gas—a common manure by-product – make up the rest of the agricultural sources. This makes animal manure not only the largest source of nitrogen and phosphorus deposited on the land, but also the second largest source that reaches the Bay, behind sewage, which is deposited directly into the water. Animal manure is a major source of the Bay's pollution and must be addressed swiftly and comprehensively.[15]"

After 40 years of intensive, watershed wide efforts to restore water quality after severe degradation by non-point pollution Chesapeake Bay maybe only holding its own because crop and farm animal sources of nutrients have proven difficult to cure:

"Controlling agricultural runoff, the largest source of nutrients, has turned out to be more complex. Significant regionwide reductions have proven difficult. Data suggest, though, that efforts over the last 15 years have held the line, despite increases in crop production and growing numbers of chickens and other farm animals."

Now, as the Bay Program celebrates its 40th anniversary, its partners are contemplating what comes after 2025, the deadline for meeting most of the 31 outcomes set in its 2014 agreement. Of those, 15 are on track, 10 are off-

[15] **Manure's Impact on Rivers, Streams and the Chesapeake Bay- Keeping Manure Out of the Water, A Report by the Chesapeake Bay Foundation** July 28, 2004 at: https://www.cbf.org/document-library/cbf-reports/0723manurereport_noembargo_7567.pdf

course and the status of four others is unclear. Nutrient goals will be missed by a large margin."[16]

Maumee River in Ohio and Western Lake Erie in Michigan

Lake Erie water quality improved greatly in the 1980s-90s when point sources of nutrient pollution were remedied by the Clean Water Act but recent expansion of intensive crop and animal agriculture (factory farms) have reversed these gains and frequent toxic algae blooms have once-again become the norm.

> *"The Maumee River, overloaded with fertilizer and manure, is the single largest source of the phosphorus that triggers blooms of toxic algae in Lake Erie. Over half of the manure in the Maumee River watershed comes from an exploding number of unregulated factory farms, a new EWG and Environmental Law & Policy Center investigation reveals.*
>
> *Outbreaks of toxic algae, fueled by pollution from manure and fertilizer from farm fields, are increasing in frequency and severity across the U.S. In 2014, a toxic bloom in Lake Erie imperiled the drinking water of 500,000 residents in Toledo, Ohio. The Lake Erie outbreak, now an annual event, is getting much worse.*[17]

Tim Boring, a sixth-generation farmer and Director of Michigan's Department of Agriculture and Rural Development has bad news about Michigan's efforts to curb the farm pollution that fuels Lake Erie's toxic green algae. He finds that farm programs designed to protect water quality aren't working and that "factory-sized megafarms" are detrimental to the traditional farm economy.[18]

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[16] **After 40 years, Chesapeake Bay Program Yields Mixed Results** – Bay Journal at: https://www.bayjournal.com/news/pollution/after-40-years-chesapeake-bay-program-yields-mixed-results/article_4af88180-92b0-11ee-9d06-ab0f3bb0d72f.html

[17] **Explosion of Unregulated Factory Farms in Maumee Watershed Fuels Lake Erie's Toxic Blooms** at:

https://www.ewg.org/interactive-maps/2019_maumee/

[18] Michigan farm czar: Our fight against Lake Erie pollution isn't working: https://www.bridgemi.com/michigan-environment-watch/michigan-farm-czar-our-fight-against-lake-erie-pollution-isnt-working

Lake Erie's phosphorus pollution problems have grown worse amid decades of consolidation in farm country. Diverse family farms have been steadily gobbled up by massive operations that primarily grow either cattle feed such as corn, or cows — and not on the same piece of land. The corn grown on one megafarm is shipped to a separate factory-sized livestock operation, which produces huge amounts of manure yet lacks the cropland on which cow poop becomes a valuable fertilizer.

The corn farm, in contrast, has plenty of acreage but no cows to fertilize it. So the farmer resorts to chemical fertilizers.

"It's not the problem that we have too much manure, it's that we have manure in all the wrong places," Boring said. Boring sees the state playing a bigger role in protecting small farms, which tend to grow more diverse crops while also raising livestock, and helping them succeed without expanding their acreage.

In doing so, he said, Michigan can bolster rural communities that rely on farming and food processing jobs.

Freshwater Futures based in Petroskey Michigan recently hosted a day-long conference on CAFO manure impacts on surface and groundwater and especially their contributions to harmful algae blooms (HABs) on Western Lake Erie. The conference was recorded and featured technical experts in all fields of concern, an attorney and a local politician. The whole recording of individual speakers and their Power Point slides can be accessed at the links below:

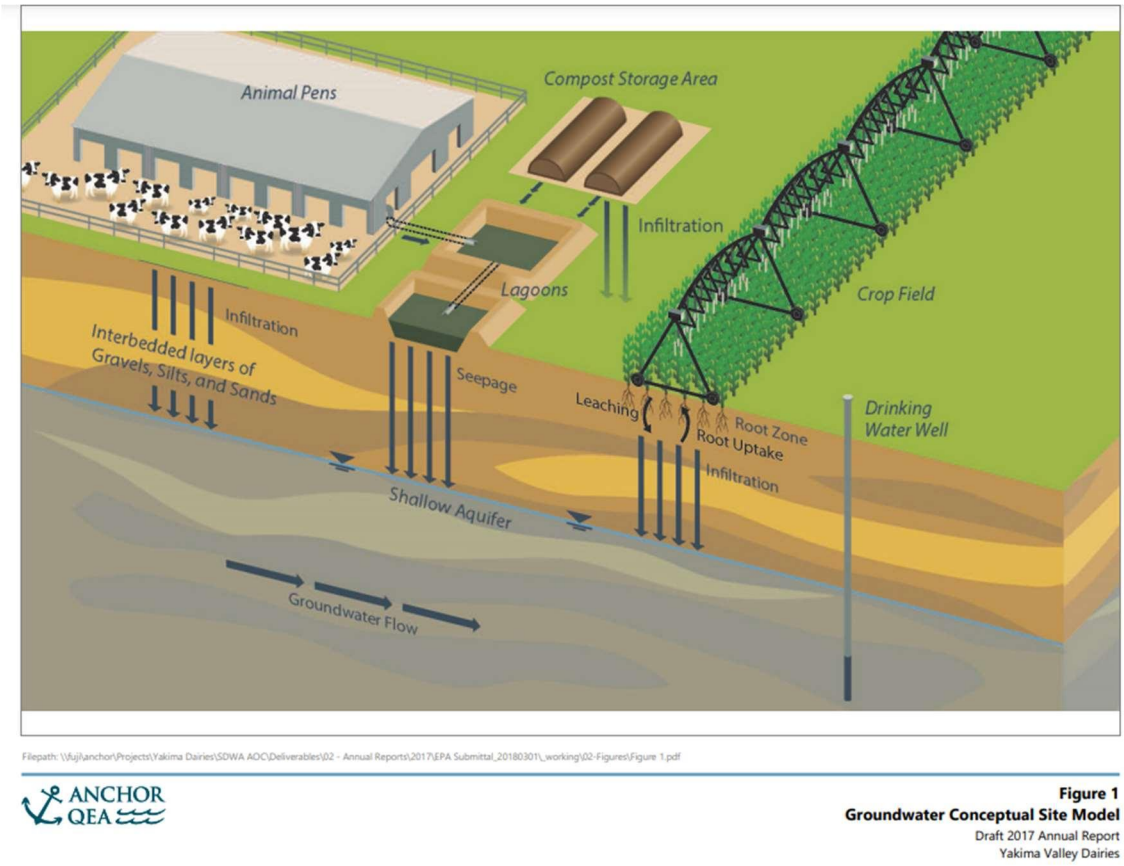
Great Lakes HABs & CAFO Manure Conference Series.[19]

- Great Lakes HABs & CAFO Manure Conference Recording
- Speaker Presentations - Power Point Slides

For additional questions and concerns on the conference or speakers please contact Sandy Bihn (sandylakeerie@aol.com) or Alexis Smith (alexis@freshwaterfuture.org) Jill M. Ryan, Executive Director, Freshwater Futures.

[19] This webinar, while useful to disclose the wide variety of environment, human health and economic problems with CAFOs may not be suitable for comp plan content. It may be better suited for a series of public education events for the Becker County Board, Planning Commission members and the public. Citizens, once well informed on CAFOs by these means can build fact-based support for the County's leaders taking appropriate actions.

The conference presenters used the graphic below to illustrate pathways for manure nutrients to reach groundwater. With permission, this graphic could be included in the pertinent section of Becker County's Comprehensive Plan.



EPA Intervenes to Protect Southeast Minnesota's Ground and Surface Water – Orders Permit and Guideline Improvements

In April, 2023, citizens petitioned the U.S. Environmental Protection Agency, saying nitrate in the groundwater in southeast Minnesota's karst region — largely from fertilizer and manure applied to crop land — poses an imminent danger to human health. They asked the Federal Environmental Protection Agency (EPA) to use its emergency authority under the Safe Drinking Water Act to intervene. [20]

[20] EPA says 'further actions' needed to protect human health from nitrate in southeast Minnesota Kirsti Marohn - November 8, 2023 at: https://www.mprnews.org/story/2023/11/08/epa-says-further-actions-needed-to-protect-human-health-from-nitrate-in-southeast-minn

In response to the citizen's petition, in August 2023 letter to four Minnesota State agencies the EPA stated that the MPCA's permit and manure management requirements for CAFOs were inadequate and needed to be "more protective" of sensitive groundwater resources. The federal agency says state agencies need to take additional steps to protect drinking water in southeast Minnesota from nitrate contamination.

> *"While this letter is largely focused on addressing immediate health concerns regarding nitrate contamination in drinking water in the Karst Region, Minnesota must also develop and implement a long-term solution to achieve reductions in nitrate concentrations in drinking water supplies. Developing a complete understanding of potential sources of nitrate contamination is an important immediate step for the state. A risk analysis of current and future nitrate contamination of the impacted groundwater will be critical for determining long-term solutions, and such analysis should incorporate the latest science and technologies. Minnesota has tools to effect reductions in nitrate concentrations through the National Pollutant Discharge Elimination System (NPDES) and State Disposal System permit programs, including development and implementation of more protective NPDES/SDS CAFO permits. In addition, Minnesota should consider adopting monitoring requirements in NPDES/SDS permits related to (1) subsurface discharges from manure, litter, and process wastewater storage, as well as (2) discharges from land application, similar to those proposed by EPA as modifications to* **the EPA-issued CAFO general permit for Idaho: https://www.epa.gov/npdes-***permits/npdes-general-permitconcentrated-animal-feeding-operations-cafos-idaho. We also encourage Minnesota to consider modifications to the state's Technical Standards for Nutrient Management with regard to land application of manure, litter or process wastewater, and any Minnesota guidelines for land application of commercial fertilizer, specific to Karst areas.*[21]

A similar petition to EPA has recently been filed by citizen groups in the Northeast corner of Iowa where identical topography and groundwater sensitivity exist. Private wells and public

[21] US Environmental Protection Agency August 2023 Letter to Minnesota Agencies found at: https://www.epa.gov/system/files/documents/2023-11/ao-rmod-reponse-letter_20230510-508.pdf

water treatments systems in this and other parts of Iowa as described above, have experienced rapidly increasing nitrate concentrations in both ground and surface waters.

> ***"The state's failure to regulate industrial agriculture pollution has steadily eroded Iowans' right to clean drinking water. For decades, Northeast Iowa residents have been exposed to dangerous levels of nitrate contaminated water. As the state reckons with high cancer levels and ongoing pollution regulation rollbacks, federal action is needed to safeguard the right to clean water. EPA must exercise emergency authority to hold polluters accountable and deliver safe drinking water in Iowa."***[22]

With this information and the additional reference material below, Becker County can learn from other's experience and hopefully take effective planning and zoning actions to avoid the predictable outcome of welcoming industrial agriculture into the county without the necessary safeguards and monitoring in place.

Becker County's sensitive surface and groundwater regions include its eastern Becker County sand plain areas with its high value trout streams, its highly developed central lakes area and its western agricultural areas served by extensive patterned drain tile and drainage ditch systems. Having sufficient, pre- and post-CAFO project construction ground and surface water monitoring in place can be a useful tool for holding industrial agriculture accountable for its operations and providing the assurances Becker County citizens need to keep from reliving the regretful experience of others.

These realities highlight the importance of using local land use plans and ordinances for proper siting, inspection and monitoring of large livestock facilities where the public can have greater confidence that pollutants are not and will not enter surface or groundwaters.

Importance of Water Sampling and Monitoring

[22] https://www.foodandwaterwatch.org/2024/04/16/iowa-environmental-groups-petition-epa-for-emergency-action-on-iowa-drinking-water/

The feedlot industry persistently claims that manure management plans limited to "agronomic rates" of application are sufficient to protect surface and groundwaters. One of the best strategies to test the performance of such plans is to actually monitor the water. New Mexico began requiring performance monitoring for large confined dairy operations as early and the 1990's. During the first six years of monitoring significant increases in ammonia and nitrates were found in groundwater.

> "*Feedlot milk production has increased dramatically in New Mexico in the past decade, along with the potential for groundwater contamination from animal wastes. State statutes require animal feedlots to maintain groundwater-monitoring wells and report water quality analyses quarterly to the New Mexico Water Quality Control Commission. This preliminary study analyzed six years of groundwater quality data from seven dairy feedlots and found elevated levels of nitrate, ammonia, chloride, total Kjeldahl nitrogen, and total dissolved solids. Samples were obtained from groundwater-monitoring wells located around dairy wastewater lagoons that were lined with clay, concrete, or synthetic membranes. Mean nitrate concentrations were significantly higher in groundwater samples taken in the vicinity of lagoons with clay liners. Lagoons with synthetic liners produced the lowest mean groundwater concentrations of ammonia and nitrate. Mean concentrations for all contaminants tended to increase as the size of dairy herds increased. Nitrate was the only groundwater contaminant measured that showed a consistently increasing trend from 1992 to 1997.*
>
> *Feedlot milk production has increased dramatically in New Mexico in the past decade, along with the potential for groundwater contamination from animal wastes. State statutes require animal feedlots to maintain groundwater-monitoring wells and report water quality analyses quarterly to the New Mexico Water Quality Control Commission. This preliminary study analyzed six years of groundwater quality data from seven dairy feedlots and found elevated levels of nitrate, ammonia, chloride, total Kjeldahl nitrogen, and total dissolved solids. Samples were obtained from groundwater-monitoring wells located around dairy wastewater lagoons that were lined with clay, concrete, or synthetic membranes. Mean nitrate concentrations were significantly higher in groundwater samples taken in the vicinity of lagoons with clay liners. Lagoons with synthetic liners*

produced the lowest mean groundwater concentrations of ammonia and nitrate. Mean concentrations for all contaminants tended to increase as the size of dairy herds increased. Nitrate was the only groundwater contaminant measured that showed a consistently increasing trend from 1992 to 1997. [23]

In 2015, the state adopted the Dairy Rule, which requires dairies to monitor groundwater impacts and to line waste lagoons. The rule came following a 2009 study by NMED's Groundwater Protection Division that found 60 percent of the state's dairies were polluting groundwater. [24]

The Public Engagement Survey used to gauge citizen priorities for the current land use planning effort found that 70% of Becker County citizens thought more should be done to protect the water quality of lakes and streams.

Becker County has already set an important protective precedent by requiring water sampling for large feedlots needing conditional use permits. But the water sampling regime lacks sufficient sophistication to assure the monitoring would accomplish the intended purpose.

The comprehensive plan could present guidelines or suggest qualified consultants for designing appropriate ground or surface water monitoring regimes to clearly gauge the effectiveness of manure lagoons or pits and manure management plans to protect waters of the county.

Ordinary Small Farmers Can Get Financially Trapped and Even Puntished by the Industry

Conventional scale (small) farmers are not at fault or in any way to be blamed for being attracted to the offers from the industry representatives. With persistently narrow profit margins it makes

[23] **Dairy Feedlot Contributions to Groundwater Contamination - A Preliminary Study in New Mexico** – Sept, 1999. At: https://go.gale.com/ps/i.do?id=GALE%7CA55884900&sid=googleScholar&v=2.1&it=r&linkaccess=abs&issn=00220892&p=HRCA&sw=w&userGroupName=anon%7Ee4bab884&aty=open-web-entry

[24] **New report looks at dairy operations in NM** -March 29, 2022 https://nmpoliticalreport.com/news/new-report-looks-at-dairy-operations-in-nm/

a lot of sense to scale up and grow overall profits even though margins remain slim. But once "in the contract system" farmers all too often discover they are on a financial treadmill that is extremely difficult to escape. Some who try unsuccessfully to escape have suffered retribution from the industry. Some farmers who once were "contract farmers" are speaking out to alert others of the risks and their efforts to transition back out. Modern Farmer's on-line ezine published one farmer's story.

> *When Paula and Dale Boles took over Dale's father's farmland in North Carolina, they thought that poultry farming would be a good way to work the land until they were ready to pass it on to their children. They obtained a contract with Case Farms, eventually switching over to Tyson, and built two poultry barns to company specifications, going $300,000 in debt to do so. It seemed like a good situation, though—as long as they could make their annual mortgage payment of $40,000, they'd be able to pay it off within 10 years.*
>
> *But soon, other expenses started getting tacked on. Tyson required a new computer system to control the temperature in the barns. This was another $70,000. Their propane bill averaged around $25,000 per year. Not making the updates wasn't really an option—no matter how much time and money you invested to be a farmer for the company, they could cut your contract at any time.*
>
> *And the income wasn't quite what they expected. Companies like Tyson pay their farmers in what's called a tournament system. There's a base pay, but whoever raises the best flock and has the best "feed conversion"—the biggest birds for the least feed— makes the most money, and payment decreases the further you go down the ladder. This essentially pits all the regional farmers against each other.*
>
> *"While contract farming, or "factory farming," has been exposed in the media for being exploitative of animals, the farmers who sign contracts with companies like Tyson, Perdue or other big players in animal agriculture also find themselves backed into a financial corner. But, over the last several years, there has been a wave of efforts to find ways to support farmers transitioning out of factory farming.*
>
> *"The way that the current structure of factory farming is designed is that the steps that carry with it the most risk and the most debt and the most liability are transitioned to the farmers," he says. "And so what you have is you have farmers building these extremely expensive facilities at the very specific direction [and] design of the company that they're working for. But they don't own the animals.*[25]

[25] **They Once Worked in Factory Farming. Not Anymore.** Modern Farmer, May 07, 2024 at: https://modernfarmer.com/2024/05/they-once-worked-in-factory-farming-not-anymore/

Antibiotic Resistence Linked to Feedlots

Becker County may not have the authority to address or curb the contribution of large animal feeding operations to antibiotic resistance but the Comprehensive Plan could provide or suggest tools to educate the public about the problem. This in turn could influence policy-makers at the appropriate level of authority to take remedial steps.

> *A **report** in 2020 by the Natural Resources Defense Council (NRDC), reveals that US cattle producers use more than 40% of all medically important antibiotics—those that are also used in human medicine—sold for use in US livestock, and use them three to six times more intensively than many of their European counterparts.*
>
> *NRDC says this overuse of antibiotics is a strategy used by the beef industry to offset heightened disease risks in feedlots, where cattle are routinely fed antibiotics to prevent disease whether or not they are ill, a practice that the World Health Organization discourages and that the European Union will no longer allow starting in 2022.*
>
> *The reports also argues that there is little transparency or accountability in the beef industry regarding its use of medically important antibiotics, and little urgency to rectify the problem.*
>
> *"Many infectious disease and antibiotic resistance experts believe such use is improper and helps contribute to reservoirs of drug-resistant bacteria on farms that can spread easily to humans through consumption of meat, exposure to soil or water contaminated with manure containing antibiotic-resistant pathogens, or contact with animals. They also worry that it reduces the effectiveness of antibiotics that are needed to fight infections in people."*[26]

The Izaak Walton League's Prairie Woods Chapter members have also compiled other authoritative reference materials including video interviews with groundwater experts, lawyers,

[26] https://www.cidrap.umn.edu/antimicrobial-stewardship/report-slams-beef-industry-overuse-antibiotics

and citizens from Minnesota and neighboring states that provide testimonials on their knowledge and experience with AFOs and CAFOs. Some of the content includes discussion of local economic impacts and local units of government adopting plans and ordinances to address industrial scale feedlots. Interactive MPCA maps of feedlot locations in Minnesota are also provided.

Other Confined Animal Feedlot Operation Resources and Video Links

Izaak Walton League Chapter Produced Videos with CAFO experts and Citizen Testimonials at:
https://drive.google.com/file/d/17fEX-Wfztuq39zN4T4uXgnFkLOzasGNf/view

Freshwater Futures' Webinar - Great Lakes HABs & CAFO Manure Conference Series | May 2, 2024 Freshwater Future
https://www.youtube.com/playlist?list=PL_JsLZuTdlRu96Q1tarJmgjsWOHEdoIYv

Explosion of CAFOs in Iowa and its Impact on Water Quality and Public health at:
https://roadactivist.org/wp-content/uploads/2018/01/Explosion-of-CAFOs-in-Iowa-and-Its-Impact-on-Water-Quality-and-Public-Health.pdf

Economic Realities of CAFOs – Dr. John Ikerd - University of Missouri-Columbia at:
https://ikerdj.mufaculty.umsystem.edu/presentation-papers/factory-farms-cafos/economic-realities-of-cafos

Antibiotic Use in Animal Medicine and Antibiotic Resistance.
https://www.cidrap.umn.edu/antimicrobial-stewardship/study-predicts-global-increase-antimicrobial-use-food-producing-animals
https://www.cidrap.umn.edu/antimicrobial-stewardship/report-slams-beef-industry-overuse-antibiotics

APPENDIX C

Minnesota Pollution Control Agency

West River Dairy Expansion Project
Environmental Assessment Worksheet (EAW)

ERRATA SHEET

1. Table 27 of the EAW did not display the existing GHG emissions of the feedlot. The corrected table is provided below.

Table 27: Operational emissions

Scope	Type of emission	Emission sub-type	Existing facility CO_2e emissions (tons/year)	Project related CO_2e emissions (tons/year)	Total CO_2e emissions (tons/year)
Scope 1	*Land Use*	*Conversion*	0	97	97
Scope 1	*Non-combustion*	*Area enteric fermentation CH_4*	33,941	47,531	81,472
Scope 1	*Non-Combustion*	*Area-barn/manure storage CH_4*	13,998	19,603	33,601
Scope 1	*Non-Combustion*	*Area-barn/manure storage N_2O*	2,848	3,988	6,836
Scope 1	*Land use*	*Are-barn/manure land application N_2O*	4,171	5,841	10,012
Scope 1	*Land use*	*Carbon sink-alfalfa conversion*	-1,901	-2,662	-4,563
Scope 1	*Combustion*	*Stationary-heaters*	90	126	216
Scope 1	*Combustion*	*Mobile equipment*	1,161	1,626	2,787
Scope 1	*Land use*	*Area-ammonia replacement*	-6,454	-9,038	-15,583
Scope 2	*Electricity*	*Grid-based*	3,641	5,098	8,739
TOTAL			**51,495**	**72,210**	**123,614**

The existing facility emissions is provided as supplemental context, representing the current baseline conditions — not an additional impact attributable to the proposed Project under review. All the manure generated at the pre-existing West River Dairy is processed through an anerobic digester that produces renewable natural gas.